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STATE OF THE ART AND ECONOMIC VIABILITY OF A PHOTOVOLTAIC SYSTEM WITH ENERGY STORAGE IN RESIDENTIAL BUILDINGS

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State of the art and economic viability of a photovoltaic system with energy storage in residential buildings

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"The secret of an opal's color lies not in its substance, but in its absence."

- Australian Geographic, nº5, July- September 1998

Abstract

In this dissertation the economic evaluation was performed for a photovoltaic (PV) solar panel system with energy storage, implemented in a residential building placed in three different locations in Portugal: Porto, Lisboa and Faro.

IESve software was used to acquire the electric consumption profile of the building, PVGIS was used to obtain the PV power production profile and a system of equations and restrictions developed in Excel was used to implement solar photovoltaic and battery storage in the building.

The PV system implemented using the available area of the roof-top of the building was not able to produce enough electricity to supply the electric consumption of the building, being this last one more than ten times higher. Other hypothetic scenarios were studied.

The scenario for the total independence of the grid was not studied once an oversized and overloaded system would be obtained. With this in mind, the systems were designed to supply only a percentage of the electricity consumption of the building.

When sizing the system of PV panels plus batteries capable of supplying 50% of the electricity consumption of the building, in Porto the best system obtained was composed by a PV peak power installed of 270 kWp and battery capacity of 768 kWh; in Lisbon, a PV peak power installed of 245 kWp and battery capacity of 732 kWh; in Faro, a PV peak power installed of 794 kWp and battery capacity of 794 kWh. The best systems for each location require different investment costs of 581 200 EUR, 547 916 EUR and 574 400 EUR, for Porto, Lisbon and Faro, respectively, but have the same payback time of 15 years. If this investment would be carried out in 5 years, this payback time would decrease to 9 years.

It was concluded that although in south of Portugal the power production from a photovoltaic panel system is higher than in the North, the electric consumption of the building studied was also higher and thus, this factor do not dictated a better performance of the system for the compared locations. Other factors would have more influence in the feasibility of this investment, such as reducing the electric consumption of the building or the possibility to implement a building integrated PV system.

Keywords: PV system; Energy storage system; Building Sector; Economic evaluation

Resumo

Nesta dissertação foi realizada a avaliação económica de implementação de um sistema fotovoltaico com armazenamento de energia num edifício residencial situado em três localizações diferentes em Portugal: Porto, Lisboa e Faro.

O software IESve foi utilizado para adquirir o perfil de consumo elétrico do edifício, o simulador PVGIS foi utilizado para obter o perfil de produção de eletricidade a partir do sistema fotovoltaico e um sistema de equações e restrições desenvolvido em Excel foi utilizado para concretizar a implementação de um sistema fotovoltaico com armazenamento de energia no edifício.

O sistema fotovoltaico implementado na área disponível do telhado (terraço) do edifício não foi capaz de produzir a eletricidade necessária para suprir o consumo de eletricidade do edifício, sendo este dez vezes superior. Outros cenários hipotéticos foram estudados.

O cenário para a total independência da rede não foi estudado uma vez que levaria à sobrecarga e sobredimensionamento do sistema. Tendo isto em conta, os sistemas foram projetados para fornecer apenas uma percentagem dos consumos de eletricidade do edifício.

Dimensionado o sistema de painéis fotovoltaicos e baterias capaz de fornecer 50% dos consumos elétricos do edifício, no Porto o melhor sistema obtido tem uma potência de pico instalada de 270 kWp e uma capacidade de bateria de 768 kWh; em Lisboa o melhor sistema obtido tem uma potência de pico instalada de 245 kWp e uma capacidade de bateria de 732 kWh ; em Faro, o melhor sistema obtido tem uma potência de pico instalada de 225 kWp e uma capacidade de bateria de 794 kWh. Estes sistemas apresentam custos de investimento diferentes de 581 200 EUR, 547 916 EUR e 574 400 EUR, para o Porto, Lisboa e Faro, respetivamente, mas apresentam o mesmo tempo de retorno de 15 anos. Se este investimento fosse feito daqui a 5 anos, este tempo de retorno de investimento passaria a 9 anos.

Concluiu-se que, embora a produção fotovoltaica de eletricidade seja superior no Sul quando comparada com o Norte, também os consumos obtidos de eletricidade no edifício estudado são superiores, e como tal, este fator não ditou uma melhor performance na comparação das diferentes localizações. Outros fatores teriam mais influência na viabilidade do investimento, como por exemplo a redução dos consumos de eletricidade do edifício e a possibilidade de implementar um sistema de BIPV.

Palavras-chave: Sistema fotovoltaico; Sistema de armazenamento de energia; Sector de Edifícios; Avaliação económica

Declaration

I hereby declare, under word of honour, that this work is original and that all non-original contributions is indicated and due reference is given to the author and source

Catarina da Cunha Durán

(Catarina da Cunha Durán)

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Notation and Glossary

$q"_{\alpha sol}$	absorbed direct and diffuse solar radiation flux	W·m^{-2}
$q"_{LWR}$	net long-wave radiation flux exchange with air and surroundings	W·m^{-2}
$q"_{conv}$	convective exchange flux with outdoor air	W·m^{-2}
$q"_{k0}$	conductive flux (q/A) into wall	W·m^{-2}
$q"_{LWX}$	net long-wave radiant flux exchange between zone surfaces	W·m^{-2}
$q"_{SW}$	net short-wave radiation flux to surface from lights	W·m^{-2}
$q"_{LWS}$	long-wave radiation flux from equipment in zone	W·m^{-2}
$q"_{ki}$	conductive flux through wall	W·m^{-2}
$q"_{sol}$	transmitted solar radiative flux absorbed at surface	W·m^{-2}
$q"_{conv}$	convective heat flux to zone air	W·m^{-2}
$q"_{CE}$	convective parts of internal loads	W
$q"_{IV}$	sensible load caused by infiltration and ventilation air	W
$q"_{sys}$	heat transfer to/from HVAC system	W
W	eat output per unit panel area	W·m^{-2}
I	incident solar irradiance	W·m^{-2}
T	panel temperature	K
T_a	outside air temperature	K
P_i	installed peak power	kWp
P_p	panel peak power (given by the manufacturer)	kWp
n_p	number of panels in the available area	kWh
E_l	energy loads	kWh
h_{sp}	sun peak hours	h
η_s	system efficiency	%

List of Acronyms

AC	Alternating Current
AGM	Absorbed Glass Mat
APREN	Portuguese Renewable Energy Association
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAPV	Building Applied Photovoltaics
BSC%	Battery State of Charge
BES	Battery Energy Storage
BIPV	Building-Integrated Photovoltaics
BTM	Behind-The-Meter
CAES	Compressed Air Energy Storage
CdTe	Cadmium-Telluride
CIS	Copper-Indium-Selenium
COP	Coefficient of Performance
DC	Direct Current
DHW	Domestic Hot Water
ESS	Energy Storage Systems
FC	Fuel Cells
FES	Flywheel Energy Storage
FLA	Flooded Lead-Acid
HB	Heat Balance
HES	Hydrogen Energy Storage
HVAC	Heating, Ventilating and Air Conditioning
IEA	International Energy Agency

IESve	Integrated Environmental Solutions Virtual Environment
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Energy
LCOS	Levelized Cost of Storage
LFP	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
LNEG	Laboratório Nacional De Energia E Geologia
LTO	Lithium Titane
NCA	Lithium Nickel Cobalt Aluminium
NMC	Lithium Nickel Manganese Oxide
PCM	Latent Heat Storage
PHS	Pumped Hydroelectric Storage
PNEC 2030	National Plan for Energy and Climate 2030
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
RNC 2050	Roadmap for Carbon Neutrality 2050
SEER	Energy Efficiency Ratio
SES	Super Capacitor Energy Storage
SMES	Superconducting Magnetic Energy Storage
TCS	Thermo-Chemical Storage
VRFB	Vanadium Redox Flow Battery
VRLA	Valve Regulated Lead-A
ZLEV	Zero or Low Emission

1 Introduction

1.1 Framing and presentation of the work

The growing concern about climate change led to the Paris Agreement, in 2015, which established the need to limit the average increase in global temperature to 1.5 ºC, recognizing that it will be necessary to achieve, by the year 2050, the carbon neutrality.

Portugal assumed the objective of achieving Carbon Neutrality by 2050 and developed the Roadmap for Carbon Neutrality 2050 (RNC2050) which established the vision, trajectories and guidelines for policies and measures to be implemented until 2050.[1]

The buildings sector (including residential and services) is currently responsible for 5% of national emissions of greenhouse gases and for 30% of the final energy consumption in Portugal. The energy consumption in the building is related to heating and cooling spaces, illumination, refrigeration, food preparation, and domestic hot water (DHW) heating. [1]

The main decarbonization drivers in the buildings sector are the transition to renewables, energy efficiency and electrification of processes in that use fuels, such as heating spaces or preparing food. Certainly, the integration of renewable energy technologies to produce electricity has increased worldwide in the past decade and continues to grow.

This scenario brings some challenges, due to the variable nature of generation from renewable sources, as it depends on weather conditions: this means net load stability problems and requires increasing system flexibility and smoothing the residual demand. Energy storage systems can be used to storage electricity produced when there is low demand, low generation costs or from renewable energy sources. This electricity stored can be used later when there is high demand, high generation costs or when no other generation sources are available. Battery storage appears to be the fastest growing option, due to its falling costs, fast construction, availability and scalability. [2]

This dissertation aims to evaluate the energetic and economic performance of a photovoltaic panels system with energy storage for a mid-rise residential building located in three different cities in Portugal: Porto, Lisbon and Faro.

IESve software was used to perform several dynamic simulations and analyze thermal and electricity requirements of the building. All the assumptions were based on the more recent Portuguese and European legislations to achieve the more realistic and best energetic performance of the new projected building. PVGIS was used to obtain the PV system power production profile. A system of equations and restrictions developed in Excel was developed to implement solar photovoltaic and the battery storage system in the building.

1.2 Presentation of the company

A400 – Projetistas e Consultores de Engenharia is a Portuguese company founded in 1995 with a strong tradition in structural engineering, project management and coordination, and offers complete services in the construction industry.

The company has more than 100 employees and its present in Porto, Lisbon, Madeira, Angola, Mozambique, Algeria and Morocco.

The company is structured in different departments such as structural, hydraulics, mechanical, electrical and telecommunications, research and development and coordination departments.

1.3 Contribution of the author to the work

The development of this work contributes for better understanding the impact of the integration of energy storage in a PV system, and how it generates savings by increasing the independency of the grid.

It stands out for being implemented in a real building project simulated for conditions as close to reality possible and it uses technologies commercially available and present market prices in order to evaluate the economic feasibility in a Portuguese context.

1.4 Organization of the thesis

This dissertation was organized in seven chapters, being: the *Introduction*, where the theme and the objectives of the dissertation are described; the *Context and State of the Art*, where a literature survey is conducted on relevant information about solar energy technologies, energy storage technologies and the integration of these technologies in residential buildings; *Proposed Methodology*, where the software, simulator used and the system of equations and restrictions performed on Excel are described; the *Case Study*, where the project and its considerations are presented; *Results and Discussion*, where the results for the simulations performed are presented and discussed in detail; *Conclusions*, where the final considerations and main conclusions are presented; *Assessment of the work done*, where is evaluated the work and whether the proposed objectives were accomplished and some suggestions for future work are presented.

2 Context and State of the Art

The integration of renewable energy technologies to produce electricity has been increasing. In 2018 they were responsible for more than 25% of total power generation globally. [3] According to the World Energy Outlook 2019, by International Energy Agency, IEA, renewables should be responsible for supplying two thirds of electricity worldwide by 2040, being 40% provided by solar and wind together. [2]

Figure 2.1 shows the share of renewables' production evolution since 1985 to 2018 for different countries in the world.

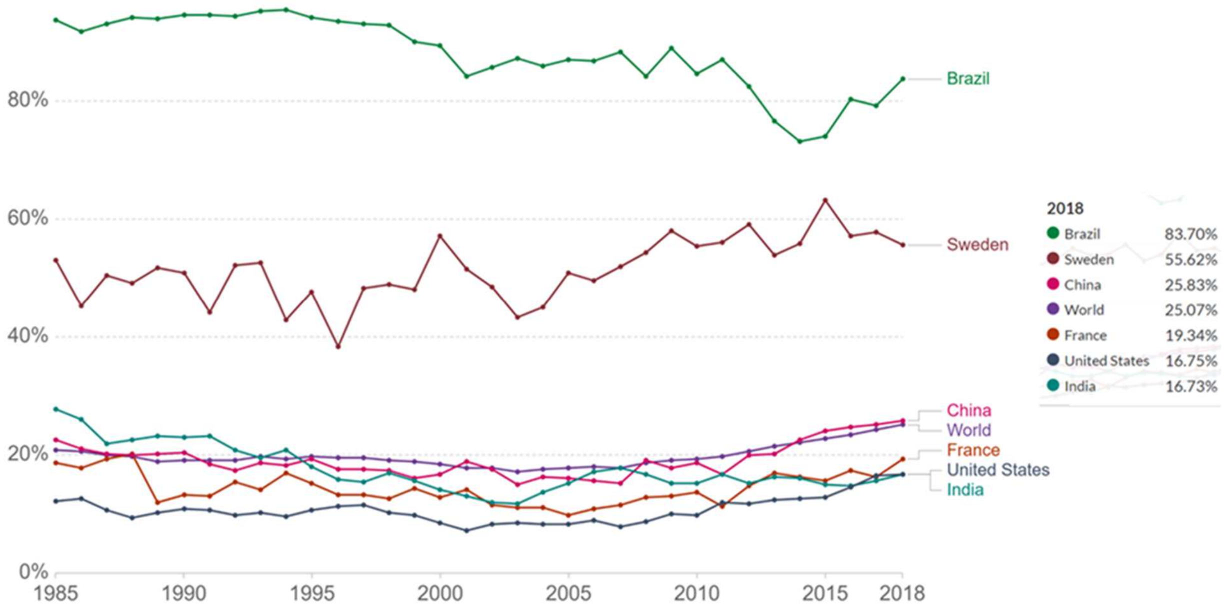


Figure 2.1 - Share of production from renewables (including production from hydropower, solar, wind, biomass and waste, geothermal, wave and tidal sources). Adapted from [3].

The building sector must be considered in the promotion of the energy transition: its electric demand is predicted to increase 70% by 2050 worldwide. [4]. There was 36% of share of renewable energy (including biomass) use in buildings in the year of 2015, and the Remap Case considers that it should increase up to 56% by 2050, with an investment required of 1.6 trillion of USD. [4].

According to the Portuguese Renewable Energy Association (APREN), in 2018 the electricity produced in Portugal had a share of renewable sources of 52.6%. Hydroelectric and wind energy are the main sources of renewable energy in Portugal, accounting for 46% of the electricity generated followed by biomass (5%), solar (1.4%) and finally geothermal (0.4%). [5]

Efforts are being made in Portugal to achieve the ambitious goals facing the energetic transition and a National Plan for Energy and Climate (PNEC2030) was presented in the end of last year (2019). It states that by 2030 at least 47% of the energy consumed must come from renewable sources, and in the electrical sector they need to contribute for 80% of electricity production. [6]

2.1 Solar Energy

2.1.1 Photovoltaic panels

Due to the decrease in renewable energy production costs over the last years, the consumers are now investing in generating electricity for self-consumption, mostly by installing photovoltaic (PV) panels. On the report of RNC 2050 the solar photovoltaic technology will raise up to 13 GW centralized and decentralized in Portugal by 2050.[1]

According to figures released by the International Renewable Energy Agency (IRENA), between 2010 and 2018 there was a decline of 74% in the total installation costs of solar PV systems and predicts that it will continue to decline, standing in the range of 340 to 834 USD/kW by 2030 and 165 to 481 USD/kW by 2050. [7]

Also. It states that the levelized cost of energy (LCOE) generated by residential PV systems is now between 0.063 USD /kWh and 0.265 USD /kWh (2019), compared to between 0.301 USD /kWh and 0.455 USD /kWh ten years ago (2010), a decline of between 47-80%. [8, 9]. It is interesting to notice that electricity produced by a PV system can now be cheaper than the tariffs offered by the energy traders.

The PV modules consist in photovoltaic cells that are connected to each other to convert solar radiation into electricity. The performance of the PV systems is influenced by different factors such as the solar radiation, PV technology, PV module temperature, tilt and azimuth angles, shading conditions, and spectral effects. [10]

There are many types commercialized, differing in technology and materials. The most common used are the silicon-based (mono and polycrystalline) for their relative high efficiencies, accounting for 90% of solar PV panels market share. [7, 10]

PV modules produce direct current (DC) electricity and when connected to the grid they are linked to an Inverter that converts the electricity into alternating current (AC). There are many ways the PV panels are mounted, being fixed or tracking systems. Sun-tracking PV systems have the PV modules installed on supports that move the modules during the day so that the modules face in the direction of the sun. Fixed (non-tracking) systems can be free-standing or building applied photovoltaics (BAPV), meaning that the modules are mounted on a structure or building-integrated (BIPV), which means that the modules are completely built into the structure of the wall or roof of a building replacing building elements (such as walls or transparent elements) instead of being applied over other elements. In Figure 2.2.**Error! Reference source not found.** the comparison between these two systems is shown. [10]

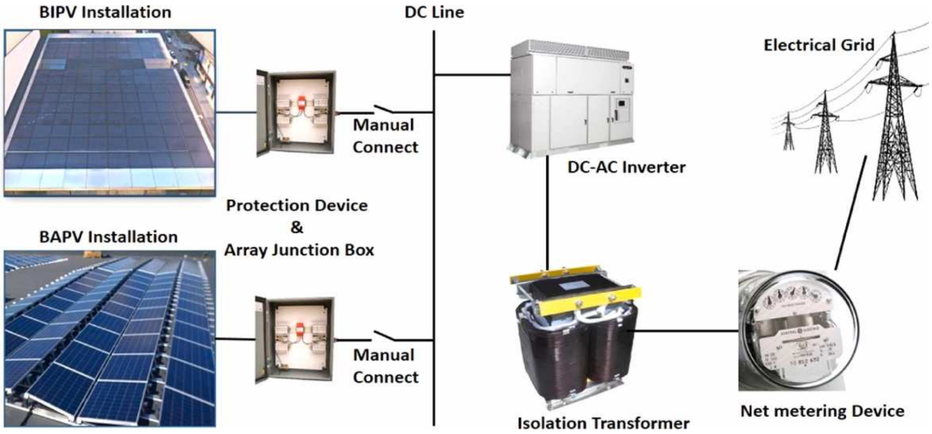


Figure 2.2 - BIPV and BAPV systems connected to the grid and its components. [10]

The way the modules are mounted will have an influence on the temperature of the module, which in turn affects the efficiency. [11] The study of the influence of module temperature on PV performance was conducted in Cotfas et. Al (2018), concluding that the maximum power decreases with values between 0.14% and 0.47% when the temperature increases with 1°C for silicon-based modules. [12]

2.1.2 Thermal solar collectors

RNC 2050 foresees the implementation of solar thermal technology as a driver for the decarbonization of the buildings, residential and services sectors. [1] By 2018, the market size for solar thermal was of more than 496 GW and will increase up to 768 GW by 2026. [13] The unit costs for this technology vary from 292 USD/m^2 to 4562 USD/m^2. [14]

Whereas the photovoltaic panels directly transform the solar energy in electric energy, the solar collectors transform solar energy in thermal energy/heat. Integrated in buildings, they are used to produce DHW and heating.

The main type of collectors available commercially are the thermosyphon and the forced circulation system, shown in Figure 2.3. The first ones have the water reservoir placed in the top of the panel so that the solar liquid may circulate naturally from the panel to the reservoir when it is heated (once it becomes lighter). On the other hand, the forced circulation systems use a pump to force the circulation of the heated solar liquid in the panel only when its temperature is above the temperature of the water in the reservoir. Both systems are composed by pipes of the solar panel and a heat exchanger in the heat accumulator. [15]

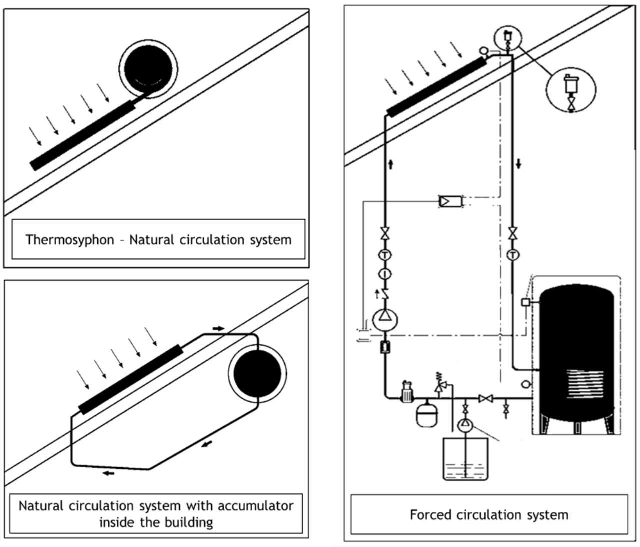


Figure 2.3 - Solar collectors technologies, adapted from [15]

As PV panels, the performance of the solar collectors depends on the solar radiation, the shading conditions and tilt and azimuth angles. Also, its efficiency will depend on the composition of panel used, its materials, if it has insulation or not, among others.

2.2 Energy storage

2.2.1 Energy Storage Systems (ESS)

Energy storage systems (ESS) are capable of storage energy in its different forms and convert into electric energy when needed. According to International Energy Agency (IEA), in the last years there has been a significant increase in the deployment of these systems. In 2018 more than 3 GW of capacity was installed, both for utility-scale and behind-the-meter energy storage, being Korea, followed by China, the United States and Germany the main contributing countries. [16]

They can be classified as mechanical, chemical, electrochemical, electrical and thermal, according to the type of energy they accumulate. The existing technologies are reported in Figure 2.4. [17]

The ESS can bring numerous advantages when connected to the different levels of the electric grid. Both for utility-scale and distributed or “behind-the-meter” (BTM) generation levels, they can help to improve flexibility, resilience and reliability of the power system, optimizing the energy consumption and reducing the use of peak power plants responsible for the increase of costs in electricity bills. Moreover, they mitigate the challenges that solar and wind power integration into the electric grid bring, derived from their variability and uncertainty. [18, 19]

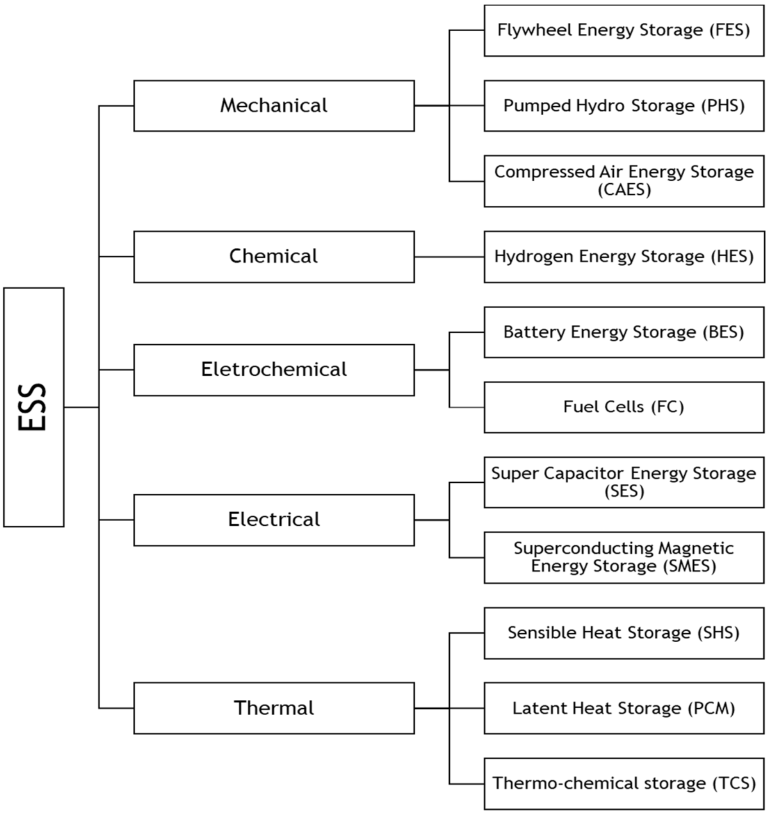


Figure 2.4 - Different types of ESS and technologies. Adapted from [17]

ESSs can have many functions and support different levels of the electricity systems. In the Figure 2.5. we can see potential locations and applications of energy storage in the power system.

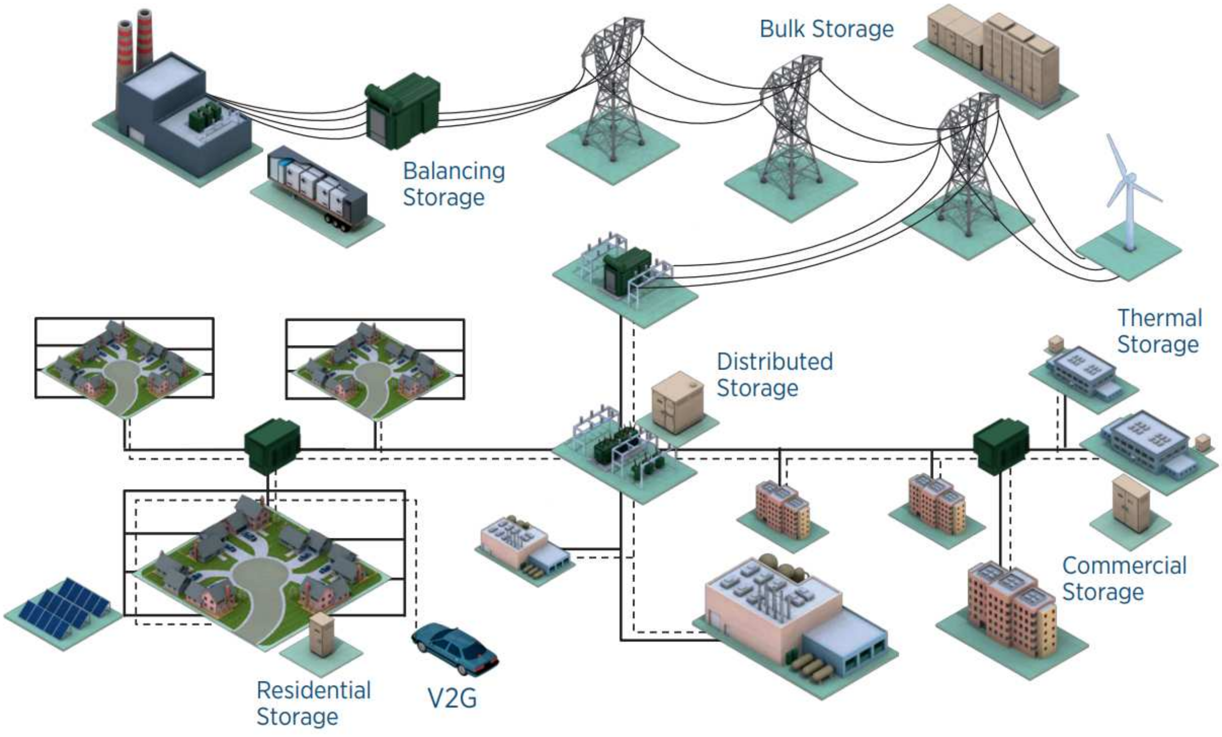


Figure 2.5 - Potential locations and applications of energy storage in the power system. [20, 21]

There are two main functions for the ESSs in the power system: power quality and reliability and energy management. Both are important to assure the power supply and set he seal on a sustainable and resilient power system. Figure 2.6.**Error! Reference source not found.** shows the categorization of the existing technologies by these functions.

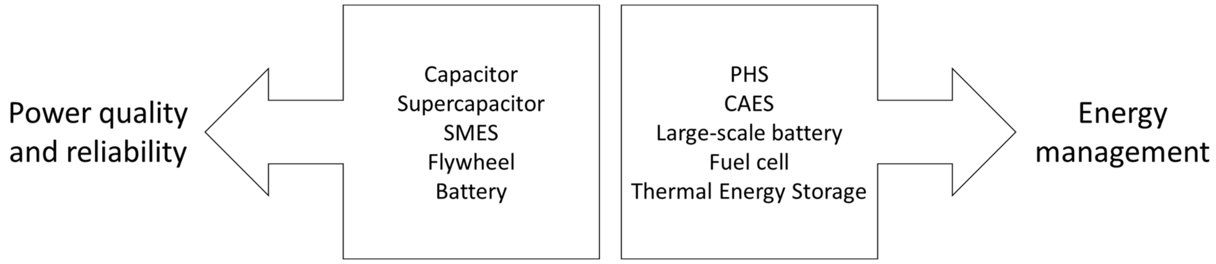


Figure 2.6 - Categorization of energy storage technologies by main functions: power quality and reliability or energy management. Adapted from [22]

The PHS is the dominant ESS implemented worldwide and it was developed to shift the electricity supply from times of low demand to times of high demand to reduce generation costs. It is composed by two big reservoirs separated in altitude, a water pump to store the water in the upper reservoir and a turbine to generate electricity from the potential energy during the water draining to the lower reservoir. It is used in large scale for its large volume (and thus great capacity) and large storage period (from hours to years) with very good efficiency (up to 85%), making it perfect as a provision reserve, for energy management (used at peak load hours) and frequency control. [20,22]

The CAES is other ESS for large scale and works as conventional gas turbine generation using compressed air stored in a cavern. [20,22]

The SMES stores energy in electric form a, has very high efficiency (around 97%), a quick response time and used for short periods of time. This ESS is suitable to voltage stability and power quality. [20,22]

The Flywheel stores energy from the rotational kinetic energy of a wheel that spins at high velocity. Although it has long lifetime, they discharge large amounts of power (high power ratings) in short time (high discharge rates) and thus they are used in high power and short duration applications, such as power support, spinning reserve and frequency/voltage regulation. [20, 22]

Batteries store chemical energy in cells composed basically by two electrodes and an electrolyte. They are suitable for many applications, from portable to large-scale ones. In stationary applications, they are a good fit to energy management once they are efficient, reliable, easy to use, easily scalable, and most of them need low maintenance. Battery energy storage (BES) has a wide range of applications, from large power stations to transportation and power backup systems. It can also play an important role in the integration of renewable sources generation as they easily smooth their intermittent output. [20, 22]

Fuel Cell's working principle and use is very similar to batteries', differing in that it uses external fuels as reactants to obtain products beside electricity and is capable of deliver continuous power as long as it is fed. [20,22]

Thermal energy storage systems use insulated materials to keep them at high or low temperatures, and the thermal energy stored is used for heating, cooling and power generation. [20,22]

IRENA (2017) describes three different sectors in which ESSs are used: grid services, behind the meter applications and off-grid applications. This report focuses on the study of behind-the-meter (BTM) applications and the energy storage technologies requirements and suitability. The BTM storage is mainly used for self-consumption, community storage, increasing power quality, peak saving, and reducing time-of-use tariffs in user's bills. Table 2.1 resumes the suitability of the different technologies to these BTM applications. [20]

IRENA (2017) also predicted and suggested the potential contribution of battery energy storage (BES) technologies for the energy transition, has being key elements for the development and improvement of self-consumption and economic solutions when integrated with photovoltaic (PV) systems. [20]

The storage installations of residential and small commercial buildings for time-of-use management normally require moderate power (installations of 2 kW to 200 kW) and energy throughput (0.5 to 1 cycle per day). These are small applications and so PHS and CAES should not be considered due to their oversize. The most suitable ESSs to be considered, are all types of batteries. Also, the use of hydrogen may be an option although not ready commercially. [20]

The Roadmap for Carbon Neutrality 2050 (RNC2050) accents the role of batteries in the stability and regulation of the power system in the forthcoming years, along with hydroelectric production using pumped water. It states that by 2050 batteries will have an installed capacity of 4 GW and will represent up to 8% of the total installed capacity in a totally renewable system. Also, batteries and pumped hydroelectric all together will represent around 14% of total installed capacity (7,5 GW). [1]

Table 2.1 - Suitability of the different energy storage (ES) technologies for BTM applications. SU- Strongly Unsuitable. U- Unsuitable. S - Suitable. SS - Strongly Suitable. Adapted from [20].

Technologies/ Applications	**Self- consumption (small residential)**	**Community storage**	**Increase power quality**	**Peak- shaving**	**Time- of-use**
PHS	SU	SU	SU	SU	SU
CAES	SU	SU	SU	SU	SU
Flywheel	SU	SU	SS	SS	SU
Flooded LA	SS	SS	SS	SS	SS
VRLA	SS	SS	SS	SS	SS
Li-Ion (NMC)	SS	SS	SS	SS	SS
Li-Ion (NCA)	SS	SS	SS	SS	SS
Li-Ion (LTO)	SS	SS	SS	SS	SS
$NaNiCl_2$	U	SS	SS	SS	SS
NaS	U	SS	SS	SS	SS
VRFB	SS	SS	SU	S	SS
ZBFB	SS	SS	SU	SU	SS

2.2.2 Battery Storage Systems (BSS)

A battery delivers electricity through controlled chemical reactions between substances. They are made of various cells put together, each one composed by an anode, a cathode, a material between them, the separator, and other submerging them, the electrolyte. The anode is the positive terminal or electrode, which is where electric current flows into when the battery is discharging. The cathode is the negative terminal or electrode, and electric current flows out of it when the battery is discharging. The electrolyte serves as a medium between electrodes, since if the anode and cathode came into contact, a short circuit would occur. The voltage delivered by the battery depends on the chemistry of its cells. [20]

- **Lithium-ion batteries**

Lithium ion batteries are available in many different material combinations, each one providing unique performance, cost and safety characteristics. They have in common the migration of lithium ions between the electrodes: these ions are stored in the anode and released during discharge (when electric current is being produced). At the same time, the cathode receives and stores them. The reverse occurs in the process of recharge. A separator is needed in order to allow the flow of ions between the cathode and the anode but to prohibit the flow of electrons inside the battery cell. Also, positive and negative collectors are part of the structure of the batteries, receiving electrons from the external circuit. The anode is normally made of graphite, while cathodes can be made of lithium cobalt oxide, lithium iron phosphate or lithium manganese oxide, and other lithium-based substances. The electrolyte is typically a solution of lithium salt in an organic solvent. [20]

- **Lead-acid (Lead-A) batteries**

In a Lead-acid battery, typically the anode is made of lead and the cathode of lead dioxide. The electrolyte is a solution of sulfuric acid. There is also the need for a separator between the electrodes. During the process of discharge, the two electrodes form lead sulphate and during recharge the reverse chemical reaction occurs, and they get partially back to its original form. [20]

There are two main designs of Lead-A batteries, the Flooded Lead-Acid (FLA) and Valve Regulated Lead-Acid (VRLA) batteries, also known as sealed batteries. The main difference between them is in the electrolyte: in the first ones the solution of sulfuric acid is moving free inside the battery between the two electrodes; while the sealed do not contain a liquid that can leak .There are two types of VRLA batteries: Gel and AGM (Absorbed Glass Mat). In Gel batteries the electrolyte is a jelly substance, while AGM batteries contain special acid-saturated fiberglass mat between the electrodes that absorbs the free electrolyte acting like a sponge. [20]

- **High-temperature batteries**

In a High-temperature battery, the anode and cathode are liquid active materials: the anode is made of molten sodium and the cathode is made of an incorporated secondary liquid electrolyte in a solid transition metal halide. A solid ceramic electrolyte made of beta aluminium separates the two electrodes serving as an ion conducting membrane. This membrane transports sodium-ions between the anode and the cathode, making possible to store and release energy in the charge and discharge processes. They are high temperature batteries because they need that conditions to ensure that the active materials are in the liquid state and thus enough conductivity of the electrolyte. [20]

The two most relevant high temperature batteries are the Sodium sulphur (NaS) and Sodium nickel chloride technologies. [20]

- **Flow batteries**

Flow batteries differ from conventional batteries in that they store energy in the liquid electrolytes in two tanks separated. These liquid electrolytes are pumped through the battery stack, where the reaction takes place and go back to the same tank. Anolyte is pumped through the anode side of the battery stack, and the catholyte is pumped through the cathode side. The anodes and the cathodes are separated by an ion exchange membrane, which ensures that only H^+ ions can cross it. [20]

Exist many different flow battery technologies, being the Vanadium Redox Flow Battery (VRFB) the most mature one. [20]

These batteries use vanadium salts in different oxidation states ($V2^+/V3^+$ and $V5^+/V4^+$ redox couples) solved in a sulphuric acid solution to exchange ions through the membrane and electrons through the external circuit. The reactions reverse during the charge and discharge processes. [20]

By incorporating vanadium in both electrolytes, unlike other flow battery types, “all vanadium” redox flow battery has no deterioration through cross contamination. No loss in power or capacity takes place due to side reactions as observed in conventional batteries. This ensures lifetimes superior to any other electrochemical storage. Also, the chemicals used guarantee low hazard potential and best possible ecological properties. Because liquid electrolytes are stored in tanks separated from the battery stack, this battery can be scaled independently for appropriated power and energy: power can be adjusted through cell size and number; and energy through the volume of the tanks, the bigger they are the more energy they can store.

All these benefits make this technology an interesting fit for stationary applications. [20]

On the other hand, these systems are expensive because they need sensors, pumping and flow management mechanisms and high-cost materials such as the membrane and the electrolytes. [20]

- **Technologies comparison**

Some intrinsic properties of the different batteries are shown in the Table 2.2 and determine their performance and suitability to applications. Table 2.3 sets the capital expenditures for the different batteries.

Table 2.2 - Properties of the different types of batteries.

Characteristics/ Technology	**Lead-Acid**	**Li-Ion**	**Sodium Nickel Chloride**	**Sodium Sulphur**	**Flow Batteries**
Power Range	some MW [23] 1kW-100 MW [25]	1 kW to 50 MW [23] 50 kW-100 MW [25]	several MW [23]	201 kW-50 MW [23] 10-100 MW [25]	several kW to some MW [23] 0,1-100 MW [25]
Energy range	> 10 MWh [23]	>10 MWh [23]	4kWh-several MWh [23]	1.2 MWh-400 MWh [23]	100 kWh- some MWh [23]
Discharge time	min > 20h [23] 1 min-8h [25]	10 min - 4h [23] 1 min-8h [25]	> 2h [23]	6h at nominal power [23] 1 min – 8 h [25]	some h [23,25]
Response time	some millisec [23,25]	some millisec [23,25]	some millisec [23,25]	some millisec [23,25]	some millisec [23,25]
Cycle life (cycles)	500-3000 [23] 250-2500 [20]	2000-10000 [23] 500-2000 [20] 1000-10000 [25]	4500 [23] 1000-7500 [20]	> 4500 [23] <5000 [20] 2500-4500 [25]	>12000 [23] >10000 [20] 12000-14000 [25]
Life duration	5-15 years [23] 3-15 years [20]	15-20 years [23] 5-20 years [20]	<15 years [23] <20 years [20]	15-20 years [23] <25 years [20]	10-20 years [23] 5-20 years [20]
Efficiency (%)	75-85 [20,24] 80-85 [20] 80-90 [25]	90-98[23] 92-96 [20] 90-95 [24] 85-95 [25]	85-95 [23] 84 [20] 75-85 [24]	70-80 [23] 80 [20] 75-85 [24] 70-90 [25]	70-75 [23] 60-85 [23,25] 70-80 [24]
Energy density	25-35 Wh/kg [23] 50- 100 Wh/L [20] 50-80 Wh/L [25]	120-180 Wh/kg [23] 200 -735 Wh/L [20] 200-400 Wh/L [25]	100-120 Wh/kg [23] 160-280 Wh/L [20]	206 Wh/kg [23] 140-300 Wh/L [20] 150-300 Wh/L [25]	10-25 Wh/L [23] 15-70 Wh/L [20] 20-70 Wh/L [25]

Table 2.3 - Cost expenditure(CAPEX) for the different types of batteries.

Technology/ Costs	**CAPEX energy**	**CAPEX power**
Lead-Acid	100-200 EUR/kWh [23] 105-475 USD/kWh [20]	100-500 EUR/kW [23]
Li-Ion	700-1300 EUR/kWh [23] 200-840 USD/kWh [20]	150-1000 EUR/kW [23]
Sodium Nickel Chloride	550-750 EUR/kWh [23] 315-490 USD/kWh [20]	150-1000 EUR/kW [23]
Sodium Sulphur	300-450 EUR/kWh [23] 263-735USD/kWh [20]	300-3000 EUR/kW [23]
Flow Batteries	100-400 EUR/kWh [23] 315-1680 USD/kWh [20]	500-1300 EUR/kW [23]

2.3 Residential Buildings Sector

The pandemic crisis brought us new perspectives: working from home became a reality. It showed us the impacts human daily activity has on environment, the importance of accelerating digitalization and the need to create new markets and business to overcome the economic collapse.

The electricity sector is changing fast and a Grid Edge is now discussed: “where an intelligent grid meets smart buildings”. With the increasing distributed energy resources, costumers are also producers and distributers, called “prosumers”, making it necessary to rethink how the grid works. [26]

“The Grid Edge comprises technologies, solutions and business models advancing the transition towards a decentralized, distributed and transactive electric grid.” [27]

This gives not only the technological change that is needed from a climate perspective but also business opportunities and economic growth.

Driven by decarbonization, an “all-electric future” is expected, once electricity is the most efficient form to transport and transform energy into other forms: into movement, heating, cooling. [26] Electric Vehicles (EV) are a good example: the European Union established that from 2030 on, at least 37,5% of vehicles must be zero or low emission (ZLEV), making mobility more connected to the grid sector. [28]

This predictable “all electric future” will have a huge impact on the demand side of the grid, not only in terms of the amount of the electricity needed, but also the fluctuations on the demand curve. [26] Actually, when you add an EV charger to a household, its electricity consumption will obviously increase and almost 50% will be consumed by the EV, changing drastically the load profile. [29]

On top of that, the power generation using mainly renewables creates an unpredictable and unreliable generation profile. New assets at the edge of the grid will be needed to stabilize it, such as battery storage systems. As well, the study of both demand and generation profiles is urgent. This will be possible by building a smart grid, with the help of digital assets, capable of control and monitor the system using and collecting data. [29]

Residential consumers will play a big role in this transition. In SolarEdge Virtual Solar Show, a Smart Energy Home was described. It is a smart home with an energy manager capable of maximizing the solar usage using a PV source, increase the energy independence from the grid using battery storage, maximize the energy efficiency and lower electricity bills. It controls and monitors the energy heavy loads such as the water heaters, heat pumps, HVAC systems and EV chargers. [29]

2.3.1 Integration of energy storage in PV systems

In fact, PV systems for residential buildings, although more efficient and cost-effective than ever, they have the particularity of producing more when the power is not being used.

Studies have been made for decades on how to suppress the problem above mentioned integrating in the PV systems other power resources such as fuel cells [30, 31], batteries [32, 33, 34], and SMES. [10].

Focusing on battery storage, it can buffer the production of electricity along the day, so that it can be available when needed.

Ampere Energy presented an interesting solution for what was mentioned above: an intelligent energy management system built with PV and Battery Storage systems capable to adapt not only to the costumer load profile, but also predicting the weather forecast and electricity tariffs by only being connected to the internet. [36]

For example, it is possible to predict if the costumer will need more energy than what is produced the next day, and so it charges the battery at the time when the electricity is cheaper to buy from the grid, normally at night.

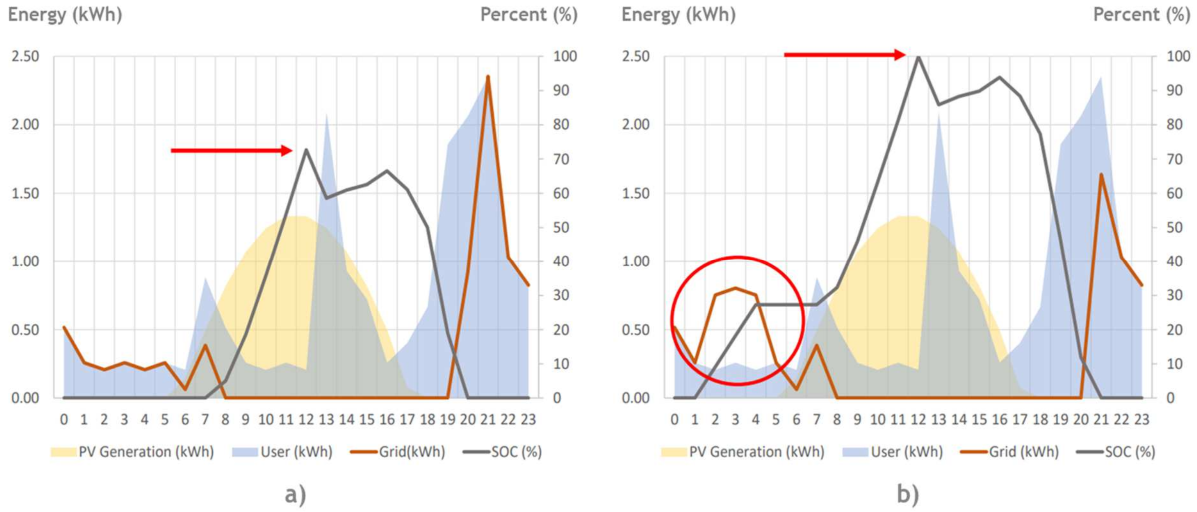


Figure 2.7 - *Ampere's energy management system operating mode. a) without "intelligent" electricity storage. b) with "intelligent" electricity storage (battery charge at night). Adapted from* [36]

The image above illustrates the difference between a system that only charged the battery with electricity produced by PVs (Figure 2.7.a) and other at right, which complemented the electricity produced from the PVs with charging the battery at night (Figure 2.7.b). The second one predicted that the energy given by the solar PVs was not enough to charge the battery at its full potential, so it charged a percentage at night when tariffs are low, and the rest by the PVs production. At the load peak, the need of buying electricity from the grid is lower and costs will be reduced. [36]

Denmark's first net-zero energy building was accomplished, using a 40 kWh VisBlue Battery System Solution. This solution for this building with 10 apartments covering an area of approximately 1200 square metres, not only manage to hit the actual zero in terms of energy by efficiently handling the energy production with PV, storage and consumption, but also to save residents around 10.000 DKK (around 1350 EUR) each year. [37]

These systems described above concern the electricity demand, and other assets must be implemented to meet the heat and cooling loads for the thermal comfort in the households.

For example, LG developed an energy storage system using batteries coupled to PV panels where you can add a heat pump to store domestic hot water (DHW) in the tank using the excess electricity from the ESS, and it states that it is four times more efficient than a conventional hot water heating system. [38]

Other system concerning not only the electrical needs but also the thermal needs is the Solenco PowerBox^{TM} described in Figure 2.8. This product uses a reversible fuel cell to produce hydrogen, H_2, (splitting water) that is stored in tanks. This stored H_2 is used to produce electricity (with the reverse chemical reaction in the fuel cell) and heat when needed. A combination of this product and the hydrogen-powered catalytic boiler "H₂ydroGEM" by Giacomini® was presented in a seminary this year (2020).[39]

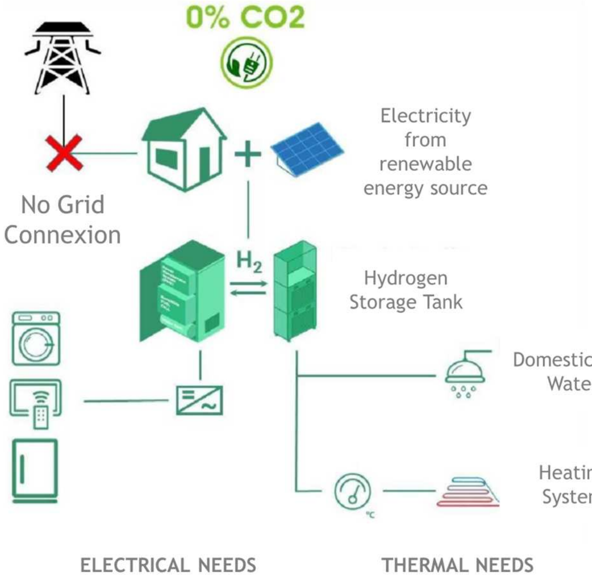


Figure 2.8 - Solenco PowerBox^{TM} system. Adapted from *[40]*

3 Proposed Methodology

This project started from the energetic analysis of a mid-rise residential building previously modelled by A400 team, for further integration of a photovoltaic system with battery energy storage in order to satisfy a percentage of the electricity consumption, also including a collector panels system to supply domestic hot water (DHW) needs. For that, it was used a software able to simulate the thermal loads and electricity consumption of the building as well as integrating the collector panels system, the Integrated Environmental Solutions Virtual Environment (IESve®); it was also used the Photovoltaic Geographical Information System (PVGIS®), which is able to predict the PV power output of a given PV panels system for different locations (in this case varying from Porto to Lisbon and Faro). Furthermore, it was developed a system of equations and restrictions in Excel® to manage the integration of battery energy storage coupled to the PV power system and its economic viability.

3.1 IESve® Software

IESve is a software with integrated analysis tools for the design and retrofit of buildings. It helps creating sustainable buildings that consume significantly less energy. The main applications used were “ModelIT” to define the building geometry, “ApacheHVAC” to design the heating and cooling systems, “Suncast” to perform solar shading analysis and “Apachesim” to perform thermal simulation. “VistaPro” was used to view and export the results from the thermal simulation.

After modelling the building geometry, some important steps and inputs were established according to the design assumptions of the A400 team and legislation, intending to calculate its energy loads:

- Set location (latitude, longitude, altitude, weather files) and orientation of the building (degrees from north);
- Create and assign opaque and glazed constructions (external walls, ceilings, windows: materials, thickness and heat transfer coefficient);
- Create room templates with:
    - Airflow and air infiltration rates and profiles;
    - The internal gains (illumination, equipment and occupation rates and their daily and weekly use profiles);
    - Climatization (comfort temperature setpoints, Domestic Hot Water consumption rates and profiles);
- Create and assign the Heating, Ventilating and Air Conditioning (HVAC), Domestic Hot Water (DHW) and solar collectors’ systems.

After performing these steps, “SunCast” simulation must be done: this application calculates the position of the sun in the sky for any hour of any day throughout the year, the shadows, solar penetration throughout the building interior and gains from sunlight. These solar shading calculations are used to see the impact of solar gains.

The final step is to run the ASHRAE heat balance loads calculations found in the “ApacheSim” application. These calculations are based on the ASHRAE Heat Balance Method to obtain room heating and cooling requirements and the sizing of heating and cooling equipment.

3.1.1 ASHRAE Heat Balance Method

The Heat Balance (HB) method calculates heat balance for each room surface (conductive, convective and radiative) and for the room air (convective), where no arbitrary parameters are set, being this an advantage. In this method, four different processes are described: the outdoor-face HB, wall conduction process, indoor-face HB and air HB.

- **Outdoor-Face Heat Balance**

$$q''_{\alpha sol} + q''_{LWR} + q''_{conv} - q''_{k0} = 0 \qquad (3.1)$$

Where:

- $q''_{\mathrm{\alpha sol}}$ - absorbed direct and diffuse solar radiation flux (q/A) / W·m^{-2}
- q''_{LWR} - net long-wave radiation flux exchange with air and surroundings / W·m^{-2}
- q''_{conv} - convective exchange flux with outdoor air / W·m^{-2}
- q''_{k0} - conductive flux (q/A) into wall / W·m^{-2}

- **Wall Conduction Process**

This process was framed differently and with more complexity than the others, using techniques such as numerical finite difference, numerical finite element, transform methods and time series methods.

On both sides of the element (indoor and outdoor faces) temperature and heat fluxes are considered and so the solution must deal with this simultaneous condition.

- **Indoor-Face Heat Balance**

$$q''_{LWX} + q''_{SW} + q''_{LWS} - q''_{ki} + q''_{sol} + q''_{conv} = 0 \qquad (3.2)$$

Where:

- q''_{LWX} - net long-wave radiant flux exchange between zone surfaces / W·m^{-2}
- q''_{SW} - net short-wave radiation flux to surface from lights / W·m^{-2}
- q''_{LWS}- long-wave radiation flux from equipment in zone / W·m^{-2}
- q''_{ki}- conductive flux through wall / W·m^{-2}
- q''_{sol} - transmitted solar radiative flux absorbed at surface / W·m^{-2}

- $q"_{conv}$ - convective heat flux to zone air / W·m^{-2}

- **Air Heat Balance**

$$q"_{conv} + q"_{CE} + q"_{IV} + q"_{sys} = 0 \quad (3.3)$$

Where:

- $q"_{\mathrm{conv}}$ - convective heat transfer from surfaces / W
- $q"_{\mathrm{CE}}$ - convective parts of internal loads / W
- $q"_{\mathrm{IV}}$ - sensible load caused by infiltration and ventilation air / W
- $q"_{\mathrm{sys}}$ - heat transfer to/from HVAC system / W

3.1.2 Integration of HVAC, DHW and Solar Collectors systems

There are two key parameters that are set in “Apache Systems” used for sizing central plant systems that supply the heating, ventilation and air conditioning of the spaces required:

- Coefficient of Performance (COP) – the efficiency of the heating system
- Energy Efficiency Ratio (SEER) – the efficiency of the cooling system

Also, in this model, other renewable technologies systems can be implemented. In this project a solar thermal water heating system feeding into the DHW system was use. The Flat plate collector system was assumed, and it consists of a solar panel using propylene glycol as the heat transfer medium, linked to a heat exchanger that transfers the collected solar heat to a storage cylinder.

The parameters set for the solar panel were its area, the azimuth angle, tilt angle, shading factor, degradation factor, conversion efficiency at ambient temperature (η_0), first order heat loss coefficient (a_1), second order heat loss coefficient (a_2), flow rate (through the solar panel), the pump power, heat exchanger effectiveness and storage tank’s volume and losses.

The performance of the solar panel is given by Equation (3.4):

$$W = \eta_0 \cdot I - a_1(T - T_a) - a_2(T - T_a)^2 = 0 \quad (3.4)$$

Where

- W - heat output per unit panel area / W·m^{-2}
- I - incident solar irradiance (after allowing for shading and degradation) / W·m^{-2}
- T - panel temperature / K
- T_{a} - outside air temperature / K

Values for η_0 , a_1 and a_2 are available from solar panel manufacturers.

3.2 Integration of PV production and Battery Storage

The analysis of the integration of PV production with energy storage was carried out using restrictions and conditions in Excel to perform 3 different systems displayed in Figure 3.1.

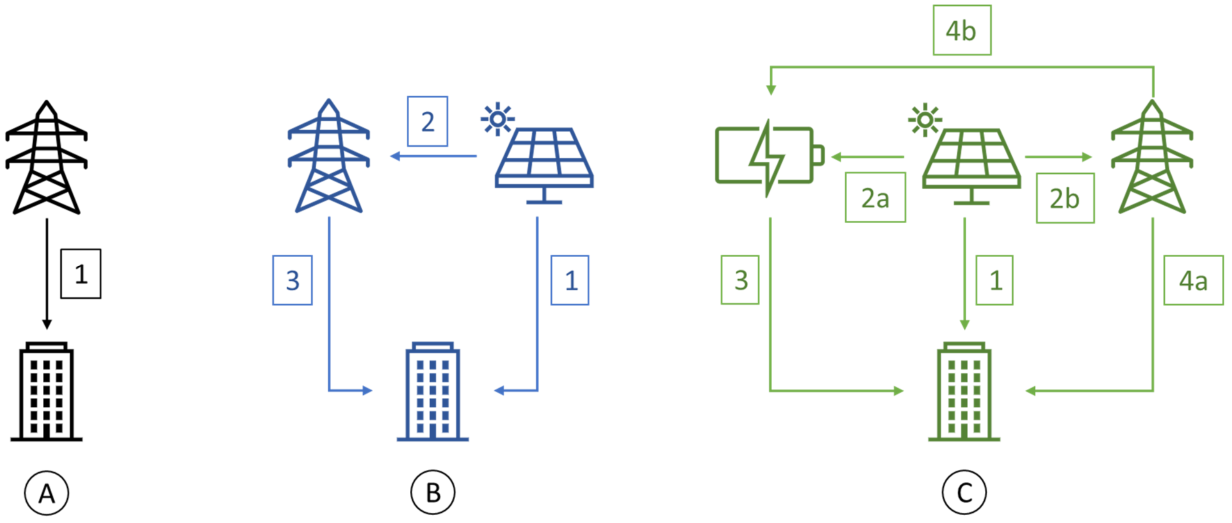


Figure 3.1. - Diagrams for the three systems analysed. A -Grid to building, B- feed-in tariff PV system, C- PV and battery system.

- In system **A** all the power consumption of the building is satisfied by the grid (1).
- In system **B**, there is PV power production, which is firstly consumed (1) and in case there is any exceeding it is injected to the grid (2). When there is no sun exposure and thus, no PV power production, then the consumption is supplied by the grid (3).
- System **C** is a more complex version of system B once it integrates battery energy storage into the PV system.

Some restrictions for system C were implemented for the better functioning of the simulation performed in Excel:

When there is PV power production:

- All the electricity produced is firstly consumed (1);
- The surplus charges the battery until its Battery State of Charge (%BSC) reaches at least 80% (2a) and then injects to the grid (2b).

Battery discharges:

- By day, when %BSC is greater than 30% (3), if not nothing happens.
- By night, when %BSC is greater than 30% (3), if not, it is charged (4b).

Battery is charged:

- By day, when there is surplus of PV production and the battery %BSC is lower than 80% (2a);

- By night, when %BSC is in between 30% and 80% (4b).

Grid supplies:

- To charge the battery (4b) and supply the electricity consumption (4a);
- To supply the consumption that neither the battery nor PV systems are able to (4a).

By day means between 7:30 a.m. and 11:30 p.m. and by night between 00:30 a.m. and 6:30 a.m.

The main purpose of this type of PV plus battery storage system (C) is to buffer the production of electricity along the day, so that it can be available when needed and when electricity tariffs are higher. The tariffs applied in the Portuguese electricity market are higher when compared to the cost of producing electricity from a PV system (LCOE) and the cost of store it in batteries (LCOS). This means that implementing this system, annual savings are generated.

The scenario for the total independence of the grid was not studied once an oversized and overloaded system would be obtained. With this in mind, the systems were design to supply a percentage of the electricity consumption of the building.

To perform this simulation in Excel, not only the electricity consumption profile of the building is needed but also the photovoltaic system power production.

Photovoltaic Geographical Information System (PVGIS) [41] is a software that calculates the photovoltaic power output of PV grid-connected systems using data from geostationary meteorological satellites. The inputs to perform this simulation are the location (longitude, latitude), the PV technology (types of modules being crystalline silicon cells, copper-indium-selenium (CIS) or cadmium-telluride (CdTe) thin film cells), the installed peak power, the system losses (including losses in cables, power inverters, dirt on the modules) and the mounting position (if it is free-standing or building-integrated). It optimizes the values of the slope (angle of the PV modules from the horizontal plane) and the azimuth (angle of the PV modules relative to southward) for a given location.

The installed peak power was calculated for different situations in each location: for the available area of the roof-top of the building, for a typical summer day, for a typical winter day and for the maximum consumption day of the year.

With the aim of calculating the Installed Peak Power, P_i, given in kWp, two approaches were taken:

- For the known available area of the roof-top of the building:

$$P_i = P_p \times n_p \tag{3.5}$$

Where:

- P_p - panel peak power (given by the manufacturer) / kWp
- n_p - number of panels in the available area

- For the typical summer day, a typical winter day and the maximum consumption day of the year:

$$P_i = \frac{E_l}{h_{sp} \cdot \eta_\mathrm{s}} \tag{3.6}$$

Where:

- E_l- energy loads / kWh
- h_sp - sun peak hours / h
- η_s - system efficiency

The number of panels, n_p, to use in this situation can be calculated:

$$n_\mathrm{p} = \frac{P_i}{P_p} \tag{3.7}$$

Where:

- P_i- installed peak power / kWp
- P_p - panel peak power (given by the manufacturer) / kWp

3.3 Economic Evaluation

The economic evaluation for the systems designed and their comparison was carried out calculating the payback time (Equation 3.8). This is a key indicator used to compare the feasibility of an investment that calculates the number of years needed to recover the cost of the investment done:

$$Payback\ time = \frac{Investment\ cost}{Annual\ Savings} \tag{3.8}$$

The $Investment\ cost$ (EUR) is the sum of the installation costs of all the equipment used in the system (photovoltaic panels and batteries).

The $Annual\ Savings$ (EUR) are the difference between the operational costs of the system A and C.

To determine operational costs, the indicators Levelized Cost of Energy (LCOE) for PV and Levelized Cost of Storage (LCOS) for battery storage were used.

- Levelized Cost of Energy (LCOE), in EUR/kW:

$$LCOE = \frac{\sum_{t=1}^{lifetime} Investment\ Cost_t + O\&M\ Costs_t) \cdot (1+r)^{-t}}{\sum_{t=1}^{lifetime} Energy\ generated_t \cdot (1+r)^{-t}} \tag{3.9}$$

Where the $Investment\ Cost$ is the installation cost for monocrystalline PV panels, in EUR, the $O\&M\ Costs$ are the operations and maintenance costs of the system, in EUR, and $Energy\ generated$ is the energy produced by the system, in kWh. The discount rate for year t is represented by $(1+r)^{-t}$.

- Levelized Cost of Storage (LCOS), in EUR/kWh:

$$LCOS = \frac{\sum_{t=1}^{lifetime} Investment\ Cost_t + O\&M\ Costs_t + Fuel\ expeditures_t) \cdot (1+r)^{-t}}{\sum_{t=1}^{lifetime} Energy\ discharged_t \cdot (1+r)^{-t}} \tag{3.10}$$

Where the $Investment\ Cost$ is the installation cost for Li-Ion batteries, in EUR, the $O\&M\ Costs$ are the operations and maintenance costs of the system, in EUR, $Fuel\ expeditures$ are the costs of producing the stored energy from a photovoltaic system, in EUR, and $Energy\ discharged$ is the energy discharged by the system, in kWh. The discount rate for year t is represented by $(1+r)^{-t}$.

Both the LCOE and LCOS indicators were used to calculate the cost of producing and using electricity from the PV system and the battery stack, taken from Lazard (2018) [42, 43]. The costs of purchasing electricity from the grid were taken from a commercial electricity bill from early 2020, for a tri-hourly tariff. [44] These tariffs are presented in Table 8.1 and Table 8.2 in the Annex A. The price for selling electricity (inject to the grid) was taken from the values of the market. [45]

Photovoltaic panels and battery costs were given by a contacted manufacturer to predict a more accurate and real initial investment cost for the system.

Besides that, a forecast of the values for installation costs, LCOE and LCOS was made in order to evaluate the investment for this system in the near future (5 years). According to Lazard [42], the installation costs of Li-Ion batteries will decrease 28% in the next five years. With that, the LCOS for this battery type can be predicted, taking into account that the installation costs count for about 60% of this indicator. The same logic was used for the monocrystalline PV panels: Lazard [42] shows how in the last five years this technology had a decrease of 13% in its LCOE per year and so, a conservative value for 10% of decrease per year of this value was considered.

4 Case Study

4.1 Building design

The study was performed in a mid-rise residential building divided in two blocks, with 4 underground floors (for parking lots) and other 8 levels dedicated studios and T1, T2, T3 and T4 apartments. Other spaces such as condominium rooms, storage areas and waste disposal rooms are considered. In Figure 4.1 we can see the building oriented towards North.

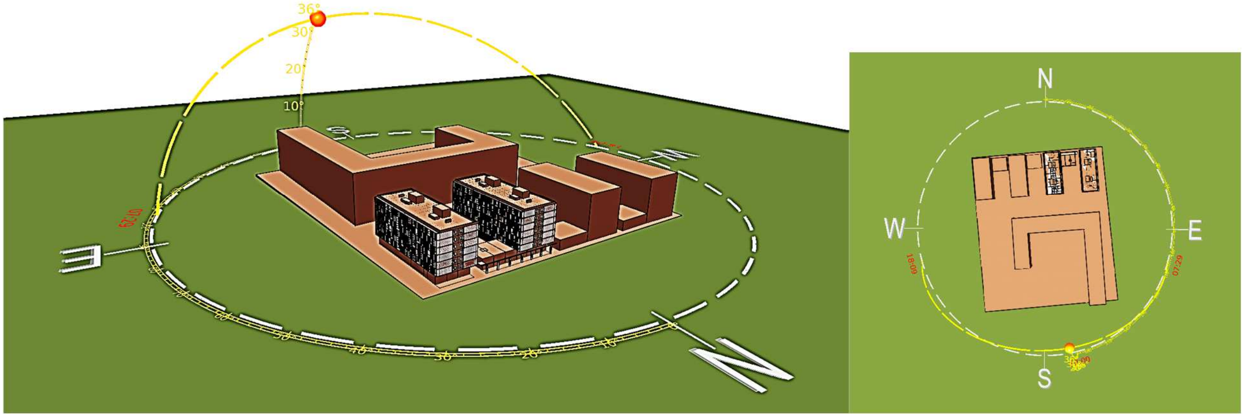


Figure 4.1 - Building under study and its orientation.

This building was placed in three different cities of Portugal: Porto, Lisbon and Faro. In Table 4.1. the latitude, longitude and elevation for these three locations are presented.

Table 4.1 - Locations studied and their coordinates.

Porto	Lisbon	Faro
Latitude (°): 41.25	Latitude (°): 38.72	Latitude (°):37.01
Longitude (°): - 8.68	Longitude (°): - 9.15	Longitude (°): - 7.97
Elevation (m): 19.0	Elevation (m): 19.0	Elevation (m):19.0

The Portuguese Building Certification System (Decree-law 118/2013 of 20 August) is incorporated in LNEG Climas–SCE software from which the location and weather files were extracted.

4.2 Building operation schedules, heat gains and ventilation

The installed power density (for illumination and equipment) as well as occupant density were assumed for the different room templates and are presented in Table 4.2.

Table 4.2 - Installed power density for illumination and equipment and occupant density for the different room templates

	People	**Illumination**	**Equipment**	
Room template	Occupant density	Power consumption (W/m2)	Power consumption	
			(W/m2)	(W)
Kitchen	2	3.5	25	
Kitchen/Living Room	4	3.5	10	
Living room T1	4	3.5		250
Living room T3	8	3.5		
Living room T4	8	3.5		250
Studio	4	3.5		250
Bedrooms	2	3.5		300
WC	-	2		200
Parking Lot	-	2.55		300

The daily schedules profiles for each room template for weekdays and weekends were also assumed to be closer to reality possible and can be consulted in the Appendix A.

4.3 Thermal envelope

The thermal envelope (external walls, ceilings and windows) defines the heat exchanges between the building interior and its surroundings. It depends on the constructions settled: the materials used, their thickness and their thermal characteristics. Each construction will have a resultant heat transfer coefficient.

The constructions assumed are presented in Table 4.3.

Table 4.3 - External walls, ceilings and windows constructions assumed.

	Materials used	**Thickness (m)**	**Heat transfer coefficient (W·m^{-2}·K)**
External walls	Expanded polystyrene Reinforced concrete	0.300	0.397
Ceilings	Plaster Common brick Expanded polystyrene Cavity Cement ponded particle board	0.440	0.430
Windows	Clear float Cavity Clear float	0.032	1.781

The heat transfer coefficients were stablished according to the design assumptions of the A400 team and the limits on the authority of the Portuguese legislation.

4.4 Heating, Cooling and DHW systems

The houses have installed individual reversible air-to-water heat pump systems, which produce hot water for heating and cold water for cooling. The values assumed for the heating COP and cooling SEER of these pump systems were 4.21 and 3.57, respectively.

For the habitations' ventilation, a collective bidirectional system (with extraction and insufflation of new air) was used, composed of an air treatment unit with a direct expansion battery that connects to a distribution air duct network.

To produce Domestic Hot Water (DHW) a collective solar thermal system of panels placed on the roof of each one of the lots was contemplated, serving the reversible heat pumps as a support system in the production of DHW. The values assumed for the heating COP these pump systems were 3.25. The total area of solar thermal panels 172 m^2 and the accumulated volume of heated water 12 440 L. The solar panels were oriented towards South (azimuth of 0º) and tilted 33º.

4.5 Photovoltaic and Battery systems

The photovoltaic system was designed using a module from a catalogue, which characteristics and price are presented in the Table 4.4. This PV module has a 15-year product warranty and 25 years of linear production warranty.

Table 4.4 - Photovoltaic module characterisation and price.

Module type	Nominal Power (Wp)	Dimensions (m (h×w×d))	Module efficiency (%)	Temperature range (ºC)	Unitary price (EUR)
Monocrystalline silicon	300	1.640×0.992 ×0.040	18.52	-45 to +85	148

In PVGIS, as stated before, the optimal azimuth and tilt angles are estimated for the different locations. The sun peak hours are also different for the three considered locations. This data is shown in Table 4.5. The system losses for the photovoltaic system were assumed to be 14% according to PVGIS methods.

Table 4.5 - Values for optimized azimuth and tilt angles and sun hours for the different locations studied.

	Tilt Angle (°)	Azimuth Angle (°)	Peak Sun hours (h)
Porto	36	6	4.8
Lisbon	33	4	5.2
Faro	33	3	5.9

Also, the battery system was sized using a battery from a catalogue, which characteristics and price are presented in Table 4.6.

Table 4.6 - Battery characterization and price.

Battery type	Nominal Capacity (kWh)	Nominal Voltage (V)	Depth of discharge (%)	Dimensions (m (h×w×d))	Efficiency (%)	Temperature range (°C)	Unitary price (EUR)
Lithium -Ion	2.4	48	90	0.100×0.442× 0.500	96	0-50	1400

To establish the economic performance for the different systems studied, the different price values for PV panels and lithium-ion batteries were settled and are presented in Table 4.7. Also, the feed-in tariff is an important value to take into account [45].

Table 4.7 - Price values considered for the economic performance study.

LCOE PV (EUR/kWh)	0.038
LCOS battery (EUR/kWh)	0.091
PV price (EUR/ 300 Wp)	148
Battery price (EUR / 2,4 kWh)	1400
Feed-in tariff (EUR /kWh)	0.05

An estimate of these prices was made for after 5 years according to Lazard's [42,43] predictions for prices and levelized costs. These values are presented in Table 4.8.

Table 4.8 - Outlook outcome prices within 5 years

LCOE PV (EUR/kWh)	0.022
LCOS battery (EUR/kWh)	0.076
PV price (EUR/ 300 Wp)	87
Battery price (EUR/ 2,4 kWh)	1008

5 Results and Discussion

5.1 Electricity consumption of the building

Table 5.1 sets the annual electricity consumption for the three locations considered in Portugal. It shows that electricity consumption of the building will depend on its location and it is higher in Faro, followed by Lisbon and Porto.

Table 5.1 - Annual electricity consumption for the three different locations.

	Annual Electricity consumption (MWh)
Porto	700
Lisbon	720
Faro	766

Figure 5.1 presents the distribution of electricity consumption from equipment (such as TV, fridge, computer and others), illumination, heating and cooling, DHW needs, fans and pumps. In the three locations studied this distribution is similar.

Figure 5.1 - Distribution of electric consumption in the building.

More than 50% of electricity is consumed by equipment followed by the cooling of spaces. This means that having efficient equipment is very important when reducing electricity consumption and bills. The heating of spaces is not significant on the electricity loads of the building.

The reason for that the consumption in Faro and Lisbon is superior compared to Porto stands for a greater need to cool the spaces, once the exterior temperatures are higher on those locations on most days of the year.

To explain the insignificant space heating needs, an additional simulation was performed in which the internal gains were not considered. The heat loads resulted much higher compared to the situation when the internal gains were not despised. The value obtained for the heating loads is smaller than the value of internal gains. This means that the internal gains are enough to overcome the heat losses and to set at least the minimum comfort temperature in the rooms of the building (20ºC). Other factors contribute for the low heating needs inside the building: it has a great window/wall ratio (and thus, high solar gains) and the constructions of a new building like the one studied has a good insulation level. Nevertheless, we should take into consideration that this simulation is only close to reality, and real values would depend on occupants' habits. For example, in winter a temperature of 20 ºC in the room is not always comfortable and we want to raise it, increasing the heating needs. On the other hand, in the summer a few more Celsius degrees than 24 ºC for the room temperature are supportable, decreasing the cooling needs.

Throughout the year, the electric consumption presented in Figure 5.2 varies in the same pattern for the three different locations: in the Summer it is higher than in the Winter. It confirms the reason for that the consumption in Faro and Lisbon are superior compared to Porto: the cooling needs have more impact in the consumption of electricity than the other needs.

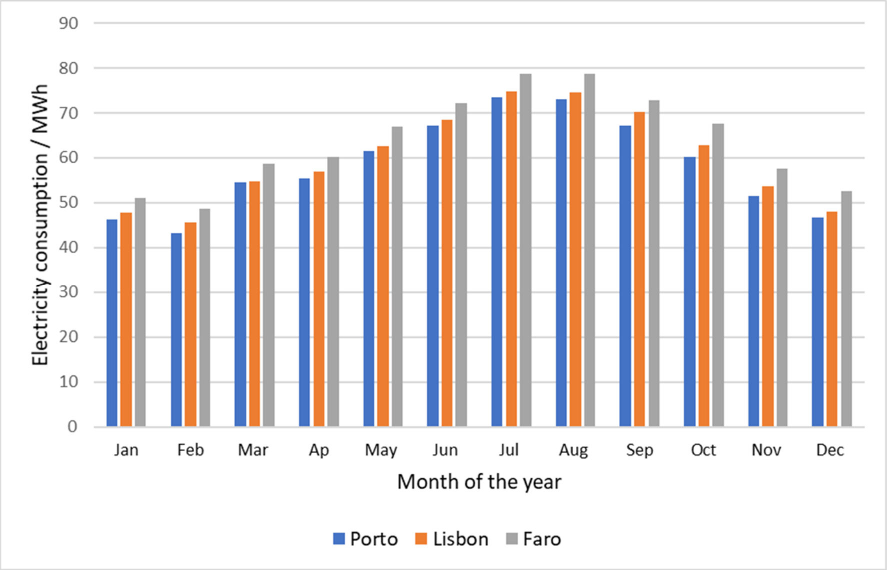


Figure 5.2 - Electricity consumption of the building in the different locations by month.

The daily electric consumption profiles for a typical summer and a typical winter weekday in the different locations can be seen in Figure 5.3 and Figure 5.4, respectively.

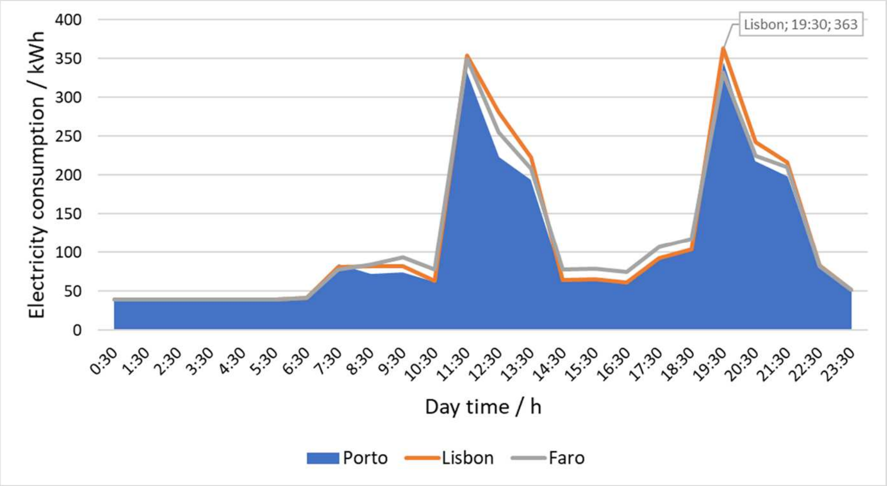


Figure 5.3 - Electricity daily consumption profile for a typical summer day in Porto, Lisbon and Faro.

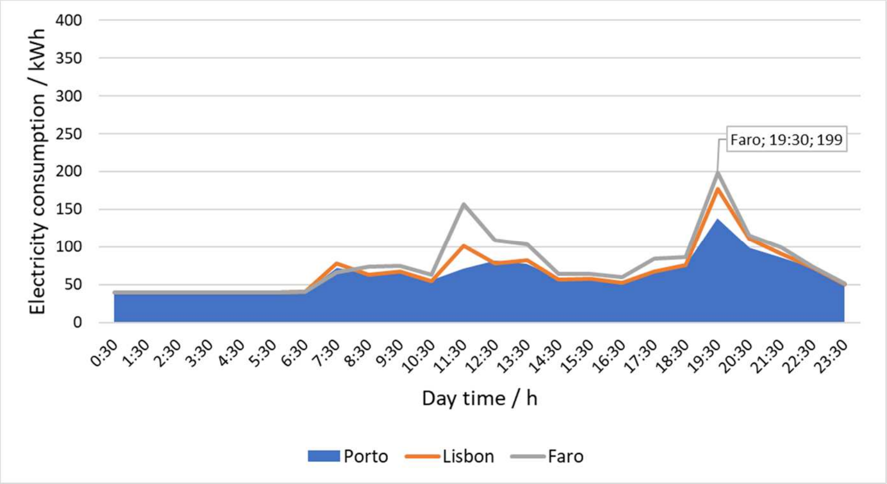


Figure 5.4 - Electricity daily consumption profile for a typical winter day in Porto, Lisbon and Faro.

In the typical summer day, there are two peak times at 11:30 a.m. and at 7:30 p.m. for all the locations studied. In the typical winter day, the consumption profile is identical in Porto and Lisbon but in Faro an additional peak outstands, at 11:30 a.m., which can be related to the additional need for cooling the spaces at that time. This profile is related to the occupancy profiles settled: a weekday was considered a workday and the times when the rooms are occupied depend on typical work schedules. The occupancy was considered maximum at lunch and dinner times for most of the room templates, and this explains why there are electric consumption peaks at that times.

In these graphics, it is also possible to notice again the disparity between the electric consumption in winter and summer, mentioned above. In summer, the maximum consumption for these days is approximately 363 kWh in Lisbon at 7:30 p.m. In winter it is approximately 199 kWh in Faro at 7:30 p.m.

5.2 Integration of Solar Collectors' system

This project contemplates a Solar Collectors' system to provide some of the needs of Domestic Hot Water. The graphic plotted in Figure 5.5, features both the DHW consumption (which is independent of the location) and the production of energy by this system (which differs with the location). It is clearly seen that in Faro this production is higher than in Lisbon and Porto. Also, at Porto in the months of October to February, the production of energy is not enough to cover its consumption for DHW supply, while in Lisbon and Faro this is only true in the months of November to February. In the other months of the year, the energy production of this system exceeds the needs for DHW.

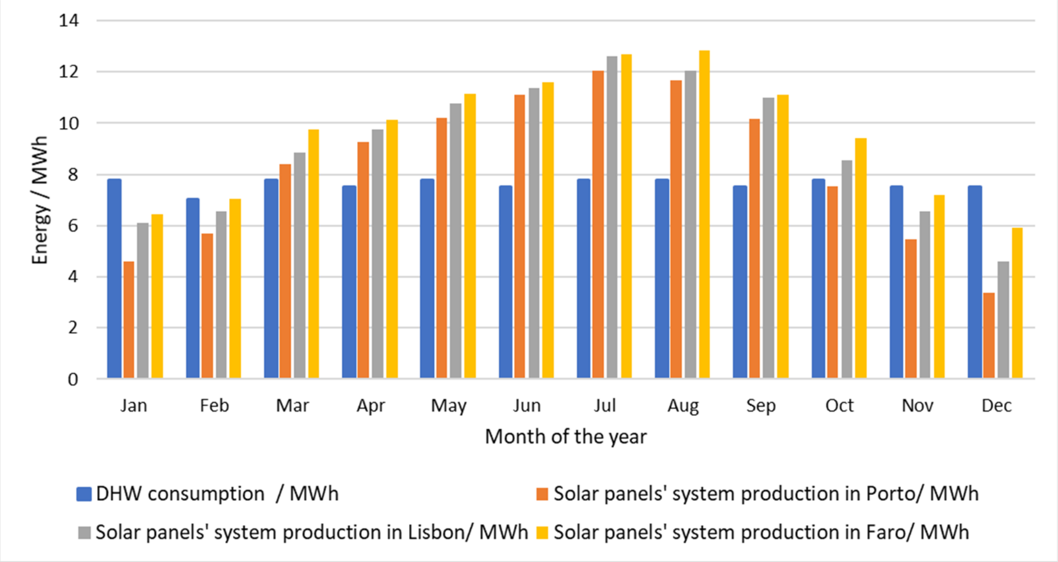


Figure 5.5 - Monthly DHW consumption and solar panels' system production in Porto, Lisbon and Faro

Annually, the summation of the production of thermal energy from the solar collectors is higher than the DHW thermal energy needs.

5.3 Integration of PV with Battery Storage system

5.3.1 PV energy production for the Available Area Scenario

The first simulation performed was made for the available area in the rooftop of the building studied. It was possible to install 108 panels mentioned in the previous Chapter 4, with a total panel area of approximately 176 m^2. The installed peak power of the system was calculated and equal to 32.4 kWp for the three locations.

The Table 5.2 sets the annual PV system production for the three locations considered in Portugal. In Faro it is possible to produce more electricity from the same PV system than in Lisbon and Porto.

Table 5.2 - Annual PV system production for available area in the three locations considered in Portugal

	Annual PV system production / MWh
Porto	52,5
Lisbon	53,4
Faro	56,4

The monthly PV system production of energy is shown in Figure 5.6. This production varies not only for the different locations but also along the year. The most visible pattern is that in the summer months there is more production than in the winter months, once the exposure of the building to solar irradiance is also higher in summer months, shown in Figure 5.7.

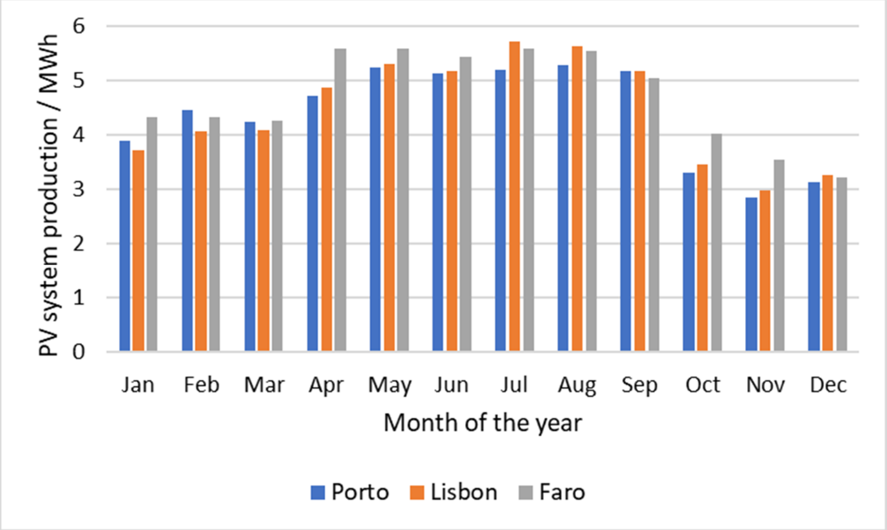


Figure 5.6 - Annual PV system production for available area in the three locations considered in Portugal

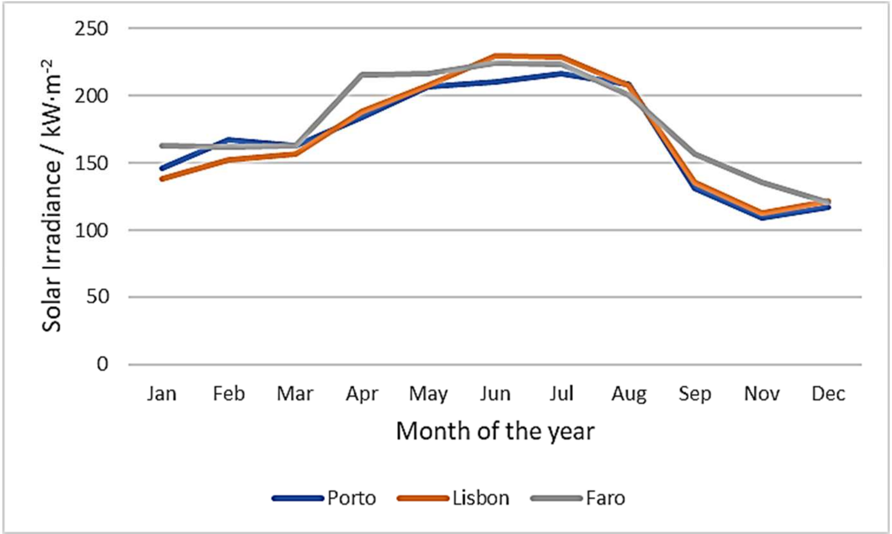
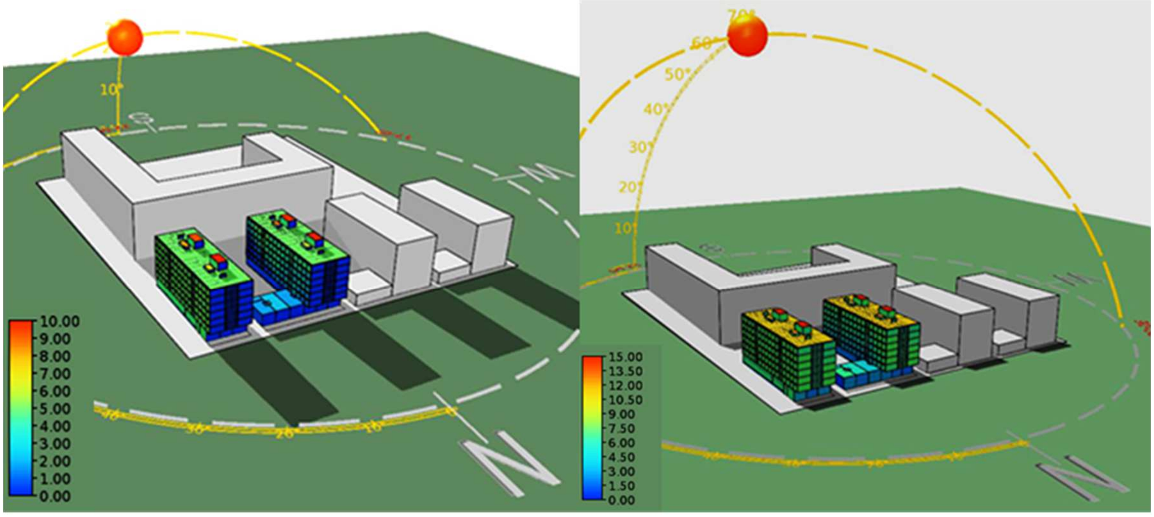


Figure 5.7 - Annual solar irradiance throughout the year in the three locations considered in Portugal

The same can be explained by the solar exposure of the building. Figure 5.8 shows the solar exposure in hours for the different surfaces of the building in a winter and a summer day. The surfaces have different sun exposure hours because of the shades caused by the adjacent buildings and its orientation. In a winter day, this solar exposure varies between 0 and 10 accumulated hours of sun exposure for the surfaces of the building and in a summer day it varies between 0 and 15 hours. This means that in summer, the rooftop surfaces will have more solar exposure than in winter and thus the production of electricity from solar energy will also be higher.



Typical winter day

Typical summer day

Figure 5.8 - Comparison of the building sun exposure hours for a typical day of winter and summer in Porto.

An inherent obstacle when designing a PV system for a mid and high-rise building (constructed in high) is that the production of the PV system using the available area of its rooftop is not even near to supply the electricity needs of the building, being these last ones more than ten times higher for the studied case. In these types of buildings, normally a BIPV system would be implemented to exploit more areas of the building. The decision for using this type of PV system should be taken in a very initial phase of the building project once it must be integrated in the building architecture.

In this scenario there will be no surplus energy to storage, and it will not be deeply explored for this reason. Hypothetic scenarios were studied further in this paper.

5.3.2 PV energy production with energy storage for supplying electricity consumption

In this studied scenario, systems as the C described in the methodology were applied to meet electric consumption needs of the building. The main purpose of this type of PV plus battery storage system is to buffer the production of electricity along the day, so that it can be available when needed.

During the day (considered between 7:30 a.m. and 11:30 p.m.), there are times with no PV power production and other times when this power production is not enough to cover the electric consumption loads of the building. At these times, a percentage of these electric consumption loads will be supplied by the battery and the rest by the grid. During the night, there is no PV power production, meaning that the electric consumption is always supplied by the battery and the grid. The installed peak power of the PV system was calculated to charge the battery so that it can supply a given percentage of consumption loads for a typical summer day, a typical winter day and the maximum electric consumption day, showed in Table 5.3.

Table 5.3 - Electricity consumption considered to size PV systems.

	Typical summer day	Typical winter day	Maximum electric consumption day
Electricity Consumption (kWh)	2700	1600	3000

The first scenario studied was supplying **50%** of the electricity consumption by the battery during the day, in the conditions mentioned before, and **5%** at night. This lower percentage at night was chosen so that there is no overcharge and oversize of the battery system.

Table 5.4 shows the resume of results obtained for the different systems implemented in the building located in Porto. Notice that the number of PV panels considered is much higher than the one used before for the available area, which means they will need a much bigger area to be explored and this is not considered in the costs.

Table 5.4 - Resume of results obtained for the different systems implemented in the building located in Porto.

PORTO	Typical winter day	Typical summer day	Maximum consumption day
Installed Peak Power (kWp)	**140**	**240**	**270**
Number of panels	467	800	900
Battery capacity (kWh)	874	744	768
Number of batteries	364	310	320
Sys. A operation costs / EUR	111 017	111 017	111 017
Sys. C operation costs / EUR	88 564	74 802	71 916
Investment cost PV sys. / EUR	69116	118 400	133 200
Investment cost Bat. Sys. / EUR	509 600	434 000	448 000
TOTAL investment costs / EUR	578 716	552 400	581 200
Payback time / Years	26	16	15

- **Maximum consumption day**

The best system obtained was the one with higher PV installed peak power (270 kWp) and a battery capacity of 768 kWh. Not only because it has the smallest payback time but also because the best performance and management of the battery system is achieved.

In Figure 5.9 , Figure 5.10 and Figure 5.11 we can see this PV and battery system performance on each day selected.

Notice that the intended scenario happens: when there is energy surplus produced from the PV panels' system the battery is low enough so that it can be charged. When the peak consumption hours occur (and tariffs are higher), the battery system is charged enough to supply the 50% of the consumption loads.

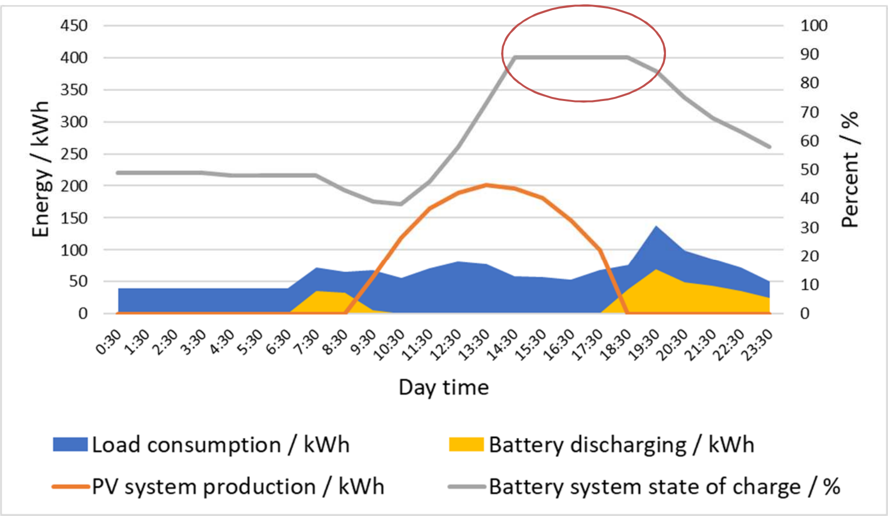


Figure 5.9 - PV and battery system (Pi=270 kWp) performance in the typical winter day in Porto.

In winter days, there is enough surplus energy production to charge the battery and inject to the grid (at the time selected in Figure 5.9 between 2:30 p.m. and 5:30 p.m.). This injection of electricity to the grid happens when the battery has no more capacity (charged above 80%) and gives an extra advantage to the system because producing electricity from the PV panels is cheaper than the market value at which the electricity is sold. For each kWh of surplus electricity injected to the grid, 0.016 Euros are earned (or discounted in the electricity bills) (Table 4.7).

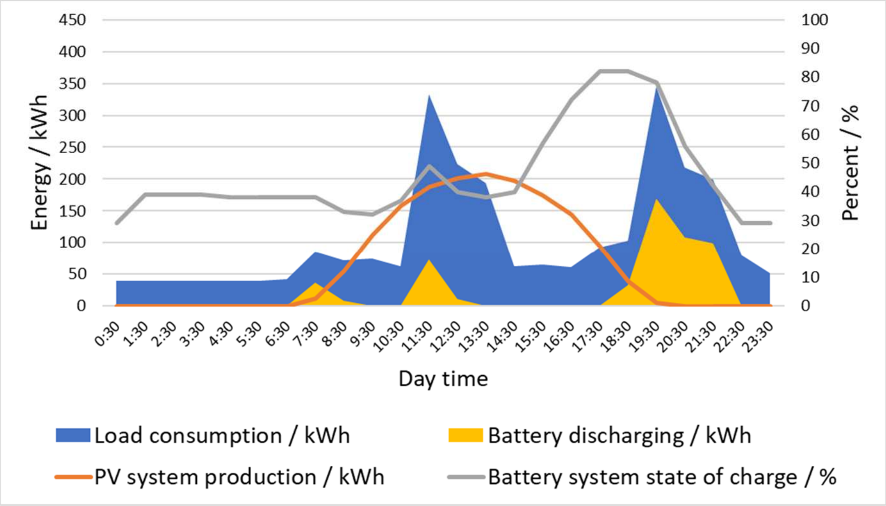


Figure 5.10 - PV and battery system (Pi=270 kWp) performance in the typical summer consumption day in Porto.

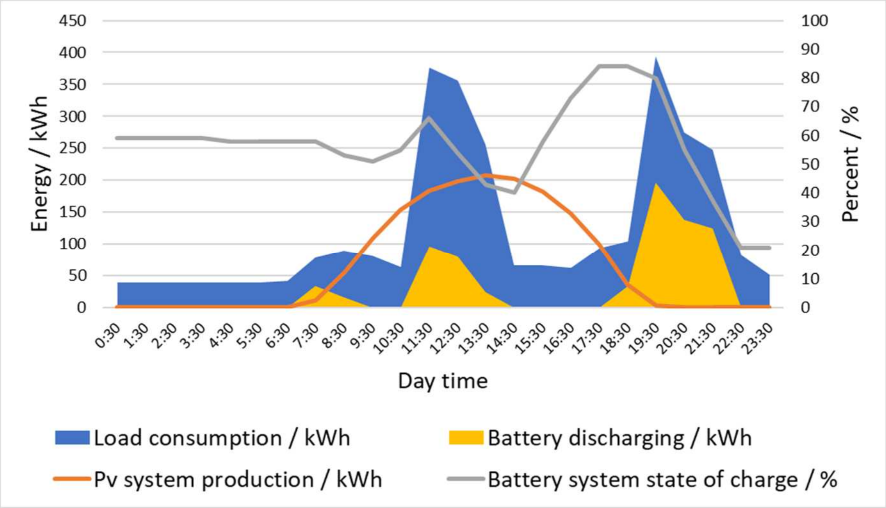


Figure 5.11 - PV and battery system (Pi=270 kWp) performance in the maximum consumption day in Porto.

In summer days there are times when there is no energy surplus, but the battery has the capacity to meet 50 % of the loads required by the building.

The total investment costs for this system is 581 200 Euros. When comparing the operation costs of this system with the system A (buying all the electricity needed from the grid), the annual savings are 39 101 Euros and the resultant payback is 15 years.

- **Typical summer day**

When the system is sized to meet the typical summer day consumption loads, the PV installed peak power is 240 kWp and the battery capacity is 744 kWh. Although the investment costs for this system are lower than for the system described above, 552 400 Euros, the annual savings obtained are smaller, of 36 215 Euros. This happens because with this system there will be less surplus of energy produced, thus the amount of electricity injected to the grid and discounted from electric bills is also lower. The payback obtained for this system was 16 years.

- **Typical winter day**

On the contrary, the worst scenario happens when we size the PV system to meet 50% of the electric consumption for a typical winter day, once there is not enough surplus power production from the PV panels in most days of the year. Beyond the battery being always at a low state of charge, it will not be able to provide electricity at the peak hours of the day, mainly in a typical summer day, shown in Figure 5.12. To improve the operation of this system, the battery should be charged more frequently at night when the tariffs are low.

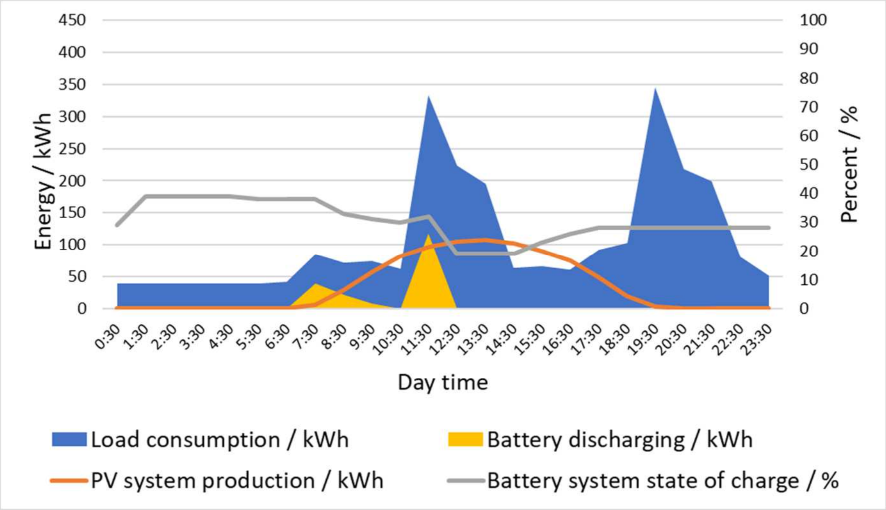


Figure 5.12 - PV and battery system (Pi=140 kWp) performance in a typical summer day in Porto.

When we oversize the PV system (installed peak power > 270 kWp), on one hand the battery will not be charged by the PV system energy surplus and this happens because its state of charge is always high. On the other hand, if we oversize the battery capacity, its high investment costs will not be compensated by the annual savings generated.

The same study was performed with the building placed in Lisbon and Faro. Table B.1 and Table B.2 from Appendix B display the resume of results obtained for the different systems implemented in the building located in Lisbon and Faro, respectively.

The results show the same conclusions of the best and worst system both in terms of payback time and energy management. The best is the one sized for the maximum consumption day and the worst is the one sized for the typical winter day.

The installed peak power conditions differ from location once it depends on the peak sun hours for each place, presented in Table 4.5. The peak sun hours in Faro are higher than in Lisbon and Porto. This means that the peak power installed for that the system designed meets the same consumption loads is lower (Equation (3.6)).

In Table 5.5 we can see the best systems selected for each location.

Table 5.5 - Results of the best performance systems for each location.

	Porto	Lisbon	Faro
Installed Peak Power (kWp)	270	245	225
Number of panels	900	817	750
Battery capacity (kWh)	768	732	794
Number of batteries	320	305	331
Sys. A operation costs / EUR	111 017	114 745	122 986
Sys. B operation costs / EUR	73 190	77 155	83 554
Sys. C operation costs / EUR	71 916	76 311	83 569
Investment cost PV sys. / EUR	133 200	120 916	111 000
Investment cost Bat. sys. / EUR	448 000	427 000	463 400
TOTAL investment costs / EUR	581 200	547 916	574 400
Payback time	15	15	15

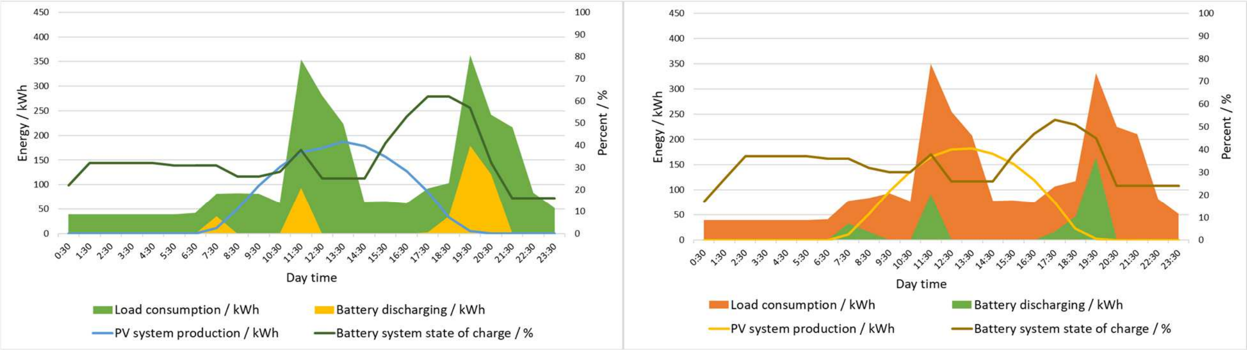
Table 5.6 shows the comparison between the total investment costs and annual savings for the systems with best performance in the three locations.

Table 5.6 - Comparison between the total investment costs and annual savings for the systems with best performance in Porto, Lisbon and Faro.

	Porto (P_i=270 kWp)	**Lisbon (P_i=245 kWp)**	**Faro (P_i=225 kWp)**
Total investment costs / EUR	581 200	547 916	574 400
Annual savings / EUR	39 101	38 434	39 432

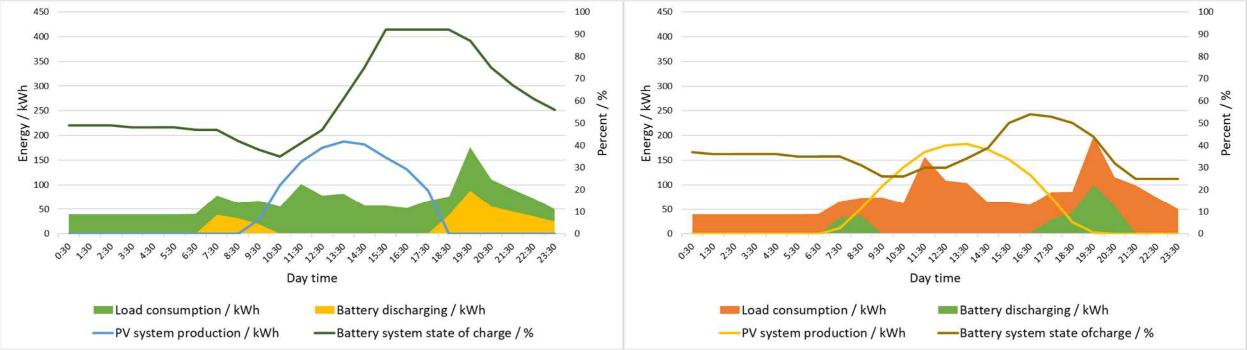
The payback for the best systems for each location selected are the same. If only total investment costs are considered, a system applied in the building located in Lisbon is cheaper to implement than in Porto or Faro, but examining the annual savings, they will be smaller.

Figure 5.13 and Figure 5.14 show the performance of the best systems selected for Lisbon and Faro (sized for the maximum consumption of the year). They have the same behaviour in terms of energy management. In wintertime, electricity surplus produced from PV system is charged into the battery system and it manages to supply 50% of the consumption loads during peak hours and when electricity tariffs are high. In summertime, there is less available electricity surplus and thus the battery is charged by night (at 00:30 a.m.) so that it can also supply 50% of the consumption loads.



Lisbon **Faro**

Figure 5.13 - Results of the best performance systems for Lisbon and Faro in a typical summer day.



Lisbon **Faro**

Figure 5.14 - Results of the best performance systems for Lisbon and Faro in a typical winter day.

5.3.3 Sensitivity Analysis

- **Percentage of consumption loads supplied by the system**

In the last subchapter it was studied the systems in which only 50% of the consumption loads were supplied by the battery during day, in the conditions mentioned above (when there is no power production from PV panels or when this production is not enough to meet the consumption loads), and 5% by night.

This study was performed in the building located in Porto, where 30% and 70% of the consumption loads were supplied by the battery during day, in the conditions mentioned above, and 5% by night. The installed peak power of the PV system was designed to support this percentages of electricity loads for the maximum electric consumption day located in Porto. The results are presented in Table 5.7.

Table 5.7 - Results of the sensitivity analysis for the percentage of consumption loads supplied by the system.

	30%	50%	70%
Installed Peak Power (kWp)	180	270	380
Number of panels	600	900	1 267
Battery capacity (kWh)	456	768	1 157
Number of batteries	190	320	482
Sys. A operation costs / EUR	111 017	111 017	111 017
Sys. C operation costs / EUR	81 014	71 916	63 830
Investment cost PV sys. / EUR	88 800	133 200	187 516
Investment cost Bat. sys. / EUR	266 000	448 000	674 800
TOTAL investment costs / EUR	354 800	581 200	862 316
Payback time	12	15	19

As it is noticeable, when this percentage is increased, also the peak power installed and battery capacity will increase and so do the investment costs. The more consumption loads are required to be supplied by the system, the higher the payback and the more overload it will be and not as efficient in energy management as when less of the consumption loads are required to be supplied by the system.

- **Economical evaluation after 5 years**

An outlook of the prices for the technologies studied within 5 years was made and described in Chapter 3 (values presented in Table 4.8). The simulation was performed using these new price values for the best systems selected for each location.

Table 5.8 displays the resume of results obtained.

The payback time for the investments made five years from now, compared to the present time (2020), diminishes from 15 to 9 years for the three locations. This means that in few years this investment will be more cost-efficient.

Table 5.8 - Results of the sensitivity analysis for the costs.

	Porto	Lisbon	Faro
Installed Peak Power (kWp)	270	245	225
Number of panels	900	817	750
Battery capacity (kWh)	768	732	794
Number of batteries	320	305	331
Sys. A operation costs / EUR	111 017	114 745	122 986
Sys. B operation costs / EUR	67 939	72 315	78 857
Sys. C operation costs / EUR	64 633	69 513	77 056
Investment cost PV sys. / EUR	78 300	71 079	65 250
Investment cost Bat. sys. / EUR	322 560	307 440	333 480
TOTAL investment costs / EUR	400 860	378 519	398 730
Payback time	9	9	9

6 Conclusion

This dissertation aims to evaluate the energetic and economic performance of a photovoltaic panels system with energy storage for a mid-rise residential building previously modelled by A400 placed in three different cities in Portugal: Porto, Lisbon and Faro. Li-ion batteries were chosen as the energy storage system to be implemented coupled to solar PV units.

For that, several simulations were performed using the IESve software, PVGIS and a system of equations and restrictions developed in Excel. The first one was used to obtain the electric consumption profile of the building, the second to obtain the PV system power production profile, and the last one to implement solar photovoltaic and battery storage systems in the building.

According to the results provided by IESve, the annual electricity consumption obtained was 700 MW, 720 MW and 766 MW for the building placed in Porto, Lisbon and Faro, respectively. The cooling needs were responsible for the higher electric consumption of electricity in Faro when compared to Lisbon and Porto and in summer when compared to winter.

Using the real area available of the roof-top of the building (that is covered already with the solar collectors and other assets) only 108 PV panels can be implemented with a peak installed power of 32.4 kWp. Results show how the PV power production varies along the year (there is more production in summer than in winter) and with the location of the building (producing more electricity in Faro, than Lisbon and Porto). In this scenario, the PV system could not produce and supply the electricity needs of the building, being these last ones more than ten times higher for the all the locations. For this reason, a system incorporating battery storage could not be implemented and thus other hypothetic scenarios where much higher PV peak powers installed were considered.

The more autonomy is pretended, the higher the annual savings, but also the investment costs. This last one is a more significative value, resulting in higher payback times.

The case scenario studied deeply was sizing the system of PV panels plus batteries capable of supplying 50% of the electricity consumption of the building. In each city, the system was sized to support 50% of the electricity consumption for three different days: a typical summer day, a typical winter day and the maximum consumption day of the year. The best results were obtained for the systems designed for the maximum consumption day of the year in the three locations studied, both in terms of energy management as well as economically. In Porto, the best system selected has a PV peak power installed of 270 kWp and battery capacity of 768 kWh; in Lisbon, the best system selected has a PV peak power installed of 245 kWp and battery capacity of 732 kWh; in Faro, the best system selected has a PV peak power installed of 225 kWp and battery capacity of 794 kWh. The best systems for each location require different investment costs of 581 200 EUR, 547 916 EUR and 574 400 EUR, for Porto, Lisbon and Faro, respectively, but have the same payback time of 15 years.

Costs for battery storage and solar photovoltaic technologies have been falling and will continue in the next years. An outlook for these costs within 5 years was performed and a new economic evaluation for the best systems selected described above was made. Both the investment costs and operations costs decreased considerably, and the payback time declined from 15 to 9 years for the three locations of the building studied, concluding that in 5 years the investment for this system will be more cost-effective.

Although in south of Portugal the power production from a photovoltaic panel system is higher than in the North, the electric consumption of the building is also higher and thus, this factor do not dictated a better performance of the system for the compared locations.

Concluding, when considering investing in the integration of a solar photovoltaic with battery storage system in a mid-rise residential building, there are many decisions to contemplate at a very early stage of the building project that have more influence than where it is placed in Portugal, such as how to reduce the electric consumption or the possibility to implement BIPV and its viability.

7 Assessment of the work done

7.1 Objectives Achieved

In this project, the theoretical study of energy storage was deeply conducted to choose the best energy storage system to implement on the building case study, being battery storage system the chosen one. The development of a system of equations and restrictions in an Excel was crucial to study the performance of battery storage coupled with a solar photovoltaic system under different scenarios, and effectively gave the results expected when compared to other studies. The results show that this system is able to storage the surplus electricity produced by the photovoltaic panels and discharge during peak hours of consumption and thus generating savings when compared to buying all the electricity from the grid and for the building's consumption profile it does not depend on its location in Portugal. Cost-effective systems were designed to meet the requirements inputted.

7.2 Limitations and Future Work

IESve is a good software for performing energy analysis in buildings, but the integration of renewable energy technologies is not so well developed. The Excel is a restrictive tool when it comes to developing a simulation, once it cannot predict future time steps, meaning that the system of equations and restrictions could be refined and the PV plus battery systems optimized.

An interesting study to perform would be the integration of a BIPV system in the building studied in order to explore more available area. Other one would be to study how a Vehicle to Grid (V2G) system implemented in the parking lots would impact on the building consumption profile of the building and how it could be coupled to a PV plus battery system.

7.3 Final Assessment

In general, the development of this project was interesting in the way that it approaches a very ongoing theme and brought me to look deeply into the Energy Sector and its current developments. Although the virus crisis put some restrictions and barriers for the normal course of this dissertation, it opened up to new opportunities such as assisting to online conferences where specialized people brought to table the last updates on energy production and storage technologies.

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Annex A - Electricity Tariffs

Table A.1 - Summer daily electricity tariffs for weekdays and weekends in EUR.

	Weekdays (Mon-Fri)	Saturday	Sunday
00:30	0,0958	0,0958	0,0958
01:30	0,0958	0,0958	0,0958
02:30	0,0958	0,0958	0,0958
03:30	0,0958	0,0958	0,0958
04:30	0,0958	0,0958	0,0958
05:30	0,0958	0,0958	0,0958
06:30	0,0958	0,0958	0,0958
07:30	0,1693	0,0958	0,0958
08:30	0,1693	0,0958	0,0958
09:30	0,2215	0,1693	0,0958
10:30	0,2215	0,1693	0,0958
11:30	0,2215	0,1693	0,0958
12:30	0,1693	0,1693	0,0958
13:30	0,1693	0,1693	0,0958
14:30	0,1693	0,0958	0,0958
15:30	0,1693	0,0958	0,0958
16:30	0,1693	0,0958	0,0958
17:30	0,1693	0,0958	0,0958
18:30	0,1693	0,0958	0,0958
19:30	0,1693	0,0958	0,0958
20:30	0,1693	0,1693	0,0958
21:30	0,1693	0,1693	0,0958
22:30	0,1693	0,0958	0,0958
23:30	0,1693	0,0958	0,0958

Table A.2 - Winter daily electricity tariffs for weekdays and weekends in EUR.

	Weekdays (Mon-Fri)	Saturday	Sunday
00:30	0,0958	0,0958	0,0958
01:30	0,0958	0,0958	0,0958
02:30	0,0958	0,0958	0,0958
03:30	0,0958	0,0958	0,0958
04:30	0,0958	0,0958	0,0958
05:30	0,0958	0,0958	0,0958
06:30	0,0958	0,0958	0,0958
07:30	0,1693	0,0958	0,0958
08:30	0,1693	0,0958	0,0958
09:30	0,2215	0,1693	0,0958
10:30	0,2215	0,1693	0,0958
11:30	0,2215	0,1693	0,0958
12:30	0,1693	0,1693	0,0958
13:30	0,1693	0,0958	0,0958
14:30	0,1693	0,0958	0,0958
15:30	0,1693	0,0958	0,0958
16:30	0,1693	0,0958	0,0958
17:30	0,1693	0,0958	0,0958
18:30	0,2215	0,1693	0,0958
19:30	0,2215	0,1693	0,0958
20:30	0,2215	0,1693	0,0958
21:30	0,1693	0,1693	0,0958
22:30	0,1693	0,0958	0,0958
23:30	0,1693	0,0958	0,0958

Appendix A - Assumed Profiles

A.1 Internal Gains

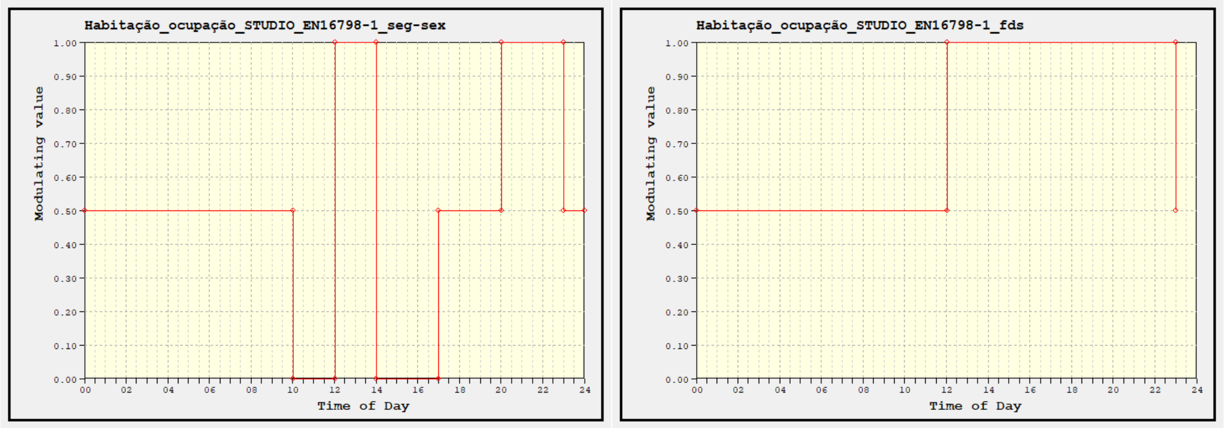

Figure A.1- Studio occupation daily profile for weekdays (at left) and weekends (at right)

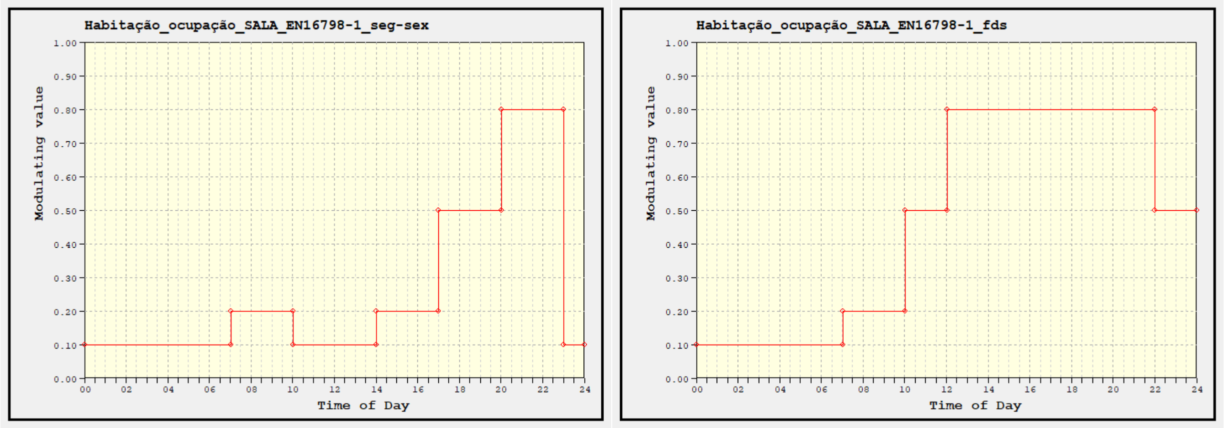

Figure A.2 - Living room occupation daily profile for weekdays (at left) and weekends (at right)

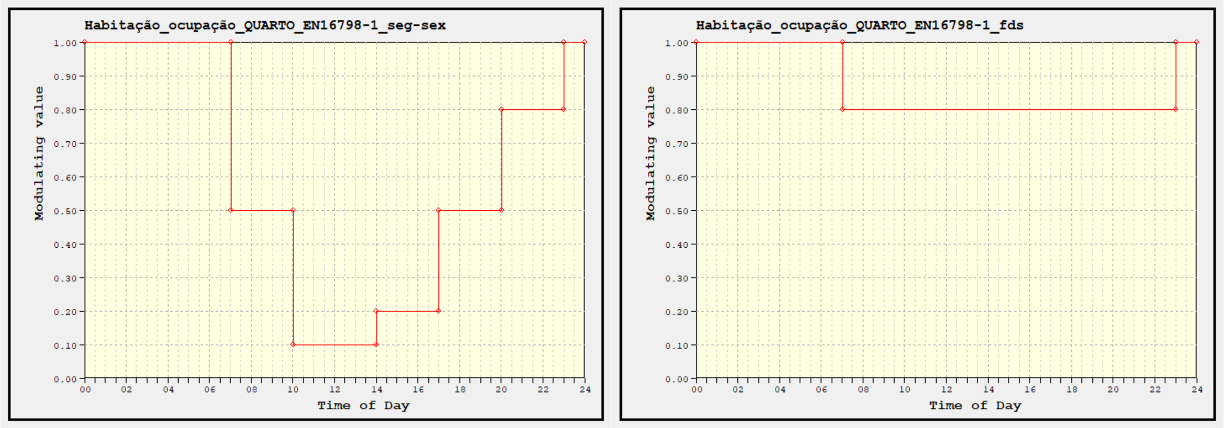

Figure A.3 - Bedroom occupation daily profile for weekdays (at left) and weekends (at right)

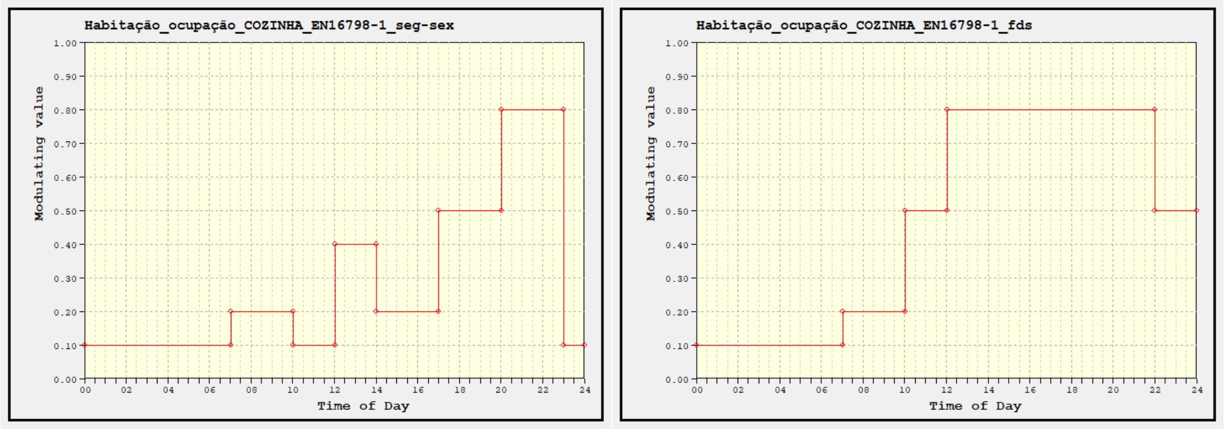

Figure A.4 - Kitchen occupation daily profile for weekdays (at left) and weekends (at right)

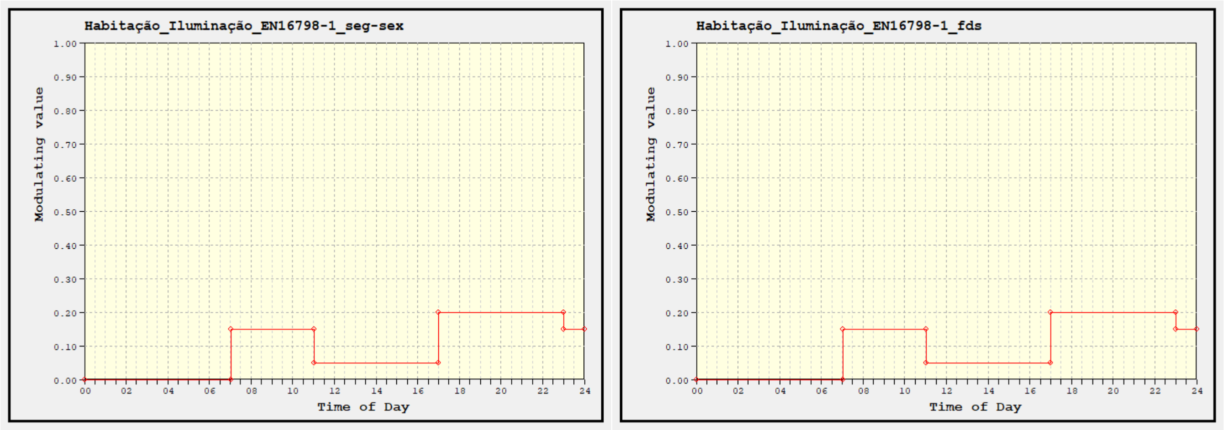

Figure A.5 - Illumination daily profile for weekdays (at left) and weekends (at right)

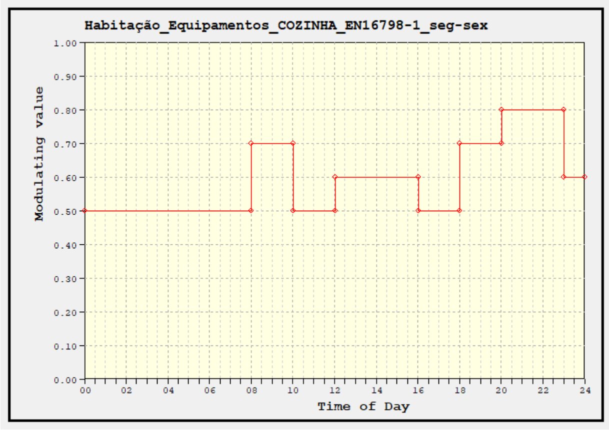

Figure A.6 - Kitchen equipment daily profile

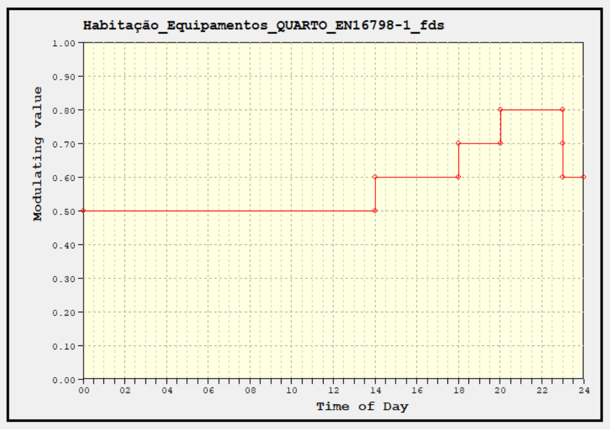

Figure A.7 - Bedroom equipment daily profile

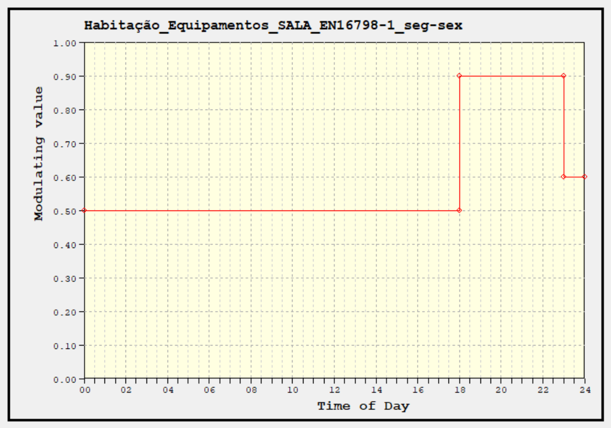

Figure A.8 - Living room equipment daily profile

A.2 Climatization

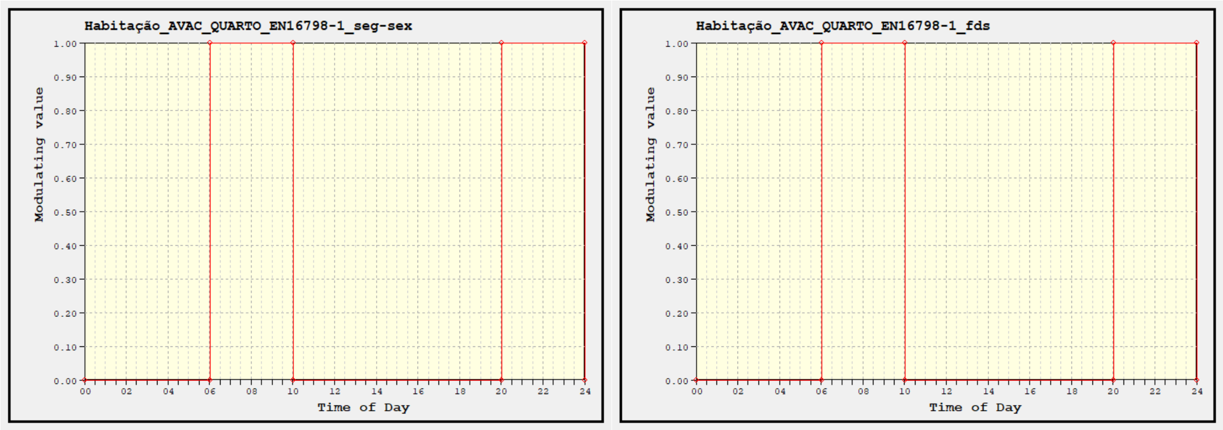

Figure A.9 - Bedroom HVAC daily profile for weekdays (at left) and weekends (at right)

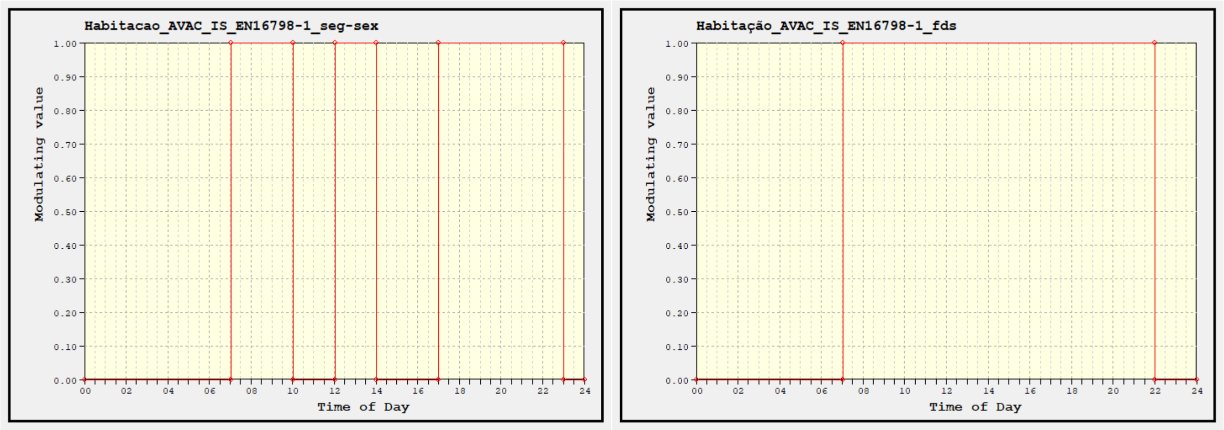

Figure A.10 - Bathroom HVAC daily profile for weekdays (at left) and weekends (at right)

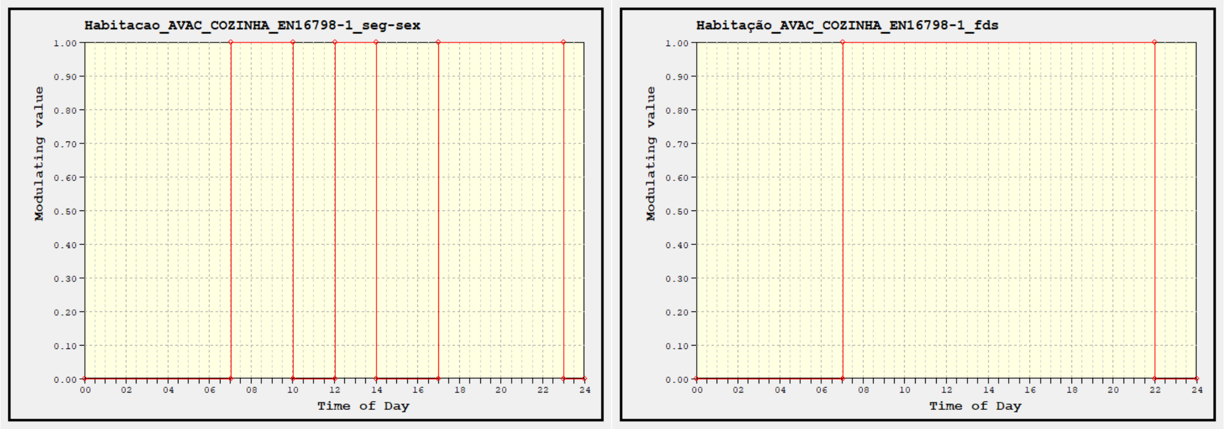

Figure A.11 - Kitchen HVAC daily profile for weekdays (at left) and weekends (at right)

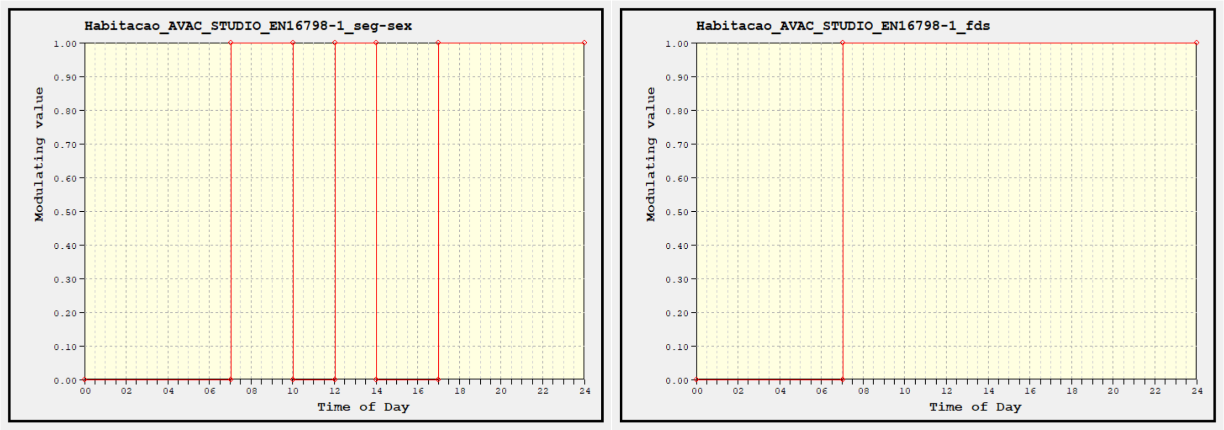

Figure A.12 - Studio HVAC daily profile for weekdays (at left) and weekends (at right)

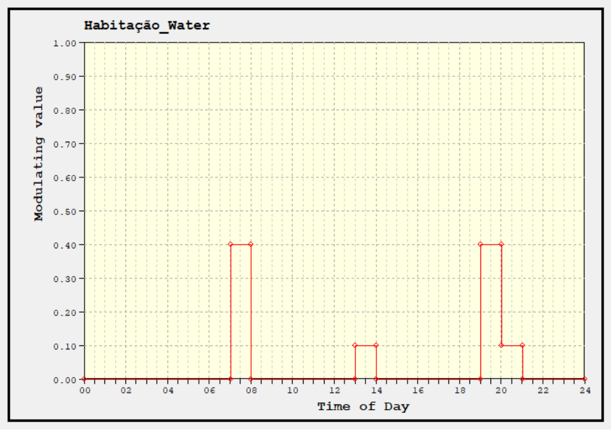

Figure A.13 - DHW consumption daily profile

Appendix B - Systems studied in Porto and Lisbon

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Table B.1-Resume of results obtained for the different systems implemented in the building located in Faro.

LISBON	Typical winter day	Typical summer day	Maximum consumption day
Installed Peak Power (kWp)	130	230	245
Number of panels	434	767	817
Battery capacity (kWh)	838	751	732
Number of batteries	349	313	305
Sys. A operation costs / EUR	114 745	114 745	114745
Sys. C operation costs / EUR	92 833	78 250	76 311
Investment cost PV sys. / EUR	64 232	113 516	120 916
Investment cost Bat. sys. / EUR	488 600	438 200	427 000
TOTAL investment costs / EUR	552 832	551 716	547 916
Payback time / Years	26	16	15

Table B.2- Resume of results obtained for the different systems implemented in the building located in Faro.

FARO	Typical winter day	Typical summer day	Maximum consumption day
Installed Peak Power (kWp)	135	205	225
Number of panels	450	684	750
Battery capacity (kWh)	703	881	794
Number of batteries	293	367	331
Sys. A operation costs / EUR	122 986	122 986	122 986
Sys. C operation costs / EUR	97 709	86674	83 569
Investment cost PV sys. / EUR	66 600	101 232	111 000
Investment cost Bat. sys. / EUR	410 200	513 800	463 400
TOTAL investment costs / EUR	476 800	615 032	574 400
Payback time	19	17	15