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Study on the implementation of a solar photovoltaic system with self-consumption in an Educational Building

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Completing this thesis and completing this 5 year adventure at IST would not have been possible without the help of my closest friends and family. Thank you to my parents for supporting me throughout this journey and allowing me to take it.

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Abstract

In this work, the study of different remuneration schemes for the implementation of a solar energy system on a building is performed. The photovoltaic system is implemented on a public educational building, and four different schemes are compared, to understand the economic feasibility of self-consuming solar energy with and without a battery system, versus selling to the electricity grid.

For this effect, the system performance is compared to the building's needs, and the different consumption and grid-injection shares are analysed. Three of the considered schemes are legislated by the Portuguese government and their application to the simulated system is done according to the stated conditions and requirements, but the remaining scheme is not allowed, and so the legislation from a chosen country is considered. Lastly, a financial analysis is performed to evaluate the feasibility of each project implementation.

The results of this analysis show that both the non-legislated and legislated self-consumption schemes make for an attractive investment, and that savings resulting from the consumption of solar energy are much higher than the revenues from selling to the grid, which presents as the least attractive scheme. Finally, the battery implementation also does not show feasibility because the cost of technology is still too high, despite the reduction witnessed in recent years.

Keywords

Photovoltaic System; Self-consumption; Net-metering; Economic Feasibility;

Resumo

Neste trabalho, foi realizado um estudo de diferentes esquemas de remuneração para a implementação de um sistema de energia solar. O sistema fotovoltaico é aplicado num edificio de ensino público, e quatro esquemas de remuneração diferentes são comparados, de modo a compreender a viabilidade de auto-consumir energia com e sem a aplicação de uma bateria, *versus* injetar e vender energia na rede.

Para este efeito, a performance do sistema é comparada com as necessidades energéticas do edificio, e as diferentes quantidades de energia auto-consumida e injetada na rede são analisadas. Três dos esquemas considerados são legislados pelo governo Portugues, e a sua aplicação é feita de acordo com as condições e requerimentos estabelecidos. O restante esquema não é permitido pela lei Portuguesa e portanto a legislação de outro país é considerada. Por fim, é feita uma análise financeira de modo a avaliar a viabilidade de cada esquema implementado.

Os resultados da análise financeira mostram que o auto-consumo é um investimento viável, e que as poupanças que resultam de consumir energia solar são bastante superiores às receitas provenientes da venda à rede. Contudo, isto não se verifica para a implementação da bateria, que não demonstra viabilidade porque os custos da tecnologia ainda são demasiado altos, apesar das recentes reduções.

Palavras Chave

Sistema Fotovoltaico; Auto-Consumo; Net-metering; Viabilidade Económica

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Acronyms

APREN Portuguese association of renewable energy

BoS Balance of System

BESS Battery Energy Storage System

CAPEX Capital Investment

DSM Demand Side Management

EPBT Energy Payback Time

EU European Union

FIT Feed-in Tariffs

GHG Greenhouse Gases

GPBT Greenhouse Gas Payback Time

IEA International Energy Agency

LCOE Levelized Cost of Energy

LCA Life Cycle Assessment

LCE Life Cycle Emissions

nZEB Near Zero-Energy Building

OPEX Operational Expenses

OM Operation and Maintenance

PV Photovoltaic

RES Renewable Energy Source

SPBT Simple Payback Time

NPV Net Present Value

IRR Internal Rate of Return

ROI Return on Investment

UPAC Production Unit of self-consumption

UPP Small Production Unit

1

Introduction

Contents

1.1 Problem Description

Nowadays, humans are being faced with the issue that the natural resources of our planet are becoming scarcer as the years go by. The planet's population is using these resources at an extremely accelerated rate and this consumption is already leading to obvious environmental consequences. Mitigating and adapting to climate change are key challenges of the 21st century, and at the core of these challenges is the question of energy — more precisely, our overall energy consumption and our dependence on fossil fuels. To succeed in limiting global warming, the world urgently needs to use energy efficiently while embracing clean energy sources if we wish to see real changes in the near future.

Global efforts to mitigate climate change culminated in the Paris Agreement in 2015. Through the agreement, 195 countries adopted the first-ever universal and legally binding, global climate deal. To support the global climate agenda, the EU adopted other necessary climate and energy targets for 2020 and proposed targets for 2030 as part of its overall efforts and principal aim to become climate-neutral (economy with net-zero greenhouse gas emissions) by 2050 [1]. It is already possible to see the results that come as a consequence of this deal. To reduce Greenhouse Gases (GHG) emissions, the reduction of production from fossil fuels is an incredibly significant step that must be taken. For the second consecutive year in Europe, in the first half of 2019, renewables produced more power than fossil fuels, which saw a reduction of 10% in production from 2018 [2].

According to data from the European Environment Agency, the residential and commercial sectors are the third biggest sector responsible for GHG emissions, only behind the transport and industry sectors [3]. This data reports back to 2015, and since then, there have been continuous efforts to reduce these emissions by reducing consumption from fossil fuels in the sector, specifically by introducing renewables as one of (or the only) consumption source. This continuous and significant integration of Renewable Energy Sources (RESs) has only been possible due to major kick-starting incentives and support policies created by governments. However, as the technologies become cost-competitive with fossil fuels, previous incentives are being lowered, and new approaches need to be employed to maintain the evolution of said technologies and reach the desired environmental goals. It is important to study these new approaches and their viability in different conditions, to understand how (and in which cases) they should be implemented.

Due to the increasing cost-competitiveness of RESs , these new policies will push for less grid dependency and more self-consumption. Other than this, energy efficiency improvement is an important aspect to consider and develop in existing buildings, but especially new ones. In these efforts, buildings with zero net energy consumption - meaning the total amount of energy used on an annual basis is equal to the amount of renewable energy created on the site - are becoming increasingly common. As we strive to achieve the goals set for 2050, a directive by the European parliament [4] established that all new public buildings planned for construction after 2018 are Near Zero-Energy Buildings (nZEBs), and therefore need to meet certain energy efficiency criteria. Member States should also ensure that when buildings undergo major renovations, their energy performance (or of the renovated part) is upgraded in order to meet the requirements set by the European Union (EU), ensuring also their technical, functional, and economical feasibility. Furthermore, the directive states that the public sector in each Member State should be the leading example for better energy performance in buildings, especially those that are "frequently visited by the public". Among the whole building sector, educational buildings are promising spaces to serve as an example for the measures and changes mentioned above. Besides being places that are visited by the public everyday (by students, teachers and other staff, and parents), these facilities present as good candidates for renovations and RES implementation. For this purpose, various projects that aim to improve energy performance in schools have been created by the EU in recent years [5,6].

For the possibility of improving a building's self-consumption even further, the viability of implementing a Battery Energy Storage System (BESS) together with the RES should also be studied, especially seeing how battery technologies have been a growing solution that has already shown viability in some industries. At the end of the day, the renewable-based electrification and energy efficiency changes in buildings are some of the most cost-effective ways to decarbonize the European economy in the short term and can have a significant contribution to achieving energy and climate targets. Educational buildings play an important part in this path forward, since they can serve as encouragement for the general public to be interested in projects concerning RES and energy efficiency, and also for other entities to implement the same kinds of changes. New and successful projects will serve as tremendous incentives for other member states to move forward in the path for a more efficient sector and better RESs integration in public buildings.

1.2 Objectives

Considering the problem description above, this thesis aims to show the feasibility of implementing a Photovoltaic (PV) system in an educational building considering new regulations and incentives for this technology. This building is located in the southern region of Portugal, and a solar PV system is to be integrated with the purpose of self-consuming the energy that it generates. The system will be dimensioned considering the building's energy needs, and a range of self-consumption shares will be tested to evaluate which implementation is more economically viable. The objective will not be to reach a self-sufficient system, as there will always be a grid connection for buying energy when it is needed and selling any surplus of PV generation. On the one hand, to allow for the system implementation considering higher self-consumption shares, the addition of a complementary storage system is studied, and on the other hand, for a 0% self-consumption share, the remuneration for the sold energy is different and other conditions and requirements have to be considered.

Only one type of solar cell technology is considered, but a number of models from different supplier are tested, in order to choose the most suitable considering the desired power capacity and investment possibilities. An economic analysis of the system is performed, as well as a Life Cycle Assessment (LCA). Given these studies, it is possible to calculate the Simple Payback Time (SPBT) of the system, the Energy Payback Time (EPBT) and the Greenhouse Gas Payback Time (GPBT). All these calculations are done using the *PVSyst* software.

The main objectives of this thesis are as follows:

- Size a PV system considering different shares of self-consumption and various remuneration methods;
- Study the possible implementation of a BESS to reach higher shares of self-consumption;
- Perform a comparative economic analysis of the various system implementations: considering distinct remuneration methods and battery implementation;
- Examine the environmental impact of the system implementation through an LCA study;

1.3 Structure

This thesis constitutes of six chapters and two annexes. In the present chapter, the problem description and objectives which are the baseline for this work, as well as the structure, are presented.

Chapter 2 presents a brief introduction to PV technology, together with a state-of-the-art review that outlines the conditions and findings of previous RES projects which analyze several aspects that will also be studied in this thesis. The cost of technology is detailed, followed by the current role and development of the technology in the world and specifically in Portugal. The shift from Feed-in Tariffs (FIT) schemes to self-consumption is analyzed, considering also the implementation of a BESS, and PV projects on educational buildings specifically, are analyzed. Finally, the research gaps to be fulfilled by this work are discussed.

Chapter 3 details the theoretical and mathematical models that will be applied during the project implementation. The model used to describe the PV cell's power output is detailed, as well as the calculation of the effective irradiance. Then, all of the compensation schemes that will be studied are presented, detailing the requirements included in the Portuguese law that should be met for a correct implementation. Lastly, the calculations for the financial analysis and the LCA are detailed.

Chapter 4 describes the conditions for the project implementation. First, the meteorological conditions of the location are detailed (temperature and irradiance), as well as the building's conditions, from available rooftop area, to the current energy consumption needs. The components of the system (modules, battery, and inverter) are chosen from a catalogue, but only the modules and inverter are dimensioned, since the battery size is dependent on the PV system production.

Chapter 5 provides the results of the project implementation. The PV production outcome is detailed and compared with the user's needs throughout the year. The BESS is dimensioned and the revenues and savings from each compensation scheme are calculated. Lastly, the total system costs are determined and the results for the financial and the life cycle analysis are presented.

Chapter 6 draws the main conclusions taken from this study and presents recommendations for possible future work, to improve on what has been done.

Annex A details the building's monthly consumption alongside its costs, and the monthly and daily consumption for each tariff period are also presented. Annex B exposes the technical specifications of the system components (module, inverter, and battery).

2

State of the Art

Contents

The present chapter serves to give a general understanding of the state of PV technology and its purpose in today's world, and how it may develop in the coming years. Beginning with an introduction to the technology, its overall characteristics are presented, followed by a detailed description of the main costs associated with PV projects. The share of PV generation and its growth in recent years is shown for the world and Portugal specifically, as well as the support policies responsible for that growth. It is seen how those policies apply today and explore PV projects for residential, commercial and, with added attention, educational buildings. Lastly, we step away from the economic benefits of this RES and review the LCA of various projects, to understand the environmental impacts of the technology.

2.1 Introduction to PV technology

Since the creation of the first commercially viable solar cell in the 1950s [7], the technology has shown significant advancements, and PV systems have evolved from a niche market of small-scale applications to a mainstream electricity source. The initial growth of the technology was mainly due to FIT, which were implemented to improve the attractiveness of RESs in general, and therefore, accelerate investments in the field. The tariff guaranteed an above-market price for the producers, and contributed greatly for the deployment of small-scale RESs in general, especially solar PV systems. Due to the significant technological advancements achieved during the past decade, the cost of electricity generated from PV systems has been decreasing significantly, which is proven with the Levelized Cost of Energy (LCOE) calculation. This parameter represents the average revenue per unit of electricity generated that would be required to recover the system's investment costs.

Besides the significant impact of FITs, the growth of PV systems is also related to its many advantages: solar energy is, of course, available everywhere in the world and does not need to be imported from other countries, which reduces environmental impacts associated with transportation and also reduces a certain country or region's dependence on imported oil. The electricity produced by PV technology is clean and silent, since neither fossil fuels nor moving parts take part in the process. Most importantly, the lack of moving parts makes the technology reliable for long periods of time with little or no maintenance. The systems are quiet and, in small scale, visually discreet since they are usually roof-mounted, taking up space that was not being used before anyway. They can be easily scaled, meaning that a system can be constructed to any size according to the specific power needs.

However, no technology or RES are perfect. Solar power is a variable energy source, meaning that it is intermittent and unpredictable, so there are times during the day when generation is very low or none at all. Particularly for off-grid systems, storage is a necessity, which leads to significant additional costs that can hurt the case for the deployment of these systems. Even without a storage system, the initial investment on a PV system is still the most significant cost the investor will have to take on. Nevertheless, as technologies evolve and conversion efficiencies are improved, the LCOE for these systems continues to decrease, also leading to a significant reduction of the systems' payback time. Nowadays, for the most part, the advantages of PV systems outweigh the disadvantages, and the technology is being deployed at large scales to help power the electric grid, while becoming increasingly cost competitive with conventional fuels [8].

2.2 Cost of technology

The costs associated with a PV system correspond to the Capital Investment (CAPEX), which refers to the amount that is payed upfront during the year of installation of the system; and the Operational Expenses (OPEX) which consist only of Operation and Maintenance (OM) costs that are payed throughout the years after the installation is finished, during which the system is operating.

2.2.1 CAPEX

The capital investments of a PV system can be divided into two components: PV modules and Balance of System (BoS), which includes a wide range of different components, from hardware to management costs. As a result of the steady growth in cumulative installed capacity every year, the price of PV modules has decreased dramatically over the past years. According to reports from the European Technology and Innovation Platform for Photovoltaics (ETIP PV) [9], the average sales price of PV modules collapsed by almost 80% between the years of 2008 to 2012. For decades, module prices have very closely followed a learning curve, meaning that each time the global cumulative PV generation capacity doubles, the price of modules decreases by a certain percentage (learning rate). In the last decade, the learning rate has been about 40%, but is expected to be around 30% for the ones to come, which is mainly due to the improvement of manufacturing processes, improved module efficiency and use of fewer materials.

The price of modules has been declining at a faster rate than BoS components, so the latter has grown to form a larger share of the CAPEX. Particulary, in smaller systems, BoS can represent more than half. Most BoS components (excluding the inverter) are still conventional technologies, so they do not show the same potential in price reduction as silicon and other semicondutor devices. However, since a large part of these components are dependent on the system's surface area, their share and impact on the CAPEX can be reduced in this sense. The system's area is related to module efficiency, so if the efficiency increases, the area decreases and the impact of BoS components on the CAPEX will decrease. The same report from ETIP PV as mentioned above, also showed that the share of area-dependence was about 50% of the total BoS price at the time. Considering a stable improvement on efficiency, it was concluded that by 2030, the total price would decrease by 15% due to the reduced PV system area alone.

The BoS can be divided into hardware and soft costs. Hardware costs include all the materials needed to construct the system: inverter, racking, electrical wiring, and battery (if necessary); and soft costs include the cost of installation labor, all relevant permits, and all overhead costs including the marketing, sales and administrative costs associated with the system. We can see these costs (along with the module) all together in Figure 2.1, which allows to get a better sense of the different contributions they have to the final CAPEX value.

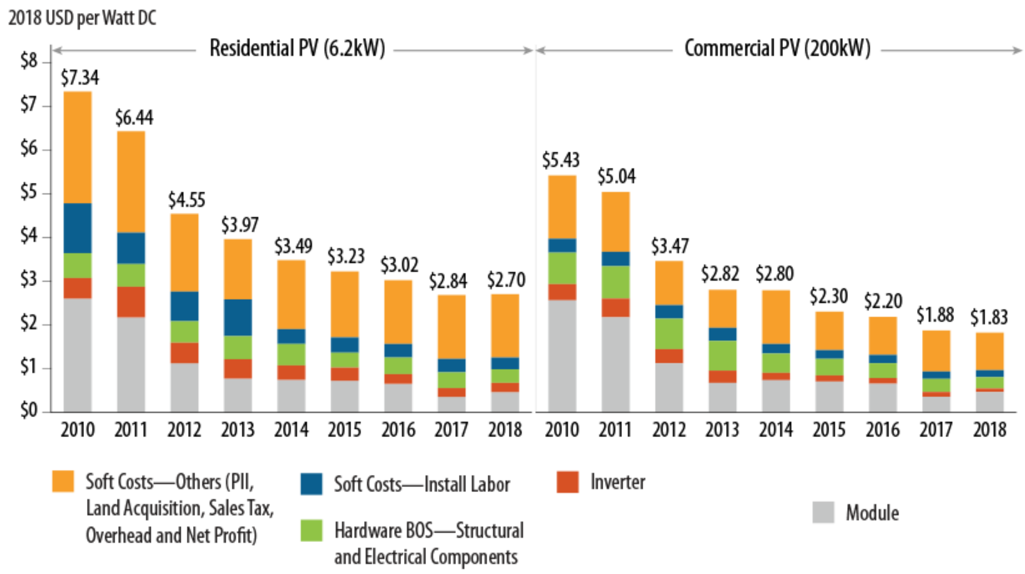

Figure 2.1: Evolution of the shares of different costs ($/Wdc) included in the CAPEX, for residential and commercial buildings in the US.

This data, taken from a benchmark report by NREL [10], presents the evolution of the CAPEX from 2010 until 2018, both for residential and commercial buildings. Confirming what has been stated before, it is very clear from this graph that the module costs have been lowered significantly in recent years, now making the BoS the main contributor to the CAPEX.

2.2.2 OPEX

For conventional energy generation, like in combined cycle power plants, the majority of the LCOE corresponds to variable OM costs, associated to fuel. In solar PV there are no fuel costs related to the generation of electricity, so operational costs are a much smaller part of the LCOE, which is dominated by the CAPEX. This was proved in a study performed by Elshurafa et al. (2018) [11], where it was seen that the OM costs represented only 8% of the LCOE, and the rest corresponded to the BoS and module costs. Usually, maintenance costs consist of all kinds of inspection to the array (general damage control, soiling removal, tilt adjustment, etc.), the mounting system, electrical connections, the inverter, and the battery. The need for OM is particular to every type of system, depending on both size and location, so it can be difficult to find a consensus, since data from different countries varies significantly. For example, most residential systems need hardly any maintenance since rain and snow will clean up the modules, and small inverters also need little to no maintenance and are usually only replaced at the end of their lifetime. Even if some systems are less dependent on maintenance, high quality services mitigate potential risks to the system, so it is up to the investor to decide how willing he is to carry that risk for lower OM costs.

2.3 Growth of PV development, and crucial support policies

2.3.1 In the World

Reports everywhere show that renewable energies, specially wind and PV generation, continue to grow far more rapidly than any other form of energy. In 2018, the generation from these two sources alone accounted for more than 40% of that year's renewable growth, with solar energy showing a growth of nearly 29% [12]. In the world, China was the biggest contributor to this growth in renewables, surpassing the entire OECD. In solar generation alone, the country contributed for almost 50% of the growth in global capacity. Their overwhelming contribution share in the generation mix can be seen in Figure 2.2.

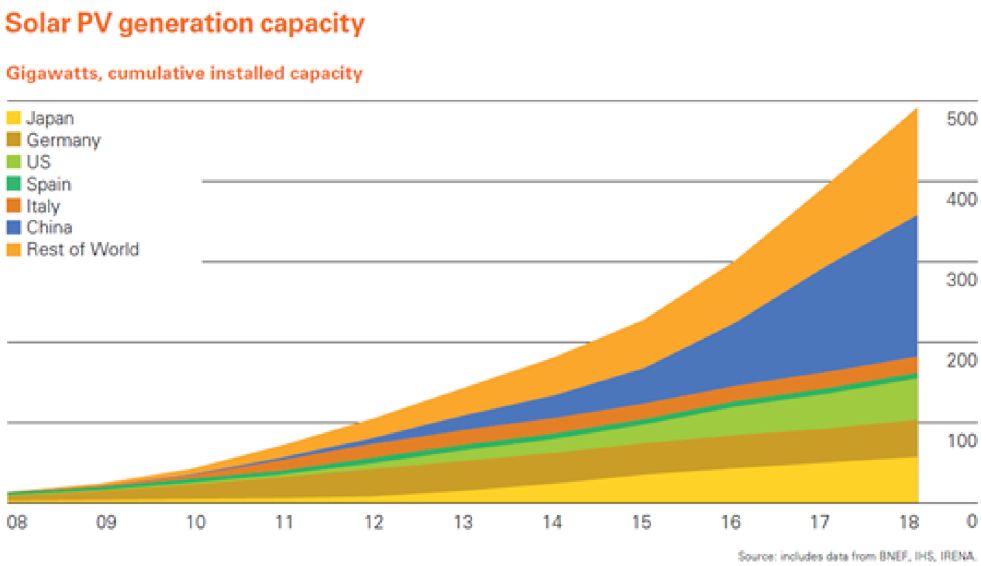

Figure 2.2: Evolution of Solar PV cumulative installed capacity, in GW, in different countries.

Over the last decade, the deployment of this technology in homes, commercial buildings and industry has been stimulated by various different policies and strong incentives, leading to its continuous exponential growth. According to the International Energy Agency (IEA), in most countries, commercial and residential systems already have electricity generation costs that are lower than the variable portion of retail electricity prices [13]. Distributed PV systems are becoming increasingly economically attractive, which could lead to a rapid expansion in the coming decades, attracting millions of private investors in the process.

In the coming years, PV capacity is expected to continue growing along a similar path than what has been observed through the last decade. As it starts to become more common for consumers to generate their own electricity, new challenges for the providers and policy makers will be presented. According to forecasts by the IEA, the expansion of PV in the EU will start to pick up with China, as projects become more economically attractive with policy improvements.

In IEA's "World Energy Outlook 2019" [14], two different scenarios for the future are considered: one that shows the outcome if the world continues along its present path, without any additional changes in policy; and another that incorporates today's policy intentions and targets. For the latter, energy demand rises 1% each year until 2040 (opposed to 1.3%) and low-carbon sources (led by solar PV) supply more than half of this growth.

Policy changes regarding RESs have been essential for an increase of their share in worldwide energy generation. For PV systems especially, as mentioned previously, the initial investment is a significant burden to the investor and even if that has been decreasing significantly over the last years, the incentives coming from governments as a way to promote RESs were incredibly important to "kickstart" their growth. In a study done by Campoccia et al. (2008) [15] different support policies for RESs adopted in the EU were analyzed. They were reinforced as a way to meet Kyoto protocol targets to reduce GHG emissions, with FIT being the most adopted one for PV systems, among four main policies. It was shown that the countries adopting the FIT policy present the most effective promotion of both PV and wind systems, and therefore the most significant growth in generation from these sources.

As a result of high FITs through the last decade, PV technology matured, and its costs have been decreasing significantly. With this decrease, PV has reached a threshold of economic feasibility and the FIT schemes have been reduced or even terminated in various countries. For electricity companies to provide PV solutions that are still affordable to costumers, innovation and sustainable solutions are needed. Currently, this means shifting to self-consumption of PV energy rather than selling it. [16]

2.3.2 In Portugal

Solar generation can only grow and reach the desired goals if we continuously invest in it, especially where it is most profitable. Portugal, like the rest of the EU, has been increasing generation from renewables in efforts to replace fossil fuels and is a very strong candidate to become one of the leaders of this shift. According to Portuguese association of renewable energy (APREN), the RES installed capacity in Portugal has had a stable increase since 2015, with a yearly average growth rate of 7% [17]. From 2015 to 2019, solar energy has grown by more than 80% and installed capacity in 2019 reached 828

MW, representing 2.2% of all power generation in the country. The main PV power plants in Portugal are located in the south, in the Alentejo region. Combining the biggest utility-scale systems, they account for more than 70 MWp of energy [18]. The popularity of this location comes from the fact that it has some of the highest values of yearly solar irradiance in Europe, and in 2015, over one third of the installed solar capacity in the country was located in Alentejo [19].

The desire for investment in solar power plants has been growing steadily in the last years, and it is currently reaching levels that not even the most optimistic supporters of RES would expect. In numbers revealed by the Portuguese Secretary of State for Energy [20], in 2020, the electricity system operator Redes Energéticas Nacionais (REN) received around 400 requests for grid connection for renewable energy power plants. A majority of these requests, adding up to 80 GW, were solar PV projects. Given the fact that the entire installed power capacity of Portugal stands at 22 GW and in 2019 only 11.8 GW were actually consumed, this serves to highlight the significance of the number of requests. The interest in installing large scale solar in Portugal can be attributed to its quickly decreasing cost, especially after a generation auction held in Portugal in 2019 set a world breaking record for the lowest winning bid at 14.76€/MWh, which is 67% lower than the tariff cap of 45€/MWh [21].

As for non-utility scale projects, a new decree-law [22] issued in 2019, that has come into force since the beginning of 2020, was created to improve self-consumption guidelines. Portugal is no exception to the recent lowering of FITs (cutting them altogether in 2012 [23]), and so new regulation needs to take effect in order to help reach the desired goals for renewable energy consumption share. This new law aims to provide a clearer and more favorable framework for the deployment of small and middle-sized RES projects and is expected to significantly increase the development of self-consumption projects.

With measures like this one falling into place, combined with incredibly low energy prices and an enormous potential of exploitation due to the characteristics of the location, utility-scale as well as smaller projects have significant room to grow in Portugal. The country gathers all the conditions for a prospective future regarding solar energy and renewable resources in general.

2.4 Shifting to self-consumption after policy changes regarding FITs

Considering these recent regulations, especially due to the lowering of FITs, self-consumption is being promoted extensively, all around the world. An identical study to [15] was performed by the same authors, some years after the first one, to show the significant changes in regulations to support PV technologies in various EU countries [24]. Due to the PV support policies in place before, retail electricity prices increased during these years, which meant that the revenue arising from compensation schemes became greater than those corresponding to FITs. In Spain, for example, the previous FIT support mechanisms were no longer in place, and even though they were still present in the remaining countries, most times it was combined with other policies like self-consumption or net-metering. The study confirmed that future development should be focused on these new policies, showing that they were active in the countries that had the highest profitability indexes.

Once again considering recent regulation changes, Rodrigues et al. (2016) [25] analyzed a representative set of countries to determine the ones with the best investment opportunities for self-consumption schemes. Four different scenarios ranging from 100% to 30% self-consumption were analyzed. For every country except two (out of 13), it was seen that the profitability of the projects always increased (and payback time decreased) with more self-consumption. Meaning that, for the majority of the countries in the study, the 100% self-consumption scenario was the most viable. This study was performed for residential-size systems only (1kW and 5kW), and therefore it is still important to further analyze the viability of PV relying on self-consumption for commercial and larger residential applications.

Lang et al. (2016) [26] does exactly this, by comparing four different types of buildings: small and large residential, and small and large commercial. Results showed that the profitability of these projects depends primarily on the electricity prices and self-consumption share of the building, and that, even in the absence of FITs and other subsidies, self-consumption can already be attractive for many buildings in central Europe, particularly, large residential and commercial buildings. On the other hand, small residential buildings are more sensitive to the absence of FITs due to low self-consumption shares, meaning that incentives represent a larger portion of the project's cash inflow. Additionally, this solution tends to be more favorable in commercial, rather than in residential buildings, due to a naturally better match of the demand and PV production curves. Since the curves will never be a perfect match, not only residential but also commercial buildings can benefit from applying Demand Side Management (DSM) or adding a BESS to the system [27].

2.5 Implications of a PV system complemented by a BESS to improve self-consumption

In [27], Luthander et al. (2015) present a detailed review of different solutions for self-consumption improvement. Battery storage and DSM were the main focus, applied either separately or combined, in different residential buildings. It was seen that battery storage improved self-consumption by up to 24%, and even more combine with DSM. The battery size compared to the installed PV capacity was found to be very similar in most papers, and the sizing proved that storage is normally used in the short term (shorter than one day). The capacity for improvement depends not only on the battery size but also on a number of other factors like consumption patterns, climate zone, and initial self-consumption share.

In order for self-consumption and battery usage to be optimized, a solution (compensation method) has to be chosen that dictates the functionality of the system, in order to improve performance. Galilea et al. (2019) [28] performed a comparative study, considering different commercial solutions applied to various residential buildings in Spain. The scenarios considered varied in the amount of PV production and battery capacity, and for each of these three, compensation methods were studied. They saw that the case with greater battery capacity contributes to higher self-consumption shares, resulting in greater savings on energy bills. However, due to the high price and short lifecycle of batteries, the overall benefit is negative. Even though there is only one building where viability is reached using some battery capacity, the remaining cases still show negative global savings, but are very close to being profitable. The results showed that the declining cost and increasing lifecycle of batteries are the main factors that will turn these projects viable in the near future.

Besides the various commercial approaches that are normally applied, one can manage the system using a different and personalized optimization model, considering different factors. Sola et al. (2018) [29] performed a comparative study for PV self-consumption systems, to determine the advantages that an optimization model might have over two different commercial solutions. While the two commercial solutions for battery management are each based on the PV production availability (instantaneous self-consumption), or a predefined time of use set by the user, the optimization model considers the energy market and the fluctuation of electricity prices. Unlike the first solutions, the optimization program runs autonomously and adjusts according to the price variations, which is a clear advantage for battery use. Even though the quantity of electricity purchased from the grid remains the same in all solutions, its average price is lower when the optimization model applies, leading to greater savings.

Like these, there are other studies [30–32] that consider the addition of a BESS to a PV system, as a way to improve self-consumption. Nowadays, we see that by implementing this change, the battery costs often represent a significant share of the system's final expenditures, and since the current price of batteries is still high compared to PV technology, the investments might not be viable in some cases. In the end, what makes or breaks a project can be how the consumed and stored energy are managed.

2.6 Viability of implementing PV systems in educational buildings

With the creation of the Energy Performance of Buildings Directive [4] it became clear that this sector is crucial for achieving new and ambitious emission targets, but we still don't know what are the roles of the different building types inside this sector, and their part in reaching the desired goals. RESs implementation in educational buildings is important to incentivize and educate younger generations, but it is crucial to study the viability a project implementation like this might present.

Fiaschi et al. (2012) [33] developed a case study of the possible energy-related improvements in public buildings and an economic analysis of those improvements. They saw that for small municipalities

(16.000 inhabitants) and medium-sized towns in Italy, school buildings are the second largest source of electricity consumption. With the implementation of RESs in schools (especially PV, that takes up previously unused roof space), these towns can achieve valuable long-term results related to energy consumption issues in the public sector. Furthermore, it was seen that the implementation of PV systems needed a relatively large initial investment even with loans and other instruments accessible to public administration, so public funding might be a necessity for the viability of these projects. This study also compared the viability of retrofitting measures, with PV implementation, and saw that even though the retrofit investment was lower, the payback time was significantly longer.

Bilir et al. (2017) [34] compared the implementation of two different systems in a school in Turkey: one to match the yearly demand of the building, and the other to cover the maximum roof area possible. Since the focus was never to generate energy to cover all months individually but rather the added consumption of one year, some months had surplus of PV generation (sold to the grid through a FIT) while others had a lack of it and the building had to consume from the grid. An LCA study and an economic analysis were performed, concluding that the project covering the maximum roof area possible (higher PV capacity) needed a bigger initial investment, but the payback time was lower (although not significantly).

Al-otaibi et al. (2014) [35] present us with a significantly different reality, for a project in the middle east, in which they also compare two different PV systems, for two schools in Kuwait. For this particular location, the project implementation is crucial at a national level, and can help the functionality of the energy grid. Since schools have very low demand during the summer, the biggest surplus of energy generated from the PV system is seen during this period (July and August). Coincidentally, the national electricity distributor faces the challenge of meeting demand around those months, therefore making scheduled blackouts a necessity in order for priority areas to maintain energy supply. With the installation of PV systems in school buildings, the surplus energy during these months will be fed into the grid and the challenges can be mitigated. Furthermore, these systems can also complement the national load on a daily level, since the schools are mostly using energy during peak production of PV systems, therefore relieving the distributor by self-consuming that energy.

Most findings from these studies are compatible with other projects for educational building. Most importantly, we see that the characteristics of school buildings are favorable for a self-consumption approach due to the building's consumption curve. The case for [35] is very specific and is not present in European countries but comes to show how these buildings can be of great importance for certain communities with poor energy distribution conditions.

2.7 General findings taken from the Life Cycle Analysis of buildings and RESs

Like mentioned many times before, the implementation of these systems is incentivized to help reach the goals set by the EU in terms of GHG emissions. Therefore, it is crucial to evaluate the environmental impact these implementations have, and so an LCA study should be performed either for the technology implemented or for the retrofitting itself (if it is performed).

Asdrubali et al. (2018) [36], performed an LCA in three different buildings, located in Italy, in order to study the correlation among the external climate, solar irradiation and two environmental payback indicators. The buildings were identical, but located in different cities, and the interventions proposed were focused on the building envelope and lighting, combined with RESs integration. Given the improvements applied to reach the nZEB standard, a shift of burdens from the use phase to the construction phase was observed after performing the LCA calculations. A variety of other studies have been performed in buildings with significant RESs integration [34, 37] and only to the technology itself [38, 39] and, with similarity to [36], they have shown that the payback periods for energy and carbon emissions are much lower than the useful life of the buildings and the technology implemented. Despite the initial burdens related to the embodied energy, the implementation of any RES and consequent decrease of consumption from fossil fuels significantly reduces the environmental impacts of the buildings in the long run.

In [37], Sumper et al. (2011) not only studied the environmental impacts of a specific PV system, but also performed an LCA on three different types of PV cells. The end result of this study was determining which technology had the lowest energy requirements. It is stated that, out of the three technologies (mono, poly, and thin film), polycrystalline usually is the preferred material because it has the lowest energy input. Furthermore, a sensitivity analysis was carried out by considering 4 locations with different levels of solar irradiation, concluding that this parameter is inversely proportional to the EPBT. Monocrystalline cells presented the worst values of EPBT, while polycrystalline and thin film had similar (and better) results, much lower than the building's life span.

Torabi et al. (2017) [40] investigated the environmental impacts of high penetration of renewable energy in the supply system of an island in Portugal. The goal was to compare the environmental impacts of a solar PV system, wind turbines, and a conventional thermal power plant. As it would be expected, the thermal power plant is the technology with the highest environmental impact. To study the other technologies, two different electricity mix scenarios were set up: one with an increment of production from the PV system, and a similar one but for wind turbines. Logically, it was seen that an increment on the production from any of the renewable sources results in less environmental impact. Even though the results from the scenario with more wind share are better, they do not differ significantly from PV.

2.8 Research gaps and further studies

It can be seen very clearly that most studies discussing self-consumption viability focus on the implementation of this mechanism in residential buildings. The application in commercial buildings is promising in terms of viability, but research is still scarce, especially regarding the addition of a BESS. Even though this work will focus on an educational building, the research regarding self-consumption was not focused on this sector specifically, due to lack of existent work. The projects presented were focused more on the methodology of implementing the system and the technology used, rather than the compensation methods and regulations involved. Furthermore, in various different projects, FITs are still considered as a compensation method, which is not the case for this work.

The projects for educational buildings tend to focus more on retrofitting because there is a lot of room for improvement in terms of energy efficiency, which ends up being a more pressing matter than the implementation of RESs. Therefore, the main objective of those studies trumps what we wish to focus on for the scenario at hand. For these reasons, the studies that focused more on studying the regulation schemes that increased the project's viability to its maximum were presented for residential and commercial buildings only, for lack of research in the desired field (educational). The findings for the residential sector are taken into consideration due to the high quantity of existent studies, and only as a way to provide a sense of which energy generation and selling schemes could be profitable, even if they will be applied to larger-scale systems. Furthermore, even though educational buildings are not part of the commercial sector, it is also important to consider the research that regards to it because when compared to the residential sector, the demand patterns and system sizes of commercial buildings are much more similar to those of educational buildings.

Regarding the use of a BESS, it became clear that the technology still needs further development and a significant price decrease in order to become a viable option in most situations studied. For this case we will further study the cost-effectiveness of this implementation, if it can be viable in the present day, and how that may change in the future.

3

Proposed Models

Contents

In this chapter the theoretical premise on which this thesis bases itself is presented. The solar cell's modelling is presented in detail, as well as the effective irradiance calculation; The different compensation schemes for the technology are then established, followed by the configurations of the battery implementation. Lastly, the financial and LCA metrics that will be later used to verify the projects viability and environmental impact, respectively, are presented.

3.1 PV system topology and parameter calculation

To understand and study the system in detail, first it is important to know the calculations that are made automatically by *PVsyst*. This way, the most important variables in all calculations will be known, and future implementation will be better understood.

3.1.1 One diode model

PV cells get their name because they are electrical devices that transform light directly into electricity, by means of the photovoltaic effect. This effect is a chemical and physical reaction and will not be studied in detail, since the focus here is not to understand the conversion process, but rather what influences and is influenced by the electric current that results from the effect. To study these relations and calculate all parameters related to the modules' energy output, *PVsyst* uses the one diode and five parameters model [41], that is defined by the equivalent circuit in Figure 3.1.

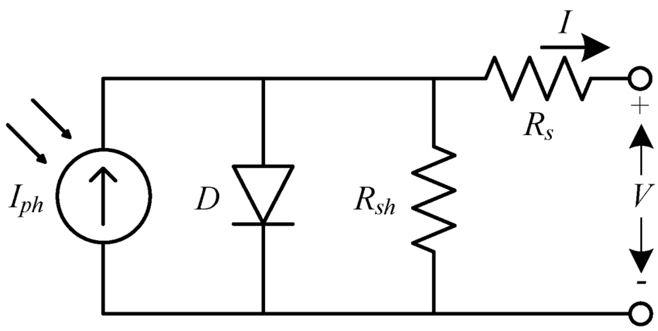

Figure 3.1: Equivalent circuit representing the one diode and five parameters model of the solar cell.

The unknown variables of this model are the current supplied by the module (I) and the voltage at its terminals (V), which will be dependent on the remaining five variables, as seen in equation 3.1. As this is an implicit equation, it needs to be solved using a successive approximations approach.

$$I = I_{ph,ref} - I_{0,ref} \times \left(e^{\frac{V + I \times R_S}{m \times V_{T,ref}}} - 1 \right) - \frac{V + I \times R_S}{R_{SH}} \tag{3.1}$$

To determine the unknown variables, the five parameters that have to be calculated are: the photocurrent $I_{ph,ref}$, the diode inverse saturation current $I_{0,ref}$, the series and shunt resistance, R_S and R_{SH} (Ω), and the diode's ideality factor m. These parameters can be calculated using the three following equations for the most relevant points on the I-V curve: short circuit (eq. 3.2), open circuit (eq. 3.3), and maximum power point (eq. 3.4).

$$I_{sc,\ ref} = I_{ph,ref} - I_{0,\ ref}^{\frac{R_s\ \times\ I_{sc,\ ref}}{m\ \times\ V_{T,ref}}} - \frac{R_{s}sc,\ ref}{R_{sh}} \tag{3.2}$$

$$0 = I_{ph,\ ref} - I_{0,\ ref}^{\frac{R_s\ \times\ V_{oc,\ ref}}{m\ \times\ V_{T,ref}}} - \frac{V_{oc,\ ref}}{R_{sh}} \tag{3.3}$$

$$I_{mp,ref} = I_{ph,ref} - I_{0,\ ref}^{\frac{V_{mp,ref}\ +\ R_s\ \times\ I_{mp,\ ref}}{m\ \times\ V_{T,ref}}} - \frac{V_{mp,ref} + R_s \times I_{mp,\ ref}}{R_{sh}} \tag{3.4}$$

where all reference values (ref) are measured at standard test conditions ($\mathrm{T_{ref}} = 298.15\ \mathrm{K}$, $\mathrm{G_{ref}} = 1000\ \mathrm{W/m^2}$). $\mathrm{V_T}$ is the thermal voltage given as $\mathrm{V_{T,ref}} = \frac{\mathrm{K \times T_{ref}}}{\mathrm{q}}$, where q is the charge of the electron[1], and k is the boltzmann's constant[2]. The reference values for the open circuit voltage $\mathrm{V_{oc}}$, short circuit current $\mathrm{I_{sc}}$, maximum power voltage $\mathrm{V_{mp}}$, and maximum power current $\mathrm{I_{mp}}$ are known from any module datasheet. Seeing that there are 5 different parameters to calculate and only three equations, the calculations involve mathematical manipulation of these equations, as well as the use of other relations [42].

This model considers that the shunt and series resistances, and the diode ideality factor are all independent from the temperature and irradiance levels that the cell is subjected to. The parameters dependent on the variation of these factors are the short circuit current and the open circuit voltage. As seen in equation 3.5 the short circuit current and irradiance are perfectly proportional, while the open circuit voltage in equation 3.6 shows a logarithmic variation with the irradiance.

$$I_{sc} = \frac{G}{G_{ref}} \times (I_{sc,ref} + \mu_{Isc}\,(T_c - T_{c,ref})) \tag{3.5}$$

$$V_{oc} = V_{oc,ref} + \mu_{Voc}\,(T_c - T_{c,ref}) + m \times V_T \times \ln\left(\frac{G}{G_{ref}}\right) \tag{3.6}$$

where the μ_{Isc} and μ_{Voc} are the short circuit current, and open circuit voltage temperature coefficients, that dictate the relation between those parameters with the temperature and are taken from any module datasheet.

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[1] q=1.602$\times 10^{19}$ $Coulomb$

[2] k=1.381$\times 10^{-23}$ J/K.

Lastly, T_C is the cell's effective temperature, which is determined with regards to the energy balance between the ambient temperature and the cell's heating up due to effective irradiance, as seen in equation 3.7:

$$T_C = T_{amb} + \frac{alpha \times G(1-\eta)}{U} \tag{3.7}$$

where T_{amb} (K) is the ambient temperature, G (W/m^2) is the effective irradiance, η is the module efficiency, *alpha* is the absorption coefficient of solar irradiation, and U (W/m^2K) is a thermal loss factor that depends on the mounting mode of the modules.

The effective irradiance, of course, depends on the sun's position, so, with hourly measured values for the global horizontal irradiance (GHI), it can be calculated with a transposition. This calculation is made separately for each irradiance component: direct, diffuse, and albedo. The direct component calculation involves a geometrical relation (cosine effect), the diffuse component is calculated using a complex model [43] that is out of the scope of this project, and lastly the albedo component depends on the tilt angle of the modules and the albedo coefficient (defined according to ground type).

3.1.2 Irradiance Direct Component Calculation

The most significant component in the calculation of the effective irradiance is the direct one, so it is important to expose the aforementioned geometrical relation in more detail. As the sun's position changes through the day, during most hours the incident solar ray will not be perpendicular to the panel's surface, and therefore a part of that energy will be lost due to the cosine effect. To maximize the system's efficiency, this effect should be minimized by finding an optimal tilt angle for the panels. Figure 3.2 shows the relations between the irradiance components on a tilted plane and based off these relations the direct component (S_{module}) can be calculated.

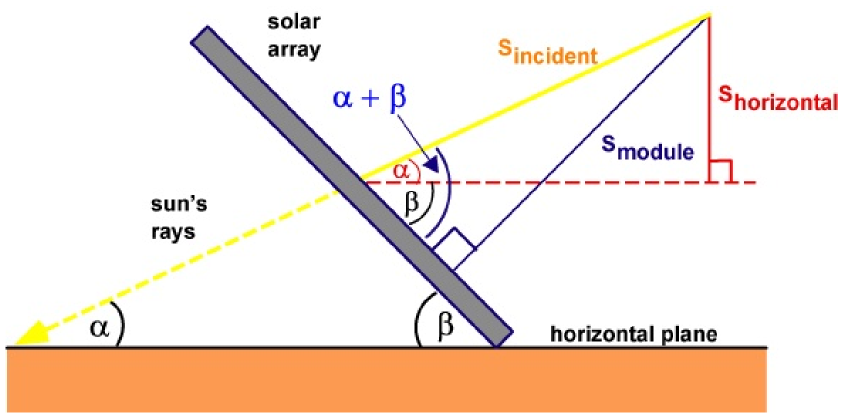

Figure 3.2: Components of solar irradiance on a tilted surface.

The relations between the three irradiance components are displayed in equations 3.8 and 3.9:

$$S_{horizontal} = S_{incident} \times \sin \alpha \tag{3.8}$$

$$S_{module} = S_{incident} \times \sin (\alpha + \beta) \tag{3.9}$$

where α is the elevation angle and β is the module's tilt angle.

The tilt angle is chosen according to an optimization tool incorporated in *PVsyst*, that presents a graph with the relation between β and the Transposition Factor (ratio between the incident and horizontal irradiance). More importantly, for each angle chosen, the system loss with respect to the optimum orientation is displayed, so with a trial and error approach and also knowing from various studies that the optimal angle for Portugal is always around 33° [42], it is simple to find the value for any project.

The elevation angle is the angular height of the sun in the sky, measured from the horizontal plane, with its maximum occurring at solar noon. This parameter is calculated using equation 3.10:

$$\alpha = 90 - \phi + \delta \tag{3.10}$$

where ϕ is the latitude of the location, and δ is the declination angle given by equation 3.11:

$$\delta = 23.45 \times \sin \left(\frac{360}{365} \times (284 + d) \right) \tag{3.11}$$

where d is the day of the year.

Knowing all the parameters involved in the calculation, combining equations 3.8 and 3.9, it is possible to determine the direct component S_{module}:

$$S_{module} = \frac{S_{horizontal} \times \sin (\alpha + \beta)}{\sin \alpha} \tag{3.12}$$

3.2 Compensation schemes for PV technology

In the project implementation, various compensation schemes are studied for a better understanding of which approach helps improve the project's viability by increasing the profit. As mentioned previously, the law in Portugal has been changing in recent years to promote self-consumption, after the end of FITs. Nevertheless, it is still necessary to study at what level this becomes viable and compare it to new schemes for full grid connections that have replaced FITs.

3.2.1 Self-consumption

This regime applies to the energy generated by a Production Unit of self-consumption (UPAC), in which, preferably, all energy generated is consumed by the installation to which it is connected. If that is not the case, when a surplus occurs, the excess energy can be sold to the grid and awarded a certain compensation fee. The activity of self-consumption can be carried out by individual or collective self-consumers, but in this project the focus will only be on the former. A strong individual self-consumption framework has been in place in Portugal since 2014 [44], and more recently another decree law was created to allow for collective self-consumption, recasting and complementing the previous framework also to simplify licensing and rules for those who wish to have UPACs [22]. In order to understand the limitations and rules of this framework, some aspects of the law should be studied, mainly those of financial nature, that will have to be considered for the project implementation.

If the UPAC is connected to the grid, there is a remuneration for the grid-injected energy, and a monthly compensation, both depending on the UPAC's installed capacity. For production units under 1MW, the revenue ($\mathrm{R_{UPAC,m}}$) received for each month's surplus energy injected in the grid, is calculated using equation 3.13:

$$\mathrm{R_{UPAC,m}} = E_{inj,m} \times \mathrm{OMIE}_m \times 0.9 \tag{3.13}$$

where $E_{inj,m}$ (kWh) is the energy injected in the grid for month m, and OMIE_m (€/kWh) is the arithmetic mean of the nominated electricity market operator's closing prices for Portugal, relative to month m. Since this parameter will not be forecasted, the OMIE[3] prices will be considered constant during the complete lifetime of the project, with OMIE_m being equal to the average price for the year of 2019 [45].

On the other hand, if the UPAC's production is insufficient and the unit cannot provide all of the necessary energy for the installation, then the missing amount must be bought from the grid. In self-consumption schemes, the energy consumed by the installation connected to the UPAC is measured instantaneously (supposedly in a 15-minute time frame, but for this study it will be hourly). According to those hourly measurements, the system will decide whether it should consume energy from the grid or if the UPAC is meeting all of the installation's needs. Furthermore, the monthly compensation that is mentioned above is related to the costs of Energy Policy, Sustainability, and General Economic Interest (CIEG), which represent a large share of the monthly electricity bills. A recent Order [46] from the Portuguese government states that self-consumption units with an installed capacity above 30 kW are exempt from paying 50% of these costs, during the first 7 years of the project's lifetime. With this exemption, the yearly cash flows from the UPAC installations will correspond to the savings resulting

[3] Iberian Market operator

from self-consumption and the exemption of CIEG costs, combined with the revenue of selling surplus energy to the grid.

Lastly, depending on whether the UPAC is connected to the grid or not, there is a registration fee in function of its installed capacity [47], as can be seen in Table 3.1. The fees for UPACs with grid connection also apply to Small Production Unit (UPP) implementations, for which the regulation will be explained in a future subsection.

Table 3.1: Registration fees, depending on installed capacity and existent grid-connection.

	Registration Fee (€)	
Installed Capacity [kW]	Grid connected UPACs and UPPs	Non grid connected UPACs
$<$1.5	30	-
1.5 – 5	100	70
5 – 100	250	175
100 – 250	500	300
250 – 1000	750	500

Now that the most relevant financial aspects associated to UPACs are known, there are some regulations regarding the installed capacity and power generation that still need to be accounted for. As stated in the Portuguese law:

- The UPAC's yearly generation must be inferior to the installation's consumption needs;
- The power connection to the grid should be less than 100% of the installation's contracted power;
- For grid-connected UPACs, two different electric meters must be installed: one at the interconnection of the installation with the UPAC to measure the installation's self-consumption, and another at the interconnection with the grid, to count the injected surplus and the purchased energy. These interconnections can be seen in Figure 3.3.

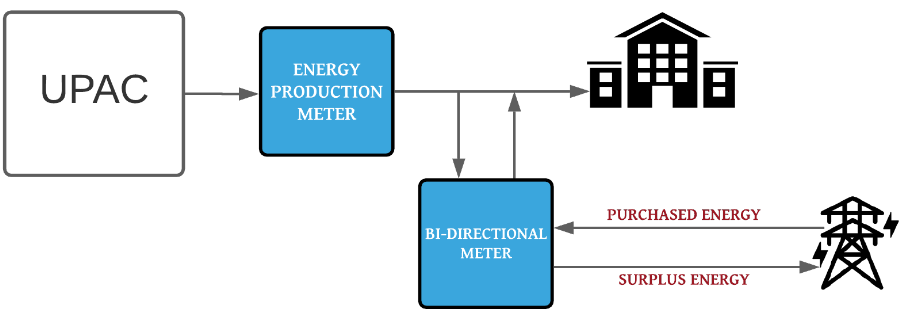

Figure 3.3: UPAC system connections and meter display.

3.2.2 Net-Metering

This model simply presents a different remuneration method for a self-consumption system, and it is based on the concept that the grid can be used as a "long-term storage". Therefore, the functioning of the system is exactly like before, given that the surplus PV production will still be injected into the grid; but in net-metering that energy is recorded as credits. As this model is applied to UPACs, the energy is measured like it is presented in Figure 3.3, and the metering is not done instantaneously, but rather after a more extended period of time (depending on the regulation). With the energy being recorded as credits, there is no remuneration or additional payments for it, and the amount that is injected (in kWh) can be recovered later, which makes the trading purely electrical. At the end of each billing period, the consumer pays only for the net energy consumption.

Even though, at present time, this operation mode is not allowed in Portugal, it will still be applied here to understand its impact on the economics of PV systems and if it would be a viable scheme to adopt. For this study to have some credibility and more real implications, the example of another EU country that allows for net metering is applied as if it were legal also in Portugal. The chosen country was Cyprus, and the legislation for net metering allows the model to be applied not only to households with small capacities but also commercial units and public administration buildings [48]. In this regime, the electricity offsetting will be carried out each month, for each calendar year. This means that if, for example, at the end of January there is a surplus of production it will be recorded as credits that are available for usage in the following months, and the credits remaining in December are not available for the following year.

3.2.3 Full grid injection

The decree-law issued in 2014 established the regulations not only for UPACs, but also for UPPs, which sell the totality of their renewable energy production to the grid. Therefore, the UPP is connected only to the grid, and the latter remains as the installation's only source for energy consumption. Since FIT schemes no longer apply in Portugal, the remuneration for the sold energy is done through a bidding scheme. In this bidding process, the participants offer a discount to the reference tariff, and the highest tariff resultant is awarded as the remuneration. For 2020, the reference tariff is 0.045 €/kWh [49], which is the price considered for this study, with no discount applied. The tariff is set for a period of 15 years, during which the producer cannot change to a different regime.

After that period, the UPP has to sell its energy to the last resort trader, through the general regime [50]. For this regime, the monthly remuneration (Rem_m) is calculated as seen in equation 3.14:

$$\mathrm{Rem}_m = \sum_{i=1}^{2} W_i \times \mathrm{OMIE}_m \times f_p \times C_i \tag{3.14}$$

Where *i* represents the tariff periods (peak or off-peak) during which electricity is delivered to the installation; W_i (kWh) is the energy generated in month m, during period i; OMIE_m (€/kWh) is the average Iberian market closing price, relative to month m; f_p is a factor to account for losses during each period; and C_i is the weighting coefficient for each period (0.86 for off-peak, and 1.13 for peak).

Besides the remuneration schemes, there is further regulation to consider when installing a UPP:

- For each kW of installed power, the maximum amount of electricity that can be sold to the grid per year is 2.6 MWh (for solar PV installations);

- Similarly to UPACs, the power connection to the grid should be lower than 100% of the installation's contracted power, and in this case, never higher than 250 kW;

- On a yearly basis, the energy produced by the UPP cannot be higher than two times the energy consumed by the installation. So, for example, if a given installation consumes 100 kWh in a year, the existing UPP cannot produce more than 200 kWh per year;

- For UPPs there should also be two electric meters installed, only in this case none of them is bi-directional. As seen in Figure 3.4, the purpose of the meters is to count the energy injected in the grid by the UPP, and the energy consumed from the grid by the installation.

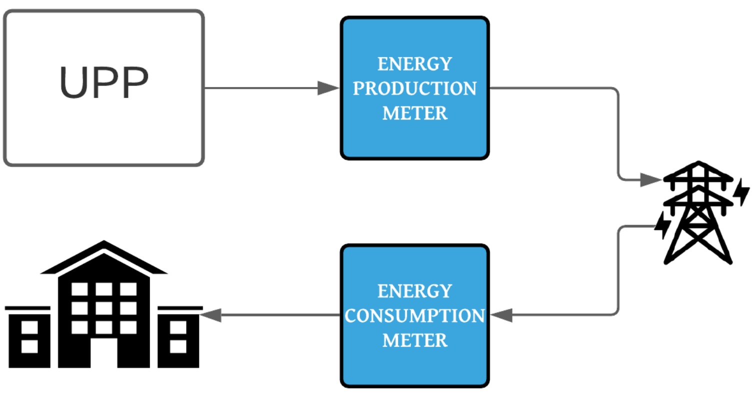

Figure 3.4: UPP system connections and meter display.

3.2.4 Battery Implementation

From the previous section it became clear that the profits for these systems come solely from savings on the electricity bill resulting from self-consumption, or energy selling to the grid. For the case of a UPP, a possible profit increase can only come from installing more capacity to sell more energy to the grid. However, for the systems with UPACs the main goal is not to sell, but rather to save energy by self-consuming it. With the implementation of BESS the self-consumption share can be increased, leading to more savings, and therefore, a possible profit increase.

In this work, only one type of implementation for the battery is considered: the energy is stored as soon as it is available (when there is a surplus of PV production), and then is “immediately” used when the consumer’s consumption needs have to be satisfied. In this implementation the battery is only connected to the PV system, and never trades any energy with the utility grid. Within this battery implementation, the system has 5 operating modes:

- **Charging**: the surplus of PV energy is utilized to charge the battery. If the battery charging reaches its maximum allowed value, the PV energy is redirected for grid-selling;

- **Discharging (day)**: once the battery reaches its maximum state of charge, it can supply energy to the user to compensate for any lack energy from the PV panels. Once the battery reaches its maximum discharge level, the grid connection is utilized to supply any demand that is not met by the panels;

- **Direct Mode**: if the PV generated energy fully meets the consumer’s demand and the battery is full, then there is no battery-related energy transaction. The PV system is only supplying energy to the consumer and selling a surplus to the grid when there is one;

- **Discharging (night)**:During the hours in which the PV system is not generating energy, if the battery is fully charged it can provide part of the consumer’s demand in combination with the grid. Otherwise, all of the consumer’s nighttime demand will be purchased from the grid.

In Figure 3.5, all the connections of the system can be observed, for better understanding of the operation described above.

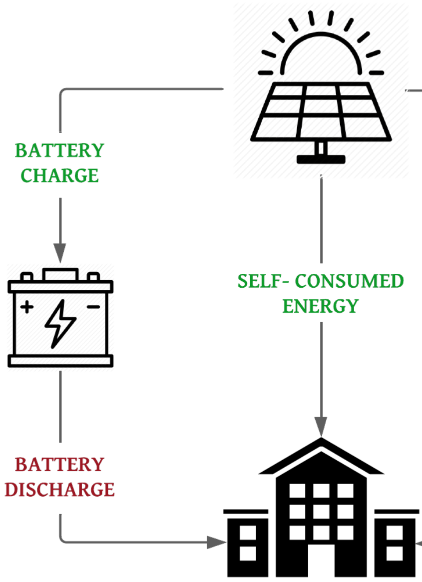

Figure 3.5: PV system interconnections and energy flows to grid, battery, and consumer.

3.3 Financial Analysis.

This analysis is based on the revenues from the different compensation schemes presented in the previous section, and, in contrast, the cost of technology that was outlined in chapter 2. The savings and compensation from the different schemes will be compared, to conclude which implementation might be the most profitable investment, by using different economic performance measurements such as the Net Present Value (NPV), Internal Rate of Return (IRR), and Return on Investment (ROI). The SPBT is also calculated. Since there are three different implementations, the yearly cash flows will be different for all of them, but generally, they can be defined by equation 3.15.

$$\mathrm{R_t} = \mathrm{Savings} + \mathrm{Compensation} - \mathrm{O\&MCosts} \tag{3.15}$$

The values of all of these components are presented in EUR (€) and differ for each of the implementations. The savings refer to the money that is saved from self-consuming energy, and the compensation is the revenue from selling energy to the grid.

3.3.1 Net Present Value.

This metric shows the difference between the present value of cash inflows and the present value of cash outflows over a period of time. It takes the time value of money into account by translating all future cashflows into “today’s money” and adding up today’s investment and the present values of all future cashflows. A positive NPV means that a project or investment’s estimated profits surpass the planned costs, and the project is considered to be profitable. An investment with a negative NPV will result in a net loss, and therefore only projects with a positive NPV are seen as a worthy investment opportunity. The calculation is done using equation 3.16:

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} - I_0 \tag{3.16}$$

where the discount rate *i* is applied to the profit R_t in €, in each year t, until the end of the project's lifetime *n*, and the initial investment is given by I_0 (€) which will be detailed later in this work, when the cost of technology is studied in more detail. This value will differ when considering a system with or without BESS implementation.

The different values of R_t (cash flows) to consider in this calculation will be different for each implementation: in the regular self-consumption and net-metering there is a constant cash flow until year 7 because of the CIEG savings, and then a different one from year 8 until the end-of-life; and in the battery implementation, because its lifetime is shorter than the project's and higher than 7, there will be one constant cash flow from year 1 to 7 with savings from CIEG exemption and higher self-consumption, another from year 8 to 10 only for the battery utilization without the CIEG exemption, and another until the end-of-life that will be equal to the cash flow from the regular self-consumption, since the battery has reached its end-of-life. Lastly, for the UPP implementation, there are two different cash flows: from year 1 until 15, and after that until the end-of-life, for the two different remuneration schemes. For this implementation there is only compensation from selling energy to the grid and no savings from self-consumption.

3.3.2 Internal Rate of Return.

The IRR is essentially the discount rate that makes the NPV equal to zero (equation 3.16), so it estimates a project's break-even discount rate, which indicates the annual rate of growth an investment is expected to generate. Therefore, if the IRR obtained is above the discount rate *i* considered in equation 3.16, then the project will most likely be accepted. Otherwise, it is rejected. However, there are limits to the practicality, since it does not measure the absolute size of the return, supporting investments with high rates of return, even if the monetary amount of the return is small [51]. The cash flows and investment in equation 3.17 are the same as described above, depending on the implementation that is being studied.

$$0 = \sum_{t=1}^{n} \frac{R_{t1}}{(1+IRR)^t} - I_0 \tag{3.17}$$

3.3.3 Return on Investment

This metric also evaluates the system's profitability, by measuring the ratio of the gain from an investment relative to the amount invested. Like the NPV, a negative ROI indicates a loss, and therefore the system is not profitable, while a positive number indicates a positive return. However, there are some limitations to this metric because it does not consider the time-frame of the investment and profit generated from it. Even though two projects might have the same ROI, one might ultimately be more profitable than the other, depending on the time it takes to obtain that profit. This is the main difference between IRR and ROI: while the ROI indicates total growth of the investment from start to finish, the IRR identifies the annual growth rate. The value can be calculated as in equation 3.18:

$$ROI = \frac{Net\ benefit}{Total\ Investment} \tag{3.18}$$

3.4 Life Cycle Analysis.

The LCA is an approach to environmental management system implementation involving the quantitative evaluation of a product's overall environmental impact. In this work, the assessment of the PV system is performed, so the energy requirements throughout its complete lifecycle (manufacturing, transport, operation, disposal, etc.) are estimated to perform the evaluation. Since all of the energy generated from the PV panels will be consumed by the installation or sold to the grid, a part of the electricity that was once consumed from the grid is now being replaced by the generation from a renewable technology. For the years in which the panels are in operation, there is no CO2 emissions that result from the energy generation, so in this stage there will be a major net saving of those emissions. However, the system still presents an environmental impact in other phases of its life, especially during the manufacturing and disposal.

The emissions resulting from all stages are considered in the final calculation, but it is during the operation that the most significant net savings are observed. According to *PVsyst*'s Carbon Balance tool, to calculate the difference between produced and saved CO2 Emissions for a PV installation the following parameters must be known:

- The PV system's energy production for a year and its lifetime, to calculate the grid energy that will be "replaced" by that production.
- Grid Life Cycle Emissions (LCE): It is given in gCO2/kWh and represents the average amount of CO2 emissions per Energy unit for the Electricity produced by the Grid.
- PV system LCE: It is given in tCO2 and represents the total amount of CO2 emissions resulting especially from the manufacturing and disposal of the PV installation.

The LCE include the complete life cycle of each component and all the stages already mentioned above. These values are highly sensitive to the region and each specific component analyzed, and so generalization often comes with implicit errors. The PVsyst software uses default values for the grid and

PV system LCE, depending on which country the system is located and the used technologies (module and BoS), respectively. Therefore, the carbon balance calculation is done using equation 3.19:

$$Carbon\ Balance = E_{output} \times n \times \text{LCE}_{grid} - \text{LCE}_{system} \tag{3.19}$$

where the Carbon Balance is given in tons, for the whole lifetime of the project; E_{output} is the yearly energy generated by the PV system, in MWh, that will no longer be consumed from the grid; LCE_{grid} and $\text{LCE}_{\text{system}}$ are the grid and PV system Life Cycle Emissions that have already been described above; and n is the project's lifetime in years.

This is not a feature from the Carbon Balance Tool, however, it is also relevant to calculate how many years it will take to compensate for the LCE of the system, which is known in the literature as the Greenhouse Gas Payback Time (GPBT) [52]. The year in which the GHG emissions are "compensated" happens when the Carbon Balance is equal to zero, so in this case, the variable *n* seen in equation 3.19 is now the GPBT, which can be calculated as:

$$GPBT = \frac{\text{LCE}_{system}}{E_{output} \times \text{LCE}_{grid}} \tag{3.20}$$

Lastly, stepping away from the analysis of GHG emissions, it is also important to consider the embodied energy of the whole system. Like the LCE refers to the emissions resulting of all lifetime stages of the system, the embodied energy parameter refers to the energy used within those same stages, from the extraction of primary resources to the deployment. To calculate how many years it will take to recover the energy spent in certain stages, the Energy PayBack Time is used, as in equation 3.21:

$$EPBT = \frac{E_{S,E} + E_{BoS,E}}{E_{output}} \tag{3.21}$$

where $E_{S,E}$ is the embodied energy of the PV modules, in kWh; $E_{BoS,E}$ is the embodied energy of the BoS, in kWh; and E_{output} is the annual energy output of the system, in kWh.

4

Implementation

Contents

This chapter presents all the conditions of the system and location, which are crucial for the project sizing that is detailed at the end of this chapter. For this effect, the location characteristics are presented, from meteorological data to the rooftop area available for installation. Then, the consumer's energy needs and billing scheme that currently applies to the installation are detailed, and lastly, the system components are chosen.

4.1 Meteorological conditions and building details

Given the solar cell model that was presented in the previous chapter, it is clear that the performance of any PV system is highly dependent on meteorological conditions, especially irradiance and temperature. For this reason, it is crucial to obtain the measurement of these parameters accurately, for a precise calculation of the incident irradiance and cell temperature, and therefore, the best possible simulation results. The hourly values for the two parameters were extracted from Solcast [53], through January 1^{st} until December 31^{st} of 2019. This data will be considered constant for the whole simulation period, meaning that the values for the following years will be the ones recorded for 2019. These parameters are used by *PVsyst* for the calculations that were detailed in the previous chapter, and the average values of ambient temperature and accumulated irradiance for each month are presented together in Figure 4.1.

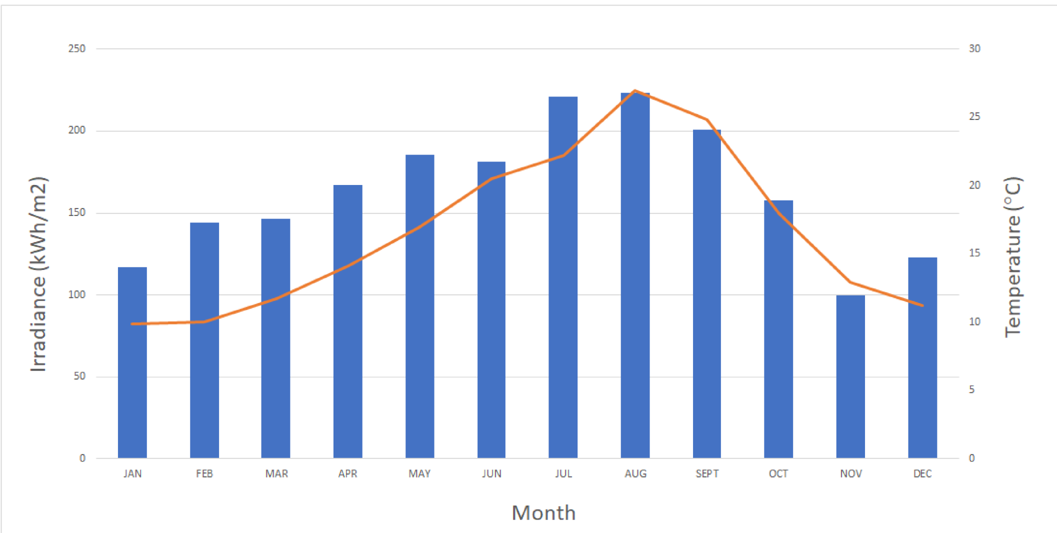

Figure 4.1: Accumulated monthly irradiance in kWh/m^2, plotted together with the monthly average ambient temperature in ºC, for the year of 2019.

The implementation of the PV system will be done in an educational building, located in Beja, Portugal. The building as it exists today was constructed in the early 90s and has since been a subject to renovations, performed by the company Parque Escolar, in 2010. All of the renovations were implemented to improve the energy performance of the building, with regards to lighting, isolation, air conditioning, among other aspects. A plant of the school building, which is composed by various smaller buildings listed from A to G, is presented in Figure 4.2.

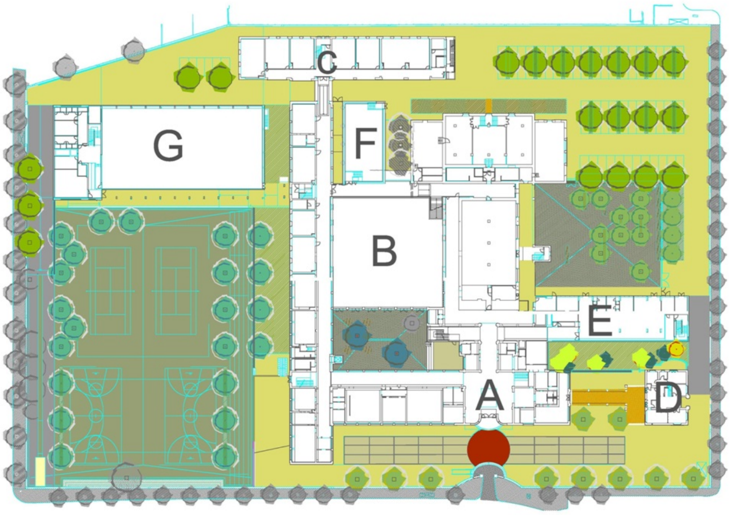

Figure 4.2: Architectural plan of the building, composed of small buildings, listed from A to G.

According to documents provided by Parque Escolar, there were plans made to install a PV system in the rooftop of building G which will be the area considered for the implementation in this work. Furthermore, for the possibility of added capacity, building E will be used, since it is the largest area available, after rooftop G. The areas for both of these buildings are presented in Table 4.1.

Table 4.1: Area of the buildings that will be used for the panels' installation.

Building	**Available Area** (m^2)
G	25.3m×44.3m
E	14.25m×38.33m

From the architectural plan in Figure 4.2, building B could be seen as the best option after G, since it has the second largest area out of all the buildings. However, by analysing satellite images of the location [54], it is seen that a portion of that area is elevated which would lead to significant shading losses in part of the PV installation. Therefore, even though rooftop E is smaller than B, the whole area of E is at the same level, which means the implementation and system design are simplified, and shading losses are minimal.

Lastly, the only alternative source of energy already utilized in the building that is not derived from fossil fuels is a renewable energy system for water heating, which is installed on the rooftop next to building G. This system was designed and implemented during the renovations and is composed of several solar thermal panels and water tanks. It is known from the renovations project that the optimized orientation for the thermal panels is 33°, there are no obstructions (like tree shading for example) to be considered, and both rooftops have a 0°slope tilt, so there is no inclination of the surface with respect to the horizon.

4.2 Consumer energy needs and billing

To size a PV system that is designed for self-consumption, the user's consumption needs must be known. To help carry out this project, the school provided the electricity bills of the building for the year of 2019, which will be the basis for the calculations. These are monthly electricity bills, from the school's chosen utility company, which is Iberdrola. The values for the monthly costs of electricity, as well as the energy consumption are presented in detail in Annex A, and can be seen together in Figure 4.3. The building has a contracted power of 465 kW, and the yearly consumption and electricity bills amount to 337.609 MWh and 53.634 k€, respectively.

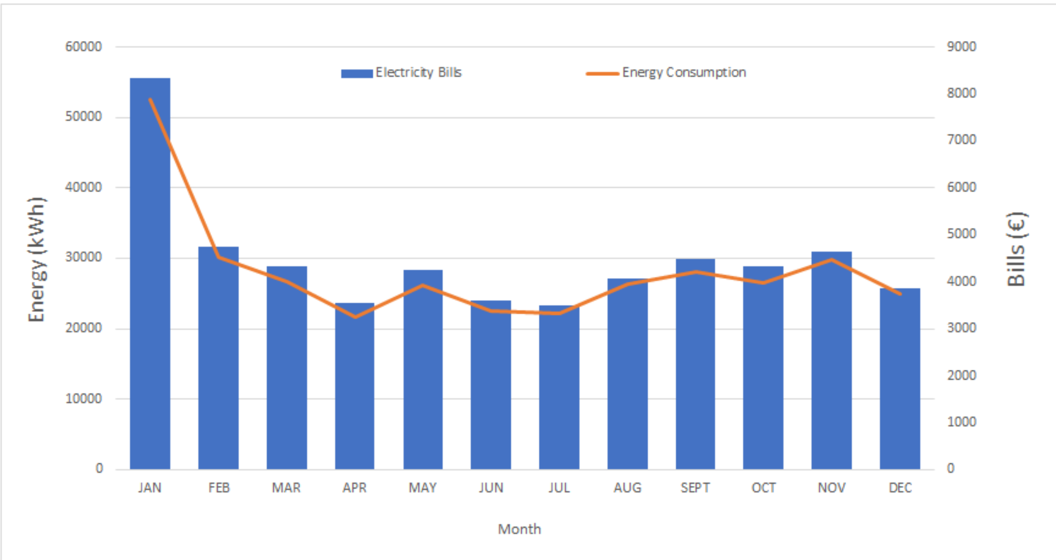

Figure 4.3: Monthly electricity bills in €, and energy consumption in kWh, for the year of 2019.

The building is connected to the grid at a medium voltage level, and so the energy consumption is charged at a tetra-hourly rate, based on a daily cycle, which means that the cycles apply equally to weekdays, Saturday, and Sunday. Even though this was the chosen billing scheme, it is also possible to opt for weekly cycles, which means that there is a differentiation between weekdays, Saturday, and Sunday. Knowing that the building in question is an educational facility, it is logical to assume that the consumption on weekends would be significantly lower than on the remaining days, and it would make sense to opt for the weekly billing scheme, instead of the daily one. However, the building's consumption is not known in such detail and every day of each month will be considered to have the same energy consumption, and, in those conditions, the application of different billing periods for weekdays and weekends is not justified. The tariffs applied to each cycle, as well as the cycles' duration are displayed in Table 4.2.

Table 4.2: Tetra-hourly cycle: duration of each cycle and corresponding tariff, for Winter and Summer schedules.

Daily Cycle (Duration)	Winter Schedule (NOV – MAR)	Summer Schedule (APR – OCT)	Tariff (€/kWh)
Peak (4h)	10h – 12h 19h – 21h	11h – 13h 20h – 22h	0.0793
Full (10h)	08h – 10h 12h – 19h 21h – 22h	09h – 11h 13h – 20h 22h – 23h	0.0728
Off-peak (6h)	22h – 02h 06h – 08h	23h – 02h 06h – 09h	0.0591
Super off-peak (4h)	02h – 06h	02h – 06h	0.0511

Since the information in the electricity bills is not detailed enough to know the hourly consumption of the building, all of the daily values will be an average, based on the monthly data that is known. For each month, the only information available is of the overall consumption for each one of the four cycles, which means that for every hour that is included in each cycle, the consumption value will be considered equal. Annex A also presents the detailed results for the consumption needs of the building in each cycle, monthly and daily. Furthermore, for a better understanding of how the daily needs of each month will look, in Figure 4.4 the daily load profile for a specific month can be seen, with the different cycles highlighted in the same colors as in Table 4.2.

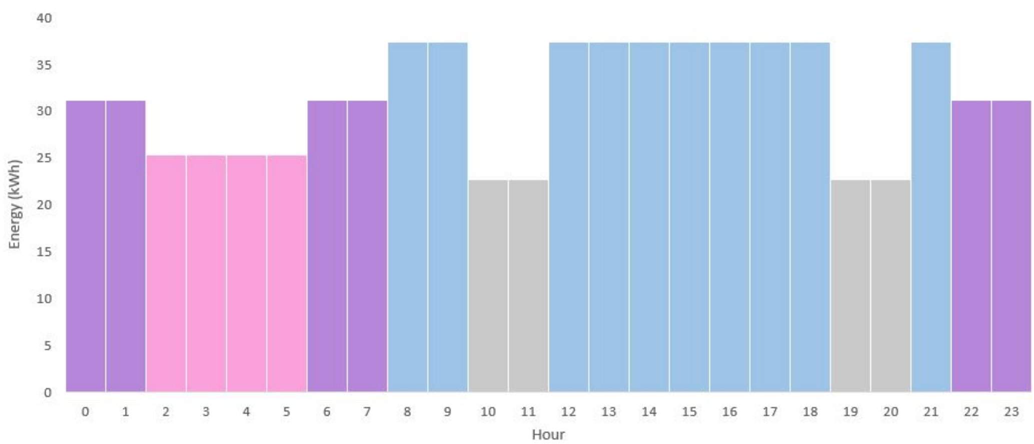

Figure 4.4: Average daily consumption during each one of the four cycles, for a given month.

4.3 System components details, sizing, and costs

The complete system is composed of PV modules, battery, and BoS hardware, including the inverter, and the choices made for these components are crucial for both the system's final costs and overall performance. All of the components were chosen from an online catalogue by Proison [55], a company that provides solar solutions. The catalogue presents detailed information about different top tier brands that manufacture the various components, always considering the price-performance ratio of all the solutions. Even though the project will not be designed to replace all of the building's consumption needs, the objective is still trying to obtain significant savings on the electricity bills, and therefore a large (commercially-sized) system will be implemented.

Firstly, the panels for the installation are chosen, and only polycrystalline technologies will be considered, since they are typically cheaper, when compared to monocrystalline solutions. Even though module efficiency is higher for monocrystalline panels, this choice was based on cost-efficiency only. Still, to guarantee good performance and durable equipment, the different manufacturers considered are all Tier 1[1]. The most cost-considerate solutions found on the market for the considered manufacturers were compared and are detailed in Annex B, and the final choice to be implemented was a 340Wp module from Trina Solar [56], since it has the best price for a higher power rating. Even though it was possible to choose a less costly option from the same manufacturer, a higher power rating (and more expensive) solution was still the final choice because it allows for a higher production output. This is especially important because the area for implementation is limited and there is only a certain number of modules that can be installed.

As for the battery choice, only one technology was considered: Lithium-Ion. Since the objective of the battery implementation study is only to understand if the addition of storage would be viable for this particular system, the chosen technology was the one that is already commercialized by various different manufacturers and is known to be prevalent across various industries. This choice is based on a report by the US Department of Energy [57], which compares the cost and performance of various storage technologies and sees that Li-ion have had a rapid cost decrease over the past decade and currently show the lowest cost of energy (271 $/kWh). The sizing of the battery is dependent on the building's consumption needs, and so it will only be performed later in this work.

Lastly, as seen already in chapter 2, the BoS is composed by the inverter, hardware components (structural and electrical), and soft costs (transport, installation, etc.). The inverter choice was still based on the Proison catalogue, and the chosen company was Zeversolar, which is a leading Chinese manufacturer that was acquired by the German company SMA. German companies are known for their product's reliability, so with this solution the product is still highly reliable at an affordable price. Even

[1] The Tier 1 ranking scale is orchestrated by Bloomberg New Energy Finance Corporation and is used to rank solar panel manufacturers in terms of their bank-ability or financial stability.

though the PV modules are the central piece of the system, the remaining technology still needs to equate the level of reliability and performance that was set, and therefore a well performing inverter is also essential. The sizing of this technology can only be done once the total system capacity is calculated, because the inverter's nominal capacity depends on the number of strings of the system, and so the cost details for this component will only be presented in a later section. Finally, to complete the BoS specifications, the hardware components and soft costs must be detailed. Differently from the aforementioned components, these costs and technology choices were not based on the Proison catalogue, but rather on reports from ETIP PV [9], which present average European costs.

4.3.1 PV Array sizing

Regarding the modules installation, the most important aspects to considered when designing the system are the possible power production losses due to shading between strings, the modules' tilt, and their orientation (azimuth angle). Because the panels will be tilted 33°, the shading between the different strings will result in production losses, and so a certain distance between each string needs to be accounted for and is calculated according to the panel's width and the sun's elevation angle. As for the orientation of the panels, they should be facing true south because in the northern hemisphere, at solar noon, the sun is always directly south. The azimuth angle describes the position of the panels in terms of how many degrees the array is from the north, so, if the modules should be facing south, then the azimuth is 180°. Therefore, by designing the system to have the best possible performance, only a portion of the rooftop areas available for installation (Table 4.1) will be utilized. The calculation for the number of panels and display on the rooftops is performed with the HelioScope online software [58], and the two different systems that were designed, one for each rooftop, can be seen in Figure 4.5.

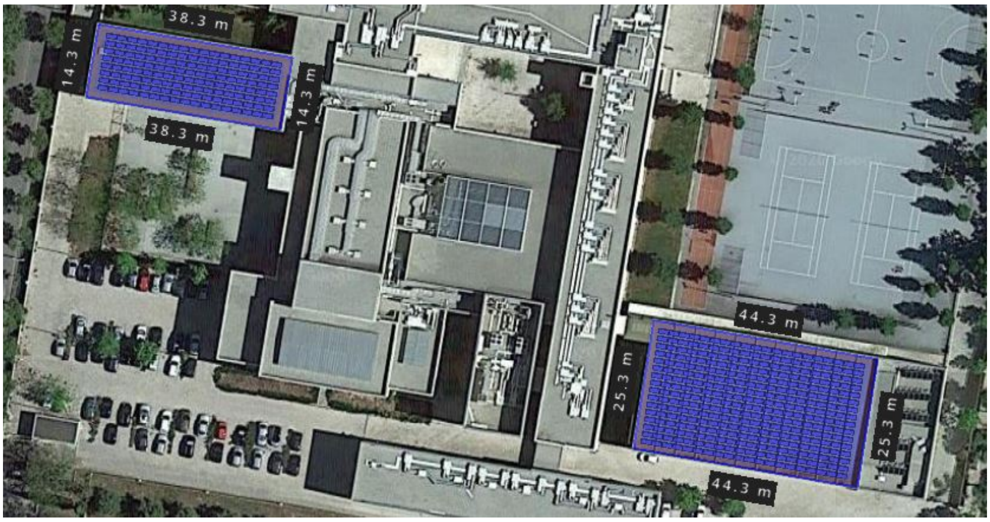

Figure 4.5: PV system display on buildings E (left) and G (right).

According to the calculations, the system on rooftops E and G will be composed of 136 and 323 panels, respectively, and the specifications for the number of arrays, number of modules in each array, and total system power are displayed in Table 4.3. As of now, the two systems will be referred to as system E and G, depending on the correspondent rooftop.

Table 4.3: Number of modules to be implemented in each rooftop and the corresponding peak power of each array and each system.

	Number of Arrays	Array size (modules)	Array peak power	Total peak power
System E	8	17	5.78 kWp	46.24 kWp
System G	19	17	5.78 kWp	109.82 kWp

4.3.2 Inverter sizing

The array and total peak power presented in Table 4.3 are calculated according to the chosen module's peak power (module specifications are detailed in Annex B). After knowing the peak power delivered by each array it is possible to get a sense of what the inverters' rated power should be, since this component should ”take on” the power that is delivered by each string. However, even though the strings should deliver a certain peak power, this only happens at STC, which is a rare occasion compared to other (less favourable) operating conditions. For this reason and also accounting for losses in the system, the power that can be delivered by each string will very rarely correspond to the peak power, and so it is possible to chose an inverter with a rated power that is lower than the array's peak power. In the PVsyst software this component is chosen based on a ratio between the array and the inverter's nominal power, which should have a value of around 1.25. Besides, one should also make sure that the string's voltage is lower than the inverter's maximum input voltage and included in the MPPT voltage range, and if strings are connected in parallel the current should be lower than the inverter's maximum input current.

In this system configuration, each inverter will be connected to only one string, and so, the maximum current it will have to withstand will be the short circuit current of the chosen module. As for the voltage, the maximum value possible to be input in the inverter will be the open circuit of each module multiplied by the number of modules in one array. Considering a ratio of 1.25, the inverter's nominal power should be 4.62 kW, so it must be slightly oversized to 5 kW. The chosen model was a Sunny Tripower 5.0 from SMA [59], for which the specifications (detailed in Annex B meet the desired requirements, and since there are 27 strings, then 27 inverters should be installed.

5

Results and discussion

Contents

This chapter details all of the findings resulting from the system simulation, for which the parameters and conditions have all been specified previously in this work. The first section details the analysis of the system's production results, comparing the monthly and daily calculations with the consumption needs. Then, the revenues and savings from each compensation scheme are presented. And lastly, the complete system costs are detailed, and the financial analysis is performed and the results are discussed.

5.1 Overall PV system production and self-consumption shares

Even though there are two different PV systems to be installed, the simulation is done for the combination of both, meaning that the considered installed capacity is the added capacity of the two systems (E and G). Therefore, in these results, the calculated generation is from a PV system of 156.06 kWp, and four different simulations are performed: three of them with self-consumption of PV energy (UPACs), and another with only grid injection of that same energy (UPP). Yearly, the PV system produces 267.131 MWh, which will also be the total amount of energy sold to the grid each year in the UPP installation. This is less than the building's yearly consumption, and well below the maximum of 2.6 MWh per each kW installed that is allowed by the Portuguese law. Furthermore, the power connection to the grid is also lower than the building's contracted power, which was a necessary condition for both UPP and UPAC installations, which establishes that the PV system implementation is within the parameters of the law for both cases.

Now, analyzing the simulations results, for the UPP implementation it is only necessary to assess the PV system output during each year like it has already been done, but for UPACs one has to relate that energy generation to the user's needs. This comparison can be seen in Figure 5.1, where the monthly building consumption (blue) and the PV generation (grey) are both presented.

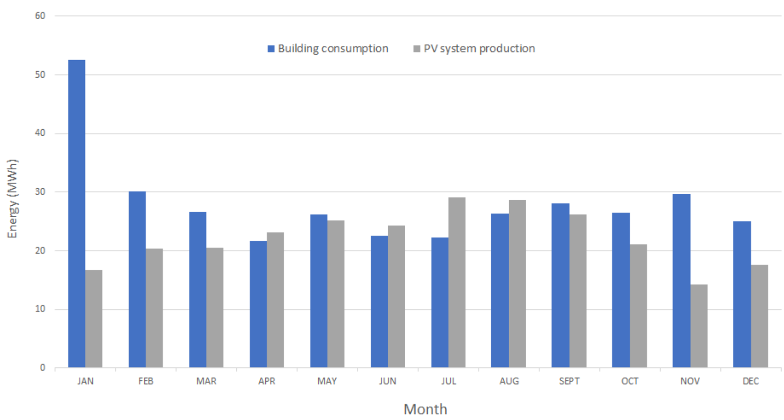

Figure 5.1: Monthly energy needs of the building (blue) and PV output energy (grey), in MWh.

From the results presented in Figure 5.1, it can be seen that, in 8 out of 12 months, the total PV production is lower than the building's consumption needs. Given that this consumption data corresponds to an educational building and knowing the usual functioning period of these facilities, it would be expected for the summer months (JUN to AUG) to show much lower values than it is seen here, which would lead to a much larger energy surplus during that period. However, from the available data, the yearly PV production represents around 79% of the user's needs, which does not mean that these needs will be reduced by that percentage, because some of this energy is surplus that will be injected into the grid. The relation between production and consumption needs to be studied on an hourly basis to understand how much of the energy will be sold to the grid, self-consumed, or stored in the battery, depending on the chosen scheme.

As it was established before, given the available data, every month is defined by just one day, so the building will have only 12 different load profiles. From these 12 profiles, only two will be presented in detail, to showcase the best and worst case scenarios: high needs and low production (January), and lower needs and high production (July). By analyzing the hourly PV output for the month of January it is seen that, in some days, the energy output is extremely low. The weak PV production (2^{nd} worst after November) combined with extremely high consumption needs are what cause the monthly discrepancy that is seen in Figure 5.1. This can be observed in Figure 5.2, where the plotted PV production corresponds to a random day for which the output of the system was considerably lower than the needs of the consumer.

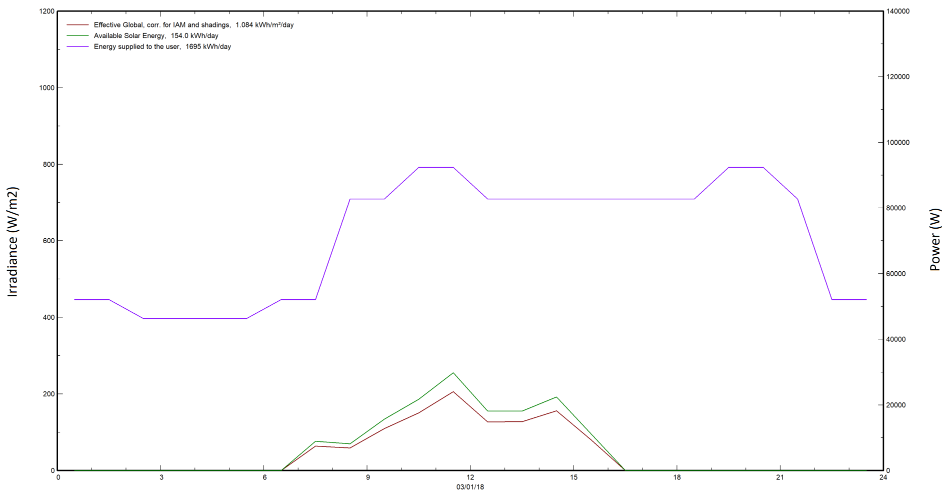

Figure 5.2: Hourly plot of the user's needs (purple), effective global irradiance (red), and output of the PV system (green), for a day in January.

In Figure 5.2, the effective global irradiance is also presented, and, as expected, its plot follows the PV system output very closely, meaning that these parameters are almost equal in shape. This is because, as it was seen before, the output of the PV system depends mainly on irradiance and temperature, and with such significant changes in irradiance the output will also vary. The results of different temperature in the energy output are not seen at this level, but rather when days of different months are compared. In this case, such low and inconsistent values of irradiance are seen due to clouds blocking the sun, which leads to lower energy outputs. This, of course, happens throughout the whole year, but it is more prevalent during the autumn/winter months (November to January), and so, during that period, the system output is greatly harmed by those conditions. However, even with low levels of irradiance the resulting system losses are only -1.1% of the array's nominal energy for the worst month (November), and much higher losses are observed due to high temperatures. Naturally, these temperature losses occur mainly in the summer months, with the worst case being August, which has the highest average ambient temperature during the whole year. So, even though it also presents the highest accumulated irradiance value, the PV output is not the highest because of temperature losses, which makes July instead the best performing month.

Therefore, for the best case scenario, a day in July is presented; besides showing the highest PV system output compared to the rest of the year this is the month in which the consumer's needs are lowest, making it the most promising case for a high share of self-consumption. In contrast to the previous example for January, here the irradiance values are considerably higher. More specifically, the accumulated global effective irradiance values in kWh/m^2 of January and July are 115.4 and 216.1, respectively, and while in January there are several days with no grid injection, in July there is surplus energy generation every day. Figure 5.3 shows a day in July with the highest levels of irradiance of the whole month, and it can be seen that the majority of the PV generated energy is surplus, that could be grid-injected, stored, or both.

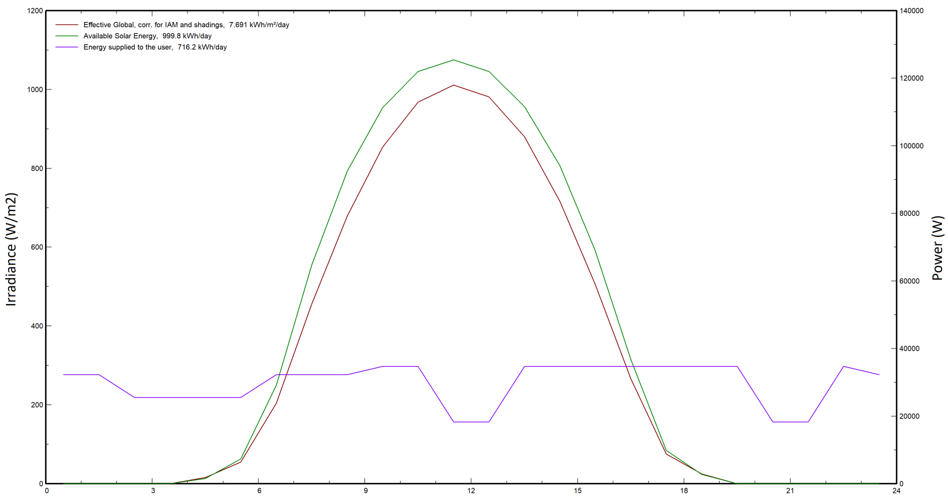

Figure 5.3: Hourly plot of the user's needs (purple), effective global irradiance (red), and output of the PV system (green), for a day in July.

5.1.1 Sizing of the BESS. Daily charging/discharging profile.

Since the system that is being studied is commercially sized, the battery should also be dimensioned for the same range as the consumption in a day (hundreds of kWh), in order for a significant increase of self-consumption to be observed. Looking at the daily surplus of PV energy, it is seen that the highest value happens in the month of July and amounts to 642.7 kWh, and to obtain levels of self-consumption that are close to the net-metering implementation (self-consuming a high share of the surplus), the total installed battery capacity should be around that value. However, knowing that the price of technology is 229 €/kWh, this investment would be too high and certainly there would be no feasibility in such an implementation. Therefore, the BESS energy capacity is chosen simply based on the options that the *PVSyst* software presents, for a BESS with an energy capacity in the 100 kWh range. One of the constraints for the sizing is that, for li-ion solutions, the maximum PV power (156 kWp in this case) should charge the battery in a minimum of 3-5 hours, so the number of cycles is not too high that the battery will have to be replaced before its expected end-of-life. For this reason, 3 battery banks are implemented, and the specifications of the chosen technology are detailed in Annex B.

The simulation is performed for this implementation and the plots of the battery charging and discharging energy, together with the grid-injected and the available solar energy, for the day in July with the maximum energy surplus, are seen in Figure 5.4. Since the BESS was not sized to store all of the PV energy surplus, it is seen that in this particular day a share of that surplus is stored, and when the battery reaches its maximum state of charge the charging energy goes to zero, with the remaining surplus of the following hours being injected into the grid. Once the PV energy fails to meet the user's consumption needs, the battery starts to discharge until it reaches its maximum maximum state of discharge.

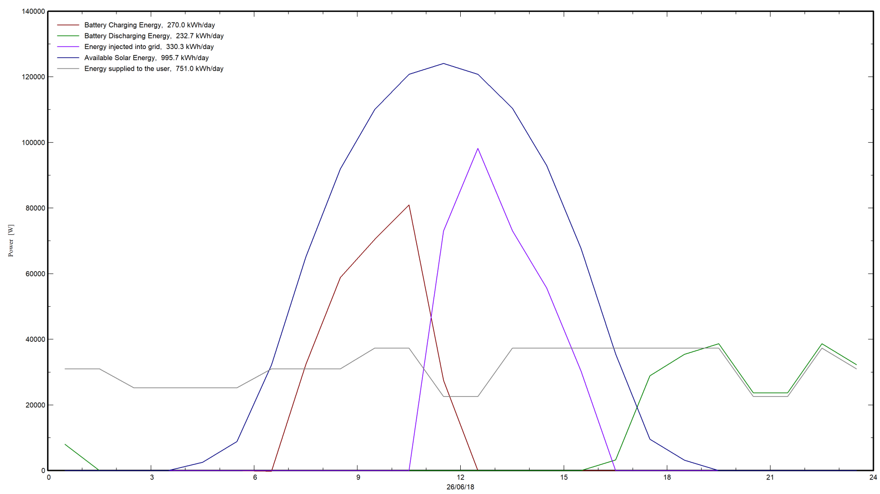

Figure 5.4: Hourly plot of the user's needs (grey), PV system output (blue), grid-inject energy (purple), battery discharging energy (green), and battery charging energy (red), for a day in July.

5.1.2 Shares of self-consumption for the different implementations

So, given these two examples and the limited information on the building's needs, it is not possible to state that the PV production curve shows any obvious similarities (or otherwise) with the daily or even monthly consumption needs that are known. As stated previously, it would be expected for the building to have lower needs during the months in which solar production is the highest, resulting in more surplus, but this is not the case. On the other hand, the daily load profile of an educational building should be similar to the production of PV energy at least in the sense that there is none or very little consumption of electricity during the night, because generally these buildings have the most activity from 8AM to 7PM. So, implementing the same project considering a more real consumption curve (at least in shape) would mean the energy that is assumed to be consumed at night would be shifted to another hour of the day, and so potentially the surplus would decrease and self-consumption would increase. However, for the conditions that were established from the available data, the shares of self-consumption might not be as high as they could be, and those results are shown in Table 5.1, presenting the breakdown of the consumed and injected energy for each of the three self-consumption implementations.

Table 5.1: Self-consumed, bought from grid and grid-injected energy for all three implementations: with and without BEES, and net-metering.

	Energy (MWh/yr)		
	Self-consumed	**Brought from Grid**	**Grid-injected**
Without BESS	133.501	200.807	133.629
Net-metering	258.019	76.289	
With BESS	211.499	129.804	48.309

As expected, it is seen that the net-metering implementation is the one with the most self-consumption of PV energy, representing a share of 76.5% of the yearly building consumption, while the self-consumption in the regular implementation (without BESS) and with BESS represent 39.5% and 62.6%, respectively. In the net-metering scheme, the energy that is grid-injected in one month is consumed in the following ones until the end of the year, and energy cannot be carried out from one year to the next, meaning that the surplus from December is not available for January of the following year, so ultimately, the surplus from December is not accounted for, and the extra energy that is self-consumed in the net-metering scheme corresponds to the surplus from January through November. This is why the grid-injected energy remains the same for the regular implementation (without BESS) and the net-metering, but the energy that is actually bought from the grid is much less because, for the most part, it corresponds to energy that was previously injected and is being self-consumed at a later time, also resulting in the increase of the self-consumed energy.

Even though it is said that the grid works as ”long-term storage” for net-metering, it is seen just how different the results are from the actual storage implementation. The BESS is of course limited by its capacity, and so there is less self-consumption and more energy bought from the grid, but there is the additional revenue of selling all of the surplus energy to the grid (like in the regular implementation). It was seen from previous studies that the self-consumption of energy is becoming more profitable than selling surplus to the grid, and so it is necessary to analyze the revenues and savings from each implementation to complement the energy consumption information and conclude which of the schemes (if any) is a viable investment.

5.2 Revenues and saving for each compensation scheme

5.2.1 Regular self-consumption, BESS implementation, and net metering

In the law it is foreseen that the energy metering for self-consumption should be done in a 15-minute time frame, which was not the case for this project. Since the building's consumption and the PV system production are only known hourly, the metering was done according to this time frame as well. In the schemes that do not apply net-metering, both with and without battery, the revenues result from the savings for the PV energy that is self-consumed and the surplus sold to the grid. This energy is sold at 90% of the average OMIE price of 2019, which was 47.87€/MWh. In the net-metering scheme, however, the surplus energy is not sold, but instead "stored" in the grid and can be used at a later time, like it has been described already in chapter 3, and again in the previous section, in which the energy consumption of each implementation was presented. The yearly savings and revenues in k€ resulting from the self-consumption and grid-injection of energy, respectively, for each of the implementations, are seen in Table 5.2.

Table 5.2: Yearly cash flows from savings and revenues of self-consumed and grid-injected energy, for each implementation.

	Cash flow (k€/yr)	
	Self Consumption	**Grid Injection**
Without BESS	9.544	5.757
Net-metering	18.446	-
With BESS	15.120	2.081

Logically, as seen in Table 5.2, the higher shares of self-consumption that were seen in the previous section result in higher cash-flows, and therefore the possibility of higher savings on the electricity bills. Since the BESS has a lifetime of only 10 years, the cash flows that are presented for that implementation are only for that period, and from year 11 until the end-of-life they will be the same as in the regular implementation. The savings from the exemption of the CIEG costs are not included in these results, but will be equal for all the self-consumption implementations. Analyzing the electricity bills, it is seen that the yearly CIEG costs amount to 11.273 k€, and so the savings for the first 7 years of each project implementation will be 5.636 k€. Figure 5.5 shows the impact of the cash flows seen on the yearly electricity bill. The values for the BESS implementation are only valid for the first 10 years of the project's lifetime, and after that the cash flows will be equal to the regular implementation, while in the regular and net-metering implementations the savings apply to the complete lifetime of the project because the savings from the exemption of CIEG costs are not included.

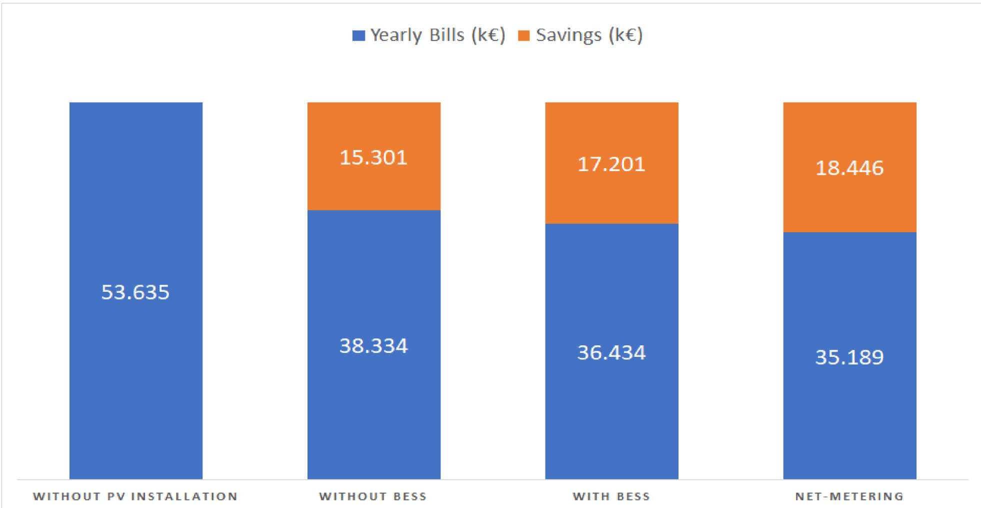

Figure 5.5: Energy bill savings for the different system implementations using self-consumption.

Recalling the results from Table 5.1, for the implementation without a BESS, the amount of energy that is self-consumed and sold to the grid is rather similar, but it is seen here that the cash flows differ significantly, with the self-consumption resulting in significantly higher savings when compared to the revenues from selling to the grid. More specifically, the average saving for each MWh that is self-consumed was 71.490€, while the revenue per each grid-injected MWh was 43.083€. This serves to confirm what was seen in the state-of-the-art; that injecting energy into the grid is being discouraged ever since FIT schemes were terminated, and energy from a PV source is sold to the grid at a much lower price than what it is bought for.

In the implementations with no BESS the system costs will be equal, and therefore, the viability of investing in these two projects can be compared to a certain degree. To conclude if investing in any of these projects would be viable it is necessary to calculate the system costs first, but from only the cash flow results presented here it can be concluded that the metrics to be calculated in the financial analysis will show the most favourable values for the net-metering scheme, out of all implementations. As for the BESS implementation, there will be the additional cost regarding the battery technology, and therefore one can cannot reach any conclusions without the results of the financial indicators, which can then be compared to the other two implementations.

5.2.2 Full grid injection

For this analysis, since all of the available energy that is generated by the PV system is injected and sold to the grid, the user's needs are not a factor in the calculations. The revenues in this implementation will be constant for the first 15 years of the project's lifetime and based on a fixed tariff of 45€/MWh. After year 15 until the end of life, the remuneration is calculated based on the same OMIE average price as in the self-consumption scheme. The pricing for these last 10 years is based on peak and off-peak hours: in winter, peak is from 12h to 22h, and in summer from 13h to 23h, with the remaining hours for both seasons being off-peak. The results of the yearly remuneration for the two periods (year 1 to 15, and 16 to 25) are presented in Table 5.3.

Table 5.3: Yearly remuneration for the grid-injected energy in two different time periods.

Years	Cash Flows (k€/yr)
1-15	11.700
16-25	9.573

As expected, it is seen that selling energy to the grid, even in this scheme, is less profitable than self-consuming. Even though, for the first 15 years of the project, the remuneration per each MWh is slightly higher than in the self-consumption scheme, for the following 10 the average value per MWh that is injected is 35.836 €. Comparing these results with the previous self-consumption implementations makes it undeniable that simply self-consuming energy is more protiable than injecting and selling surpuls (or all) energy to the electricity grid.

5.3 Financial and environmental analysis

5.3.1 Detailed system costs

The system costs and revenues are the two factors that need to be detailed for the financial analysis calculations, as it was already mentioned in Chapter 3. At the beginning of this work it was also presented that the total cost of the system is composed of the installation/investment costs, and operational costs (CAPEX and OPEX), and therefore all that is entailed in these costs should be detailed. The OPEX costs are simple as they are just composed of the OM costs, which are considered to be 2.5% of the CAPEX [60]. As for the CAPEX, some of the costs have already been detailed (modules and battery), but the details of other components and services that are also as important still need to be presented. Besides the modules, inverter, and battery, all of the CAPEX costs were based on [9].

Table 5.4 is presented first, with the breakdown of the BoS, detailing all of its components and services. The summation of those values which makes for the total BoS costs is then presented in Table 5.5, together with the module and battery costs. Depending on whether the BESS implementation is considered or not, the value of the CAPEX will change, since the battery technology is a crucial added cost, and therefore the OPEX will also differ, depending on the implementation.

Table 5.4: Breakdown of the BoS with the respective costs per Wp.

BoS Breakdown	Cost (€/Wp)
Inverter	0.181
Mounting System	0.075
Installation	0.05
Cabling	0.05
Infrastructure	0.04
Transformer	0.02
Grid connection	0.07
Total Cost	0.486

Table 5.5: Breakdown of the CAPEX with the respective costs per Wp.

CAPEX Breakdown	Costs (€/Wp)
Modules	0.41
BoS	0.486
Battery	0.494

Besides the values already presented, according to the installed PV capacity (between 100 and 250 kW), the system costs also include the registration fee equal to 500 €, for each of the implementations. Finally, the total costs of each system implementation can be seen in Table 5.6. Since the PV system installation is equal for all of the schemes, these costs will be constant for all simulations and the only possible value to add to the initial investment will be if the battery is implemented or not, which is how these final costs are organized. Table 5.6 presents the total system costs (CAPEX and OPEX) for the implementations with and without battery.

Table 5.6: Final system costs, detailing the CAPEX and OPEX, depending on whether BESS implementation is considered or not.

	System Costs (€/Wp)	
	CAPEX	**OPEX**
Without BESS	0.896	0.0224
With BESS	1.39	0.0348

5.3.2 Investment viability

To perform the financial analysis, the models described in chapter 3 are used, and a number of different parameters need to be set. The considered investment period/lifetime of the project is 25 years, the discount rate *i* is considered to be 6%, and a VAT of 23% is applied to the income cash flows that have been previously detailed. Now that the OM costs are known, they are considered in the cash flows that are presented in Table 5.7, which depend also on the revenues and savings of each implementation. These values are presented alongside the metrics of the financial analysis: SPBT, NPV, IRR, and ROI. With the results of Table 5.7, the viability of investing in the different project implementations can now be studied precisely.

Table 5.7: Results of the financial analysis for each implementation. Comparison of the SPBT, NPV, IRR, and ROI.

	Years	Cash Flow (k€)	SPBT (years)	NPV (€)	IRR (%)	ROI (%)
Without BESS	1-7	16.639	12.04	186.39	6.01	1.829
	7-25	11.003				
Net-metering	1-7	19.784	9.36	38 114.36	8.63	2.287
	7-25	14.148				
With BESS	1-7	16.169	21.08	(109 394.11)	0.67	1.087
	7-10	10.533				
	11-25	11.003				
Grid Injection	1-15	7.402	> 25	(79 084.76)	(0.4)	(4.735)
	16-25	5.275				

By analyzing these results, it can be seen that the statements that were made about the profitability of some implementations were in fact correct. The net-metering scheme is the most profitable implementation out of all four, above the regular self-consumption (without BESS), which is the only other implementation in which the investment shows a positive financial outcome. Both of these implementations show a positive NPV, an IRR above the discount rate, and a positive ROI, and so, these projects can be considered economically viable. Looking at the ROI, the results seem to be positive for every configuration except the grid injection, with results above 1, which means that at the end of the project's lifetime a certain percentage above the initial investment has been recovered. In the BESS implementation, the NPV and IRR present unattractive results, but the ROI remains positive, with a small percentage (8.7%) above the initial investment being recovered, showing that this metric is not reliable on its own and should be calculated alongside at least the NPV or IRR, to clearly analyze the viability of investing in a certain project.

Only now, knowing the system costs for the BESS implementation and considering them in the financial analysis, can it be concluded that the cost of this technology is a definite setback for the investment. This implementation and the grid-injection both present unattractive financial results, especially the latter, showing negative values for all of the calculated metrics. Even with negative values for the

BESS implementation it is still seen that, because there is self-consumption of energy, the project might present a less unattractive investment, compared to full grid-injection. However, it is still relevant to denote the considerably negative impact that the high costs of battery technology have on the system's financial results. This shows that the existent battery technologies have not matured enough to be a viable self-consumption solution, and even considering a BESS technology that is widely commercialized and generally the cheapest option (Li-Ion), it still was not able to make the investment reach a level of attractiveness, showing that the technology still has a lot of room to evolve. Possibly, not considering the future decrease in cost of technology, the viability of this approach would only be seen if DSM was also applied, to improve the self-consumption shares even more, and compensate for the investment that is made for the battery technology. As for the implementation with only grid injection, it is not surprising that the project is unable to reach attractiveness in this configuration, given the results for the cash flows that were previously compared to the remaining implementations.

5.3.3 Life Cycle Assessment

In this assessment, the life cycle carbon emissions of the implemented PV system are calculated. These results are related to the system components, and therefore, they apply to each scheme implementation equally, because the same PV system installation is applied for all cases. To calculate the Carbon Balance, as seen in equation 3.19, the project's lifetime and energy generated by the PV system are known, the Grid LCE for Portugal is considered to be 310 gCO2/kWh [61], and the system LCE is calculated according to the default values set by *PVSyst* for the manufacturing, transport and disposal of the modules and BoS components. Table 5.8 presents the values for the LCE and and embodied energy of each system component.

Table 5.8: LCE and embodied energy of the different system components.

System components	LCE (gCO2/kWp)	Embodied Energy (kWh)
Modules	1 662	338 208
Inverter	227	36 685
BoS	2.29	17 841.6

The sum of the embodied energies of all components is equal to the total system LCE, so knowing this value the Carbon Balance can be calculated, and it is estimated that the implementation of this system saves 1 567.142 tons of CO2 emissions during its lifetime. Lastly, with the results from Table 5.8, the GPBT and EPBT are calculated and it is seen that it takes around 3.5 to compensate for the CO2 emissions of the transport and manufacturing processes, and just 1.5 years to recover the energy that was spent during those stages.

6

Conclusion

Contents

This work presented the study of different compensation schemes for PV technology, and their financial viability, as well as the environmental impacts and gains of the implementation. The different schemes were applied as it is foreseen in the Portuguese law, excluding the net-metering implementation, which is not allowed. Other than self-consumption with net-metering, this study presented the impacts of implementing a PV system with regular self-consumption, self-consumption with the addition of a BESS, and full grid injection.

In the regular self-consumption scheme the solar surplus is sold to the grid and the remaining is self-consumed. With the BESS implementation the same conditions are applied, and the battery allows for more self-consumption, storing surplus when possible and supplying it to the building when solar power is unavailable. Lastly, in the net-metering scheme, the surplus injected into the grid can be ”stored” there and consumed at a later time, improving the self-consumption even more than with a BESS. It was seen that, in most months out of the simulated year, the PV produced energy did not match the needs of the building, and yearly it represents around 79% of the needs. With the regular self-consumption, the solar energy consumed by the building was still lower than the amount that was bought from the grid, but with the BESS and net-metering, the self-consumption was 1.6 and 1.9 times higher, respectively, compared to the regular implementation.

To understand and compare the profitability of self-consumption and selling energy to the grid, the positive cash flows for each implementations were calculated. It was seen that the self-consumption allows for an average saving of 71.49 €/MWh, while the revenues from selling energy to the grid were 43.083 €/MWh, clearly showing why self-consumption is preferred over the selling of surplus. This is observed because of the termination of FITs, and therefore, continuous discouragement of grid-injection schemes. With this information it could only be concluded that the net-metering scheme would be the implementation with the most favourable financial outcome, but to know if any of the implementations were in fact viable, the metrics of the financial analysis still needed to be calculated, according not only to the positive cash flows but also the system costs, which only differed for the BESS implementation.

The results of the financial calculations showed that only the net-metering and regular self-consumption schemes would be a viable investment, both with a positive NPV and an IRR above the considered discount rate, and as expected, the net-metering scheme showed the most attractive results for investment. As for the BESS implementation and the full grid-injection, both schemes show negative results overall and the investment fails to reach attractiveness, with the lowest NPV result seen for the BESS implementation, and the only negative IRR for the grid-injection. The overall results of the analysis show that the self-consumption of energy is more profitable than grid-injection, and BESS technology still needs to improve to see a significant price reduction for its implementation and become viable on a medium-system scale.

6.1 Future Work

Considering the findings of this project, improvements could still be made to the implementation, considering better data for certain calculations. Furthermore, taking on the work that has been done, there is also the possibility of further developments of certain aspects to complement the findings of this work.

For the project implementation, the daily consumer needs that were considered in the calculations are composed of average values, based only on monthly electricity bills that showed the consumption for each tariff period in each month. As a consequence the daily load profile of the building did not have the shape that is expected from an educational building, meaning that the needs of the building were not fairly modelled. Even if only 12 different load profiles are considered (one for each month) for the whole year, if the hourly values for a day in each month were known, the results would present a better replica of a real-life project. Having a load curve that is closer to the real behaviour of the building would also allow for a better evaluation of the tariff scheme that is consider, and study the impact and viability of changing to a different scheme.

For the system costs, the only prices that were gathered from online stores were the module and inverter. All of the remaining costs, from the BESS to the BoS soft costs were based on averages from different research works, in some cases for utility-scale systems, and never considering the location of the installation to which the soft costs are particularly sensitive. Knowing that a project's financial feasibility is highly dependent on the system costs, a more precise study of these should be done, considering maybe price quotes from solar installation companies in Portugal, to understand how close from the reality the considered values are.

One of the most relevant steps forward from this work would be to implement further renovations on the school building, in order to achieve nZEB status. Since the current building has been renovated in the last decade, it would be necessary to study if those conditions reflect a good enough energy performance, and what energy efficiency measures should be taken to achieve the desired status. Even though the deployment of RES projects alone is an incredibly important step for the future of the energy sector, the efforts to achieve the climate goals set by member states should not be focused solely on the utilization of RES, but also on the efficient consumption of that energy. More specifically, there have been a number of successful projects across Europe that performed the retrofitting of several educational buildings and achieved nZEB status, which shows the potential of following this research path. Furthermore, with the possibility of renovating the building envelope, the implementation of building-integrated PV modules could also be studied, instead of the roof-mounting, since the technology is emerging and the implementation within the renovations would be simplified.

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A

Detailed consumer needs

This Annex details the building's consumption for all the months of 2019. Both tables show the consumption in kWh: Table A.2 presents the total consumption for each cycle of each month, and Table A.3 presents the daily consumption for each cycle. As all days of the week are considered the same, the daily consumption is the same through every day of a certain month.

Table A.1: Monthly building consumption and electricity costs.

	Consumption (kWh)	Costs (€)
JAN	52543	8325.03
FEB	30170	4735.31
MAR	26676	4334.33
APR	21679	3539.18
MAY	26229	4239.55
JUN	22528	3603.49
JUL	22205	3498.05
AUG	26287	4059.35
SEPT	28125	4483.96
OCT	26466	4315.89
NOV	29733	4646.86
DEC	24968	3853.51

Table A.2: Total building consumption for each cycle of each month.

	Monthly Consumption (kWh)			
	Peak	Full	Off-peak	Super off-peak
JAN	11455	25647	9695	5746
FEB	6202	13910	6194	3864
MAR	5032	13118	5216	3310
APR	2813	9431	6592	2843
MAY	3699	13492	5833	3205
JUN	2712	11202	5587	3027
JUL	2266	10770	6004	3165
AUG	2871	12848	6822	3746
SEPT	3985	14176	6449	3515
OCT	4813	12768	5798	3087
NOV	4813	12768	5798	3087
DEC	4433	10645	6632	3258

Table A.3: Daily building consumption for each cycle of each month.

	Daily Consumption (kWh)			
	Peak	Full	Off-peak	Super off-peak
JAN	92.38	82.73	52.12	46.34
FEB	55.38	49.68	36.87	34.50
MAR	40.58	42.32	28.04	26.69
APR	23.44	31.44	36.62	23.69
MAY	29.83	43.52	31.36	25.85
JUN	22.60	37.34	31.04	25.23
JUL	18.27	34.74	32.28	25.52
AUG	23.15	41.45	36.68	30.21
SEPT	33.21	47.25	35.83	29.29
OCT	38.81	41.19	31.17	24.90
NOV	40.11	42.56	32.21	25.73
DEC	35.75	34.34	35.66	26.27

B

System specifications

In this Appendix, the specifications for the system components are detailed. Firstly, the considered options for the choice of PV modules resulting from a brief market study are presented in Table B.1. From these options, only one was chosen and used for the system implementation, and the specifications for that module are detailed in Table B.2. Lastly, Tables B.3 and B.4 present the inverter and battery specifications, respectively.

Table B.1: Power rating, efficiency and price comparison of PV modules from different manufacturers.

	Power Rating (Wp)	**Maximum Efficiency (%)**	**Price (€/Wp)**
Jinko Solar	280	17.11	0.271
	330	17	0.397
Trina Solar	285	16.7	0.298
	340	16.7	0.388
Talesun	275	16.8	0.485
	330	17.0	0.542

Table B.2: TallMax TSM-PE15H module datasheet specifications.

	TallMax TSM-PE15H
Peak Power (W)	340
Max. peak Voltage (V)	37.5
Max. peak current (A)	9.06
Open circuit Voltage (V)	46.2
Short Circuit Current (A)	9.53
Efficiency (%)	16.7

Table B.3: Evershine TLC 5000 inverter datasheet specifications.

	Evershine TLC 5000
Max. PV array power (Wp)	6600
Max. input voltage (V)	1000
MPP voltage range (V)	200 - 900
Max. DC short-circuit current (A)	16.5
Max. operating inupt current (A)	11
Efficiency (%)	97.5

Table B.4: LG Chem R1000 BESS datasheet specifications.

	LG Chem R1000
Energy (kWh)	110.9
Capacity (Ah)	126.0
Nominal Voltage (V)	725
Voltage Range (V)	588 - 823