Promotion of Energy Efficiency Measures in SIBS Forward Payment Solutions

Ricardo Júlio Ruas Pessoa Dinis

Thesis to obtain the Master of Science Degree in

Mechanical Engineering

Supervisors: Prof. António Luís Nobre Moreira

Dr. Rui Pedro da Costa Neto

Examination Committee

Chairperson: Prof. Edgar Caetano Fernandes

Supervisor: Dr. Rui Pedro da Costa Neto

Member of the Committee: Dr. Laura Elena Aelenei

January 2021

Acknowledgements

First, I would like to thank my good family, especially my parents, Fernanda and Júlio and my sisters Maria, Mafalda and Filipa, for all the sacrifices, their unconditional love and support. For all the motivation in the most difficult phases and for never stopped believing in me throughout my life.

I would also like to thank GALP and Prof. Dr. António Luís Nobre Moreira, for creating the opportunity to carry out such an interesting and challenging work and for the trust deposited in me.

I hereby express my gratitude to my supervisor, Prof. Dr. Rui Pedro da Costa Neto for all his support, availability and optimism demonstrated during the realization of the dissertation.

To Dr. Luis Duarte and Dr. Jorge Mouta from SIBS, for their availability and contribution demonstrated throughout the internship.

To Instituto Superior Técnico for the values instilled, which will certainly remain with me and for all the opportunities created.

Finally, I would like to thank my good friends who accompanied me on this journey, whose support was essential for carrying out this work.

Ricardo Dinis

Abstract

To avoid extreme exploitation of fossil fuels and reenforce the need of growing sustainably, the European Union has strategized a plan and several targets to be achieved by the years 2020 and 2030, that force the implementation of renewable energy sources as well as the improvement in energy efficiency. Moreover, the building sector is crucial in this plan, being one of the most important points, the retrofitting of already existing buildings. Better and more energy efficient buildings improve the quality of citizens' life while bringing additional benefits to the economy.

This case study is one of the national's internships programs provided by GALP21 and Instituto Superior Técnico. The study was carried out with the aim of performing the energetic and economic evaluation of implementing some energy efficiency measures to SIBS Forward Payment Solutions' building.

Firstly, a careful analysis of the SIBS's electric consumption was performed and a review to existing literature to provide basis of knowledge to guide the implementation of the proposed energy efficiency measures. Those measures were the replacement of the current luminaries with more energy efficient ones and the installation of photovoltaic modules on the roof of the building.

From an economic standpoint, the obtained results are reasonable. The net present value for the measures applied turned out to be positive, proving the project's profitability, returning 6592.34€ in annual financial savings for SIBS. On an energy standpoint, if applied, the measures will result in a 9% energy saving and 9% reduction in CO_2 emissions for the company.

Key Words: Energy Efficiency, Energy management, Renewable energies, LED luminaries, Photovoltaic systems, Office buildings

Resumo

Para evitar a exploração extrema de combustíveis fósseis e reforçar a necessidade de crescer de sustentavelmente, a União Europeia traçou um conjunto de metas a serem alcançadas até aos anos de 2020 e 2030, que obrigam a implementação de fontes renováveis, bem como a melhoria de eficiência energética. Além disso, o setor dos edifícios é fundamental neste plano, sendo um dos pontos mais importantes, a renovação de edifícios já existentes. Edifícios mais eficientes melhoram a qualidade de vida e trazem benefícios para a economia.

Este caso de estudo está inserido num dos programas nacionais de estágios desenvolvidos pela GALP21 e pelo Instituto Superior Técnico. O estudo foi realizado com o objetivo de avaliar energética e economicamente a implementação de medidas de eficiência energética no edifício da SIBS Forward Payment Solutions.

Em primeiro lugar, foi realizada uma análise cuidadosa do consumo elétrico da SIBS e uma revisão da literatura existente para fornecer uma base de conhecimento para orientar a implementação das medidas de eficiência energética propostas. Essas medidas foram a substituição das luminárias atuais por outras de maior eficiência energética e a instalação de módulos fotovoltaicos na cobertura do edifício.

Do ponto de vista económico, os resultados obtidos são razoáveis. O valor presente líquido das medidas aplicadas revelou-se positivo, comprovando a rentabilidade do projeto, tendo um retorno de 6592.34€ em poupanças anuais para a SIBS. Do ponto de vista energético, se aplicadas, as medidas resultarão numa poupança de energia de 9% e na redução de 9% nas emissões de CO_2.

Palavras Chave: Eficiência energética, Gestão de energia, Energias renováveis, Luminárias LED, Sistemas fotovoltaicos, Edifícios de serviços

List of content

List of Figures

List of Tables

Nomenclature

Abbreviations

CIBSE	Chartered Institution of Building Services Engineers
NZEB	Near-Zero Energy Building
LED	Light-Emitting Diode
CFL	Compact Fluorescent Lights
HVAC	Heating, Ventilating and Air Conditioning
PMV	Predicted Mean Vote
PPD	Predicted Percent Dissatisfied
PV	Photovoltaic
LCOE	Levelized Cost of Energy
CER	Comunidade de Energia Renovável
UPP	Unidade de Pequena Produção
UPAC	Unidade de Produção para Autoconsumo
AHU	Air Handling Units
IU	Induction Units
NPV	Net Present Value
PP	Payback Period
IRR	Internal Rate of Return
CRI	Colour Rendering Index
LPD	Lighting Power Density
MPP	Maximum Power Point
STC	Standard Test Conditions
MPPT	Maximum Power Point Tracking

Symbols

A	Useful interior area
$A_{installed}$	Area occupied by the PV modules
A_l	Area per lamp
C_u	Coefficient of utilization
d	Total distance between modules
d_{month}	Number of days related to the month which the quantity of energy produced is being calculated
$d1$	Shading distance generated beyond the module itself
$d2$	Shading distance generated to the module itself.
E_0	Solar constant

E_{PV}	Energy that the photovoltaic system produces monthly
F_o	Occupancy control factor
F_D	Control factor for availability of natural light
G	Solar radiation on a surface at 90 ° of inclination
h	Hour Angle
I	Illuminance
i	Discount rate
I_{cable}	Current that flows through the DC cable
I_m	Maintained average illuminance
$I_{\max\ INV}$	Maximum current input of the controller(s) in the MPP
I_{MPP}	Nominal current
I_n	Maximum current in row n
$I_{n,AC}$	Nominal current output of the inverter
$I_{INV\ max}$	Inverter's maximum current input
$I_{INV\ max}$	Inverter's maximum input current for each MPPT controller
I_{sc}	Short circuit current
$I_{SC\ (module)}$	Module's short circuit current
$I_{SC\ PV}$	Photovoltaic system's short circuit current
$I_{\max,\ SC\,INV}$	Controller(s) maximum short circuit input current
I_0	Initial investment
L	Local latitude
L_{AC}	Length of the cable from the inverter to the low voltage distribution board
L_{DC}	Length of the cable in the row
L_l	Luminous flux per lamp
L_{LF}	Light loss factor
n	Number of years of the project
n_{max}	Maximum Number of Modules
P_{AC}	Energy losses in the AC cable for a three-phase system
P_c	total power of the control equipment for the luminaires in operation
P_{INV}	Inverter's Power
P_t	Total power of the installed luminaries' systems
P_{MPP}	Nominal power
P_{PV}	PV system's Power
R_t	Net cash flow during a single period t
S_{AC}	Cable's cross-sectional area
S_{DC}	Cable's cross-sectional area
t	Time period for which the NPV is obtained

$V_{INV(MPP)}$	Value provided by the manufacturer that represents the minimum operating voltage of the inverter
$V_{Max,INV}$	Inverter's Maximum allowable voltage
$V_{Module\ at\ 70°C\ (MPP)}$	Module's voltage at the maximum power point at 70 ºC
V_{MPP}	Nominal voltage
$V_{MPP,\ INV}$	Interval of voltage input of the MPPT controller(s) provided by the manufacturer
V_n	Nominal voltage of the grid
V_{OC}	Open circuit voltage
$V_{OC(Module\ at\ Tmin)}$	Module's open circuit voltage at the minimum temperature of operation
$V_{OC(STC)}$	Module's open circuit voltage under standard test conditions. Value provided by the manufacturer
w	PV module's width;
Z_s	Surface azimuth angle
ΔV	Variation of module's voltage as a function of temperature in $°C$

Greek Symbols

β	Module's tilt angle
γ	Incidence angle of the sun on a flat surface
δ	Declination angle
η_{module}	Module's efficiency under STC
η_{system}	Systems efficiency
η_{inv}	Inverter's efficiency
η_{rel}	Annual efficiency related to the power losses in the module
θ	Angle of incidence
κ	Electrical conductivity of the conductive material
Φ	Solar zenith angle

Chapter 1

Introduction

1.1 Problem Background and Motivation

The transition to a climate-neutral society is both an urgent challenge and an opportunity to build a better future for all. To reenforce the need of growing sustainably, the European Union has strategized a plan and several targets to be achieved by the year 2020. The plan primarily focuses on three key targets:

- 20% reduction in greenhouse gases emissions, comparing to 1990 levels;
- 20% of energy consumption must be produced by renewables sources;
- 20% improvement in energy efficiency [1];

The European Union strategy is a long-term plan, and so, there are already proposed initial targets for 2030. These targets include:

- 40% reduction in greenhouse gases emissions, comparing to 1990 levels;
- 32% of energy consumption must be produced by renewables sources;
- 32.5% improvement in energy efficiency [2];

For 2030, the targets are more ambitious than for 2020. In September 2020, an update to 2030 targets was approved, implementing a 55% reduction in greenhouse gases emissions instead of 40%. A complete and formal proposal, with wide targets and policy objectives for the period from 2021 to 2030, will come forward by June 2021 [2]. The reinforcement of these policies proves the interest and need of the European Union on moving towards a climate-neutral economy. This means an economy with net-zero greenhouse gas emissions, which is the target by 2050 [3].

In order to achieve the proposed goals, there had to be an increase in investment by the governments in technologies based in renewable sources, energy efficiency and infrastructures that are less energy consuming, like Near-Zero Energy Buildings (NZEB), buildings with very high energy performance, having energy mostly coming from renewable sources. Moreover, the building sector is crucial in this plan, being one of the most important points, the retrofitting of already existing buildings. Better and more energy efficient buildings improve the quality of citizens' life while bringing additional benefits to the economy and the society.

This is where this dissertation is inserted, on the retrofitting of one of SIBS Payment Solutions' buildings, by promoting energy efficiency measures.

1.2 Methodology

The study was carried out with an internship at SIBS Forward Payment Solutions with the aim of performing the energetic and economic evaluation of implementing some energy efficiency measures to its building. To achieve this project goal, the tasks were performed as it is shown in figure 1.1:

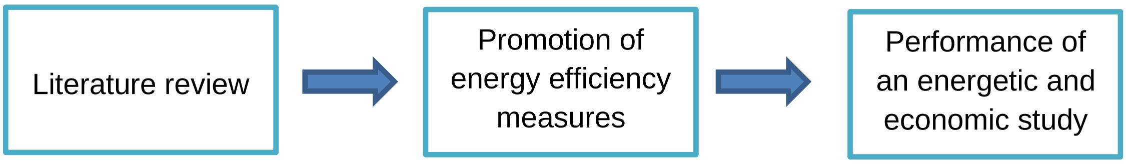

Figure 1.1: Work Squeme

The Literature Review encompasses important definitions associated with the project's theme and showcases previous work done in the area, presenting various articles with case studies to help choosing the measures to be applied in this case.

The measures applied were the replacement of the current luminaries with more energy efficient ones and the installation of photovoltaic modules on the roof of the building. The promotion of these measures implied some visits to the facilities to understand its dynamics and goals, the study of the different technologies applied and the market search for the better equipment to install.

The energetic study was carried out using different software to simulate the energy savings of the measures applied. After, the economic study was performed calculating the relevant financial indicators, to assess the viability of the different investments.

In the end of the internship, due to the extraordinary conditions the world lived in, a study on the spread of the COVID-19 virus on the workplace was carried out, as well as the assessment of the impact of the imposed regulations on the energy consumption of the building.

1.2 Document Structure

The present dissertation is structured in 6 chapters. Its description is shown in the following table 1.1:

Table 1.1: Document structure

Chapter	Description
1	Brief contextualization to the problem, presenting the motivations and objectives of the current work
2	Literature review to provide basis of knowledge and possible approaches to the problem presented
3	Introduction to the case study, presenting the company and the facilities in study
4	Replacement of the luminaries, presenting the methodology applied, the results and relevant analyses
5	Installation of a photovoltaic system, presenting the methodology applied, the results and relevant analyses
6	Study on the dissemination of the COVID-19 virus on the workplace and the impact it had on the energy consumption of the building
7	Conclusions to be drawn from the present study and considerations for future work

Chapter 2

Literature Review

The purpose of this chapter is to review the existing relevant literature to check the work already done in this field of study, in order to provide basis of knowledge and possible approaches to the problem presented in the previous chapter. The aim is to analyse ways of applying energy efficiency measures to buildings, particularly office buildings, and the challenges posed to applying them. To promote better understanding, this chapter is divided in 4 sections.
In section 2.1 an analysis is made on benchmarking of energy consumption values for office buildings and a review to previous papers presented on the subject. In section 2.2, a short revision of different measures promoting energy efficiency applied in different case studies was presented. In section 2.3, the topic of how to evaluate user comfort in the workplace is assessed and then some case studies about user comfort are showcased. Then, in section 2.4, a broad study on solar photovoltaic technology is made, presenting advantages historical evolution in the technology, progression in costs and context of it in the world and in Portugal.

The content of this chapter was obtained through a literature review that included books, papers, articles, and webpages. Most of these sources were found using search engines like Google Scholar and research database webpages, specifically ScienceDirect and ResearchGate. The key words applied were, among others, “Energy Efficiency”; “Office Buildings”; “Solar Photovoltaic”; “Promotion of Energy Efficiency measures”; “Office Energy Efficiency”

All the gattered content was in English or in Portuguese.

2.1 Energy Benchmarking values in office buildings

In Europe, Buildings are the single largest energy consumer, being responsible for approximately 40% of European Union energy consumption and 36% of the greenhouse gas emissions [4].

This makes Benchmarking of energy consumption values in the building sector very important, especially in office buildings, to help verify if the energy consumption of a certain building is within the expected range of values and enabling the creation of strategies to decrease energy consumption.

Basically, a “benchmark” is a reference or measurement standard used for comparison. It can be understood as a continuous activity of identifying and adapting the best practices and processes that will improve performance. The process of benchmarking is very useful, allowing the target setting for promoting best practices and achieving better energy efficiency in buildings and industrial facilities. The figure 2.1 expresses a typical benchmark process, starting in the identification of the metrics evaluated until the complete process of analysis and promotion of improvements.

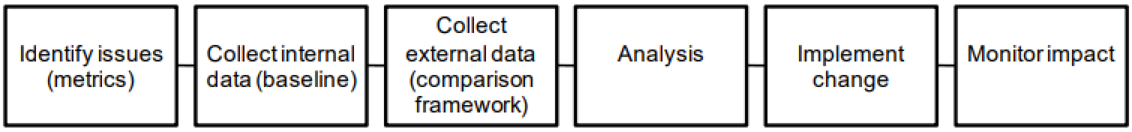

Figure 2.1: Typical benchmark process [5]

There are three general approaches to benchmarking:

- Tracking approach: comparison of the building’s performance to itself, i.e., previous performance data;
- Target finder approach: comparison to a sample of a similar buildings;
- Simulation model approach: energy simulation model, using predefined baseline characteristics, such as meeting an energy code or standard.

Table 2.1, represents some examples of building energy benchmarks, divided by sector of activity and by building characteristics, provided by the Chartered Institution of Building Services Engineers (CIBSE):

Table 2.1: Examples of building energy benchmarks [5]

Building type	Energy consumption benchmarks for existing buildings (kWh per m^2 per year)				Basis of benchmark
	Good practice		Typical practice		
	Fossil fuels	Electricity	Fossil fuels	Electricity	
Offices:					
- air conditioned, standard	97	128	178	226	Treated floor area
- air conditioned, prestige	114	234	210	358	Treated floor area
- naturally ventilated, cellular	79	33	151	54	Treated floor area
- naturally ventilated, open plan	79	54	151	85	Treated floor area
Hotels:					
- holiday	260	80	400	140	Treated floor area
- luxury	300	90	460	150	Treated floor area
- small	240	80	360	120	Treated floor area
Retails:					
- clothes stores	65	234	108	287	Sales floor area
- department stores	194	237	248	294	Sales floor area
- small food shops	80	400	100	500	Sales floor area
- supermarket	200	915	261	1026	Sales floor area

However, benchmarking of this values is not an easy task, energy consumption in this type of buildings depend on too many different factors like location, building structure, size, number of occupants, type of activity, type of energy consuming systems, such as heating and cooling system, lighting system, ventilation system and office equipment. This disparity of factors makes it difficult to find an appropriate acceptable range of energy consuming values. Nonetheless, companies are constantly working on trying to consume less energy, because that benefits them on an environmental and economic aspect.

Despite the difficulties associated with benchmarking, there are still people studying and trying to create ways of doing so, like Oliveira Veloso et. al. (2020) [6] that developed a methodology to create a benchmarking of electric energy consumption for office building towers in a mild temperate climate using as an example the city of Belo Horizonte, Brazil. The methodology aimed to predict an accurate energy consumption range and they found that simulation predictions can present a good estimation for the energy consumption of a fully conditioned office buildings but for office buildings conditioned in mixed mode, predictions show higher consumption levels than consumption measures let foresee. This means that a benchmarking scale set from measured data can better portray the actual electricity energy consumption of buildings and serve as an effective calibration tool for computer simulations.

2.2 Promotion of energy efficiency measures

In this section, there is presented a short revision of different measures promoting energy efficiency applied in different case studies:

Sun et al. (2018) [7] presented a case study of a retrofitting of an already existing building to a Near-Zero Energy Building (NZEB). In his work, he showcased a different number of measures that could be applied to diminish energy consumption (see Table 2.2). According to Sun, measures can be categorized into active or passive measures. Active measures involve improving lighting systems, heating, ventilation, air conditioning (HVAC) systems, and other service energy intensive systems. Passive solutions aim to improve the energy efficiency of building envelopes (e.g., façade systems).

Table 2.2: Energy efficient retrofitting strategies of NZEB [7]

Design Strategies		Retrofitting
Passive design solutions	Reduce heat gains	Green walls and green roofs
		Low-emissivity glass
		Solar film coating
		Sunshade devices
	Enhance daylight	Mirror ducts
		Light shelves
		Light pipes
	Increase natural ventilation	Solar assisted natural ventilation (Solar Chimney)
Energy-efficient building services	Energy-efficient Air conditioning and mechanical ventilation	Single Coil Twin Fan system
		Variable Speed Drive
		Displacement ventilation system
		Under-floor cooling
		Personal ventilation system
	Energy-efficient Lighting	LED
		Task lights
		Dimmers
	Intelligent BMS	Sensors
		Building Management system
Renewable Energy system	Solar energy system	Solar panels

The most relevant measures, for this work, are the active ones, particularly the one Sun analysed in the case study, replacement of T5 fluorescent tubes with LED (light-emitting diode) lighting. In addition, each LED panel was equipped with an intelligent sensor grid that could determine lighting levels according to occupancy conditions. These measures resulted in savings of around 71,264 kWh annually for the lightning retrofitting and 2990 kWh annually for the lighting control.

However, a few years ago, the replacement of the fluorescent luminaries for LED luminaries was not a usual measure because LED technology was not as developed as it is nowadays. In 2012, Ryckaert [8] evaluated the performance of LED linear lamps as replacement of conventional T8 fluorescent tube lamps. A case study was developed, where twelve fluorescent lamps in a small office room were replaced by LED linear lamps to compare the illuminance distribution on the workplace. It was concluded that the luminous flux values of the LED tubes tested are low and do not provide acceptable illumination levels, even though the luminaire efficiency increases slightly when replacing a T8 lamp by a LED.

Yiqun Pan et. al. (2017) [9] presented a study of the energy performance of various lighting systems and control strategies applied in open-plan offices. All the experiments were carried out on a test bed. The energy saving potential of various lighting control strategies was simulated and analysed, and a combined lighting control strategy of background dimming lighting plus task lighting was studied on the test bed. Moreover, visual comfort was investigated to determine the optimal background dimming lighting illumination and energy performance of the combined lighting system. It resulted in savings from general lighting control of 50% or higher. With task lighting control combined with dimmable general lighting, the energy savings rate can be increased to 59%.

Luewarasirikul et. al (2015) [10] assessed the consequences of replacing compact fluorescent lights (CFL) or incandescent lights with LED lights, in an office, located in Thailand. His research provided useful information as he concluded that in both cases, LED lights are more energy efficient and have a much longer life span (of around 50000 hours), also he summarized some characteristics of the different types of lamps in table 2.3. The payback period of replacing the lamps would be of around 10000 hours of use and would produce savings of $280.50 and $41.25, switching from incandescent and CFL respectively.

Table 2.3: Comparison of the characteristics of LED, CFL and incandescent lamps

Source: [10]

	LED	CFL	Incandescent
Frequent on/off cycling	no effect	shortens lifespan	some effect
Turns on instantly	yes	no, takes time to warm up	yes
Durability	durability	fragile	fragile
Heat Emitted	3.4 BTU / hour	30 BTU / hour	85 BTU / hour
Sensitivity to temperature and humidity	no	yes	some
Hazardous Materials	none	1-5 mg of mercury / bulb	none

Capozzoli et. al. (2017) [11] investigated the influence of occupancy patterns on the energy consumption of a building and regarding that investigation, he optimized the functioning schedule of the Heating, Ventilating and Air Conditioning (HVAC) system in the Zaanstad Town Hall, a five-storey office building in the Netherlands. The process is based on dividing the building into different thermal zones and subzones and rearranging the occupancy of the zones by displacing groups of occupants with similar occupancy patterns to the same thermal zone. This way, it is easier to analyse the problem because for the different zones the arrival and exit times of the workers are very similar, and so the working time for the HVAC system can be adjusted to those arrival and exit times. It was found, for the analysed office building, that about 38 h of operation of the HVAC system could be saved during the typical week, in comparison to the fixed 6:00–21:00 schedule assumed for the entire building. Applying this method during the monitored period (4 months), it saved 20 MWh (14%). This means that the energy use of the HVAC can be reduced in a significant way by applying this occupancy-based schedule and it proved to be a good low-cost real-life management solution, especially for buildings with no-intermittent occupation.

2.3 User comfort in the workplace

User comfort in the workplace is defined as the conditions wherein the average person does not experience the feeling of physical or psychological discomfort, and it is assessed by subjective evaluation. Due to this subjectivity, it is nearly impossible to gather the necessary work conditions to please everyone, thus the user comfort is predicted using a predicted mean vote (PMV) index and the predicted percent dissatisfied (PPD). The PMV index predicts the mean response of a large group of people according to the ASHRAE thermal sensation scale ranging from -3 to 3, from cold to hot respectively, where 0 is the neutral, the ideal state. After acquiring the PMV, the

PPD can be obtained through a mathematical relation. This model has its comfort zone in the PMV range of -0.5 to 0.5, where it corresponds to 10% of people dissatisfied, see figure 2.2. Even with a PMV equal to 0, 5% of people are still dissatisfied, so there are no models that can please everyone [12].

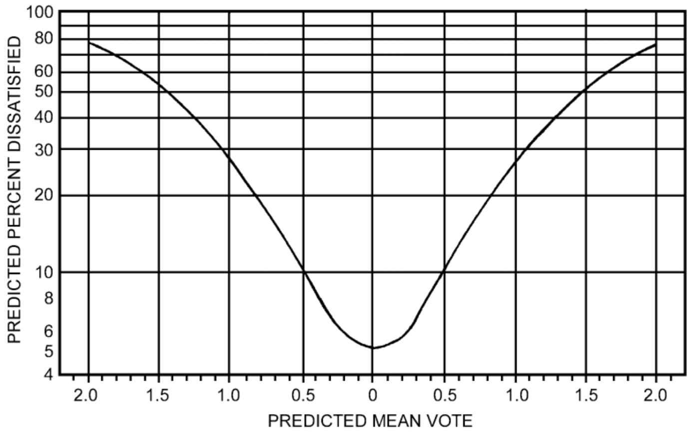

Figure 2.2: PPD in function of PMV [12]

This subject is a recurrent theme of investigation, being interesting to companies because it is directly related to productivity, so they are always looking to improve the user comfort in the workplace, in order to, increase company's productivity. However, there should be a balance between user comfort and energy consumption, as Shahzad et. al. (2015) [13] had investigated. He compared the user comfort and energy efficiency of two office layouts, respectively Norwegian cellular and British open plan offices. The Norwegian office expected users to find their own comfort, since they were provided with control over a window, blinds, door, and the option to adjust heating and cooling. In opposition, in the British office, the users' control over the environment conditions were more limited, since only the occupants seated around the perimeter of the building could control the openable windows and blinds and a centrally operated displacement ventilation was the main thermal control system. Users' perception of thermal environment was inquired, and it resulted in 35% higher user satisfaction and 20% higher user comfort in the Norwegian office compared to the British open plan office. However, the consumption of energy was much higher in the Norwegian office compared to the British. This reenforces the importance of balancing between thermal comfort and energy consumption, as either extreme presents difficulties for the other.

Salimi et. al. (2020) [14] studied how to optimize energy consumption and occupants' comfort in an open-plan office using local control based on occupancy dynamic data. He developed full-year dynamic occupancy profiles with high resolution of 1 min, using real occupancy data capturing the stochastic behaviour of occupants. With these profiles, he was able to create occupancy patterns and develop local control algorithms for building energy-consuming systems, like the HVAC system, which he found the best settings to operate it, including the functioning schedule and the resolution level used to control it. In his case study, the local control of HVAC resulted in improving the thermal condition by 50% and 2% savings in energy consumption. His work was significant in reenforcing the importance of optimizing operations in occupancy-centred buildings by finding the trade-off between buildings' energy consumption and occupants' comfort, maintaining the PMV index within the comfortable range.

2.4 Solar photovoltaic energy

2.4.1 Advantages of solar photovoltaic energy

Solar photovoltaic technology experienced a lot of development in the last years. Nowadays, this type of technology is a strong alternative to the electricity produced in power plants, and to other renewable energy technologies, due to these factors:

- It relies on an inexhaustible source of energy, the sun;
- Reduces or eliminates the dependence on the electric public grid, especially in the hours when the solar radiation is more intense during the day. This factor makes the cost of electricity lower;
- Due to reducing the consumption of electricity from the public grid, it reduces the emission of greenhouse gases, having less production of energy in the powerplants;
- Knowing the location of the panels, it is possible to predict energy production;
- Operation and maintenance costs are relatively low;
- It doesn't emit any noise [15];
- Very reliable technology, usually doesn't have any moving parts [15];
- Adaptable, It easily can be applied to existing urban architectures, like roofs, facades, glazed surfaces or even roads [15];
- Solar panels' acquisition costs are decreasing year by year, making it an appealing investment;

It is very clear the benefits of using PV technology on both economic and energetic aspects. To prove that, Jurasz et. al (2019) studied the contribution of photovoltaics to the reduction of peak load in office buildings, thus reducing the dependence on the grid and the energy costs. He presented a case study of an office building in Poland and performed an economic and energetic simulation using three different energy tariffs. The results showed a decrease of approximately 27% (from 60kW to 44kW) on peak load and reduction of 5.8% on energy costs using the most expensive energy tariff [15].

2.4.2 Solar photovoltaic energy in the world

The constant development of technology and the recurrent search for more greener energy production technology allied with the implementation of regulations by the governments limiting the emission of greenhouse gases and encouraging renewable sources of energy, created a significant increase in the implementation of solar photovoltaic technologies, in a global scale, in the last decade. The global solar installed capacity grew from 40 GW in 2010 to 579 GW in 2019 [16] (see Figure 2.3).

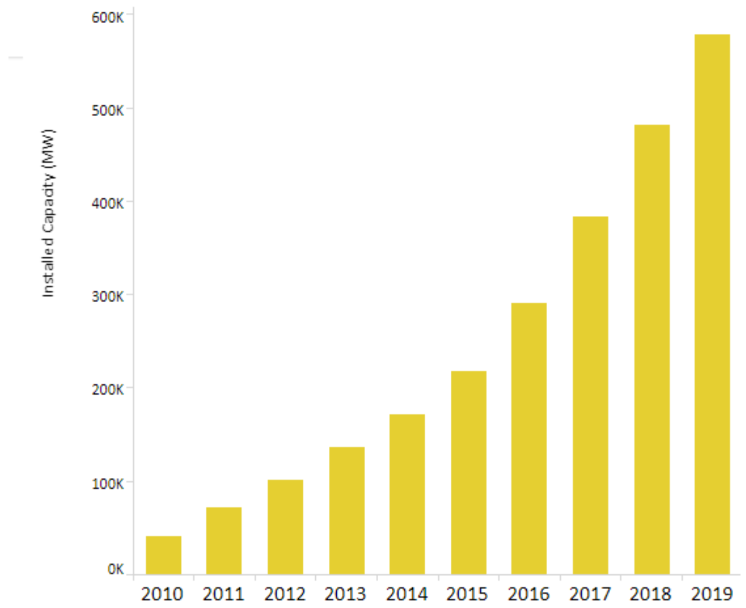

Figure 2.3: Global annual solar PV installed capacity 2010-2019 [16]

In figure 2.4, one can see that in 2019 there was an increase in solar installations in Europe, representing 16.7 GW of new installations added, thus a 104% increase over the previous year [17]. This increase was very accentuated in some countries, being Spain the largest solar market, adding 4,7 GW, followed by Germany with 4 GW and then the Netherlands with 2,5 GW. However, it is possible to see that some countries have been reducing their solar PV installed capacity throughout the years, this could be justified with the end of some government subsidies. Nevertheless, the global values of solar installations have been increasing every year, the decrease in Europe from 2011 to 2018, has been highly compensated by the recent growth in the Asian market, particularly in China and Japan.

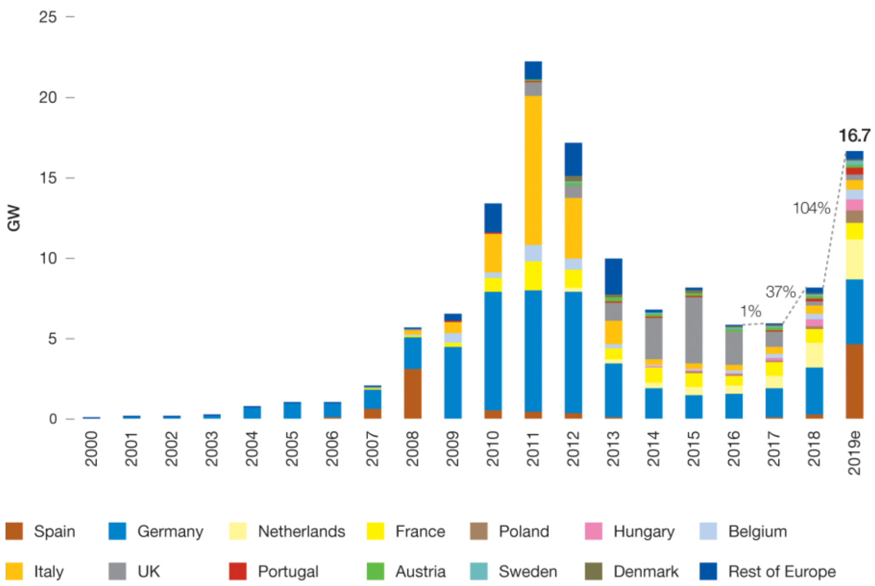

Figure 2.4: EU-28 annual solar PV installed capacity 2000-2019

Source: [17]

2.4.3 Solar photovoltaic energy in Portugal

In the year 2019, Portugal registered an electric energy consumption from the public grid of 50.3TWh, 51% of this energy was produced from renewable sources, being 2.1% produced by solar photovoltaic [18] (see figure 2.5). Portugal's renewable production suffered a significant growth in the last few years, being well positioned to meet the EU's target for Portugal's renewable production, that is 31% of the gross final consumption of energy, having registered 30.3% in 2018 [19], check figure 2.6.

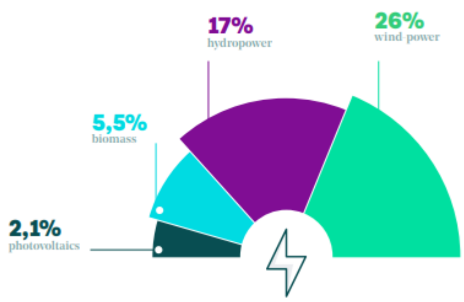

Figure 2.5: Percentage distribution of renewable production [18]

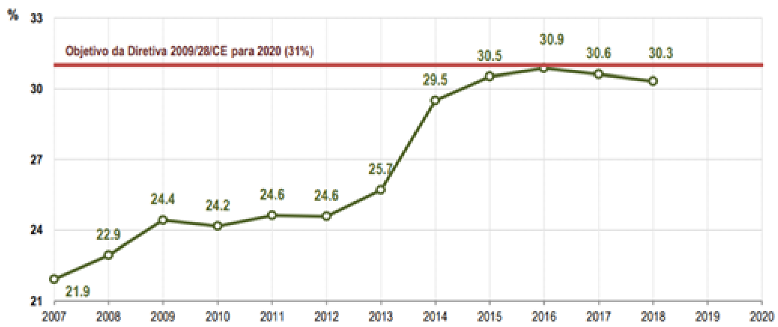

Figure 2.6: Evolution of renewable production on gross final consumption of energy in Portugal in the year range 2017-2018 [19]

The Installed capacity also has been growing in Portugal, mainly for renewable, increasing from 8459 MW in 2008 to 14370 MW in 2019, representing 64.7% of total installed capacity in Portugal [20], as can be seen on the figure 2.7.

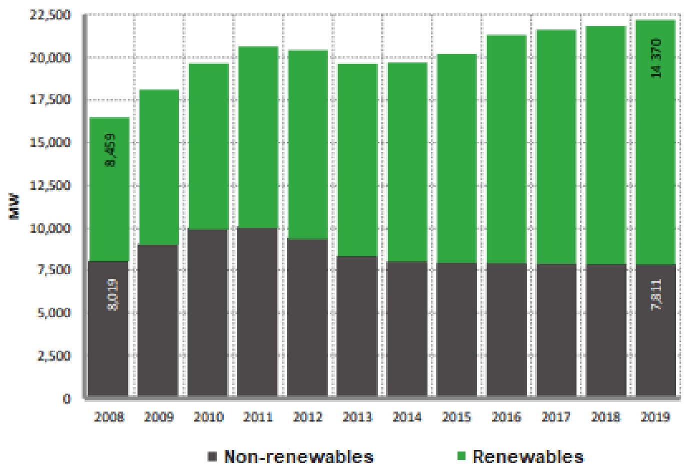

Figure 2.7: Evolution of installed capacity in Portugal in the year range 2008-2019 [20]

The solar photovoltaic sector is the one that has suffered the major increment in installed capacity, with 914 MW in 2019, more 36% in comparison to 2018, and 8 times higher than in 2009 [20]. In 2019, the solar photovoltaic component represented 6.4% share in the total renewable capacity installed, in 2009, that share was 1.2%, has it is shown in figure 2.8.

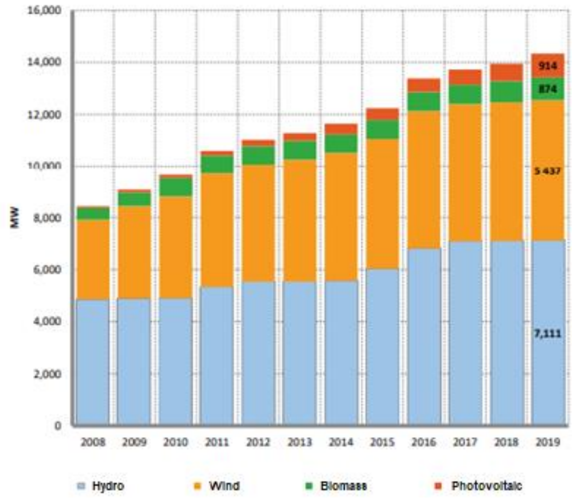

Figure 2.8: Evolution of the energy renewable production in the year range 2008-2019 [20]

2.4.4 Evolution of solar photovoltaic costs

In the 90's, the easy access of fossil fuels made them an attractive way of producing energy, in contrast to renewable energies, that were perceived as an unattainable and expensive form of producing energy, thus, this delayed the development of this kind of technology. However, the costs of fossil fuels depend largely on two factors, the price of the fuel that they burn and the power plant's operating costs. Renewable energies are different, their operating costs come from the technology itself since its fuel (solar energy in the case of PV systems) is free, making the total cost comparatively low.

In the last 15 years, environmental awareness increased significantly, leading to the industrialization and development of the renewable market, turning it into a global scale. Therefore, new countries adopted and started producing this kind of technology, creating competition in this sector. This worldwide awareness and improvement in production, lead to more demand, that consequently increased the production, which lead to falling prices (see figure 2.9). This created an economy of scale in this sector, that explains why the cost of manufacturing solar panels has plummeted dramatically in the last decade, making solar the world's cheapest source of electricity today [21].

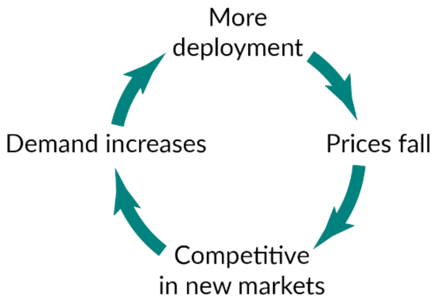

Figure 2.9: Diagram of an economy of scale [21]

The figure 2.10 represents the decrease of the price per watt of solar photovoltaic modules from 1976 to 2019. It shows that the price of solar modules decreased from $106 to $0.38 per watt, representing a decline of 99.6%. Both axis on the graph are represented on a logarithmic base and on a logarithmic axis a measure that appears to follow a straight line, represents an exponential growth. This means, that the price per watt decreased exponentially as the installed capacity increased exponentially. This relation between experience and the price of that technology is called the learning curve of that technology and can be seen in the figure 2.10.

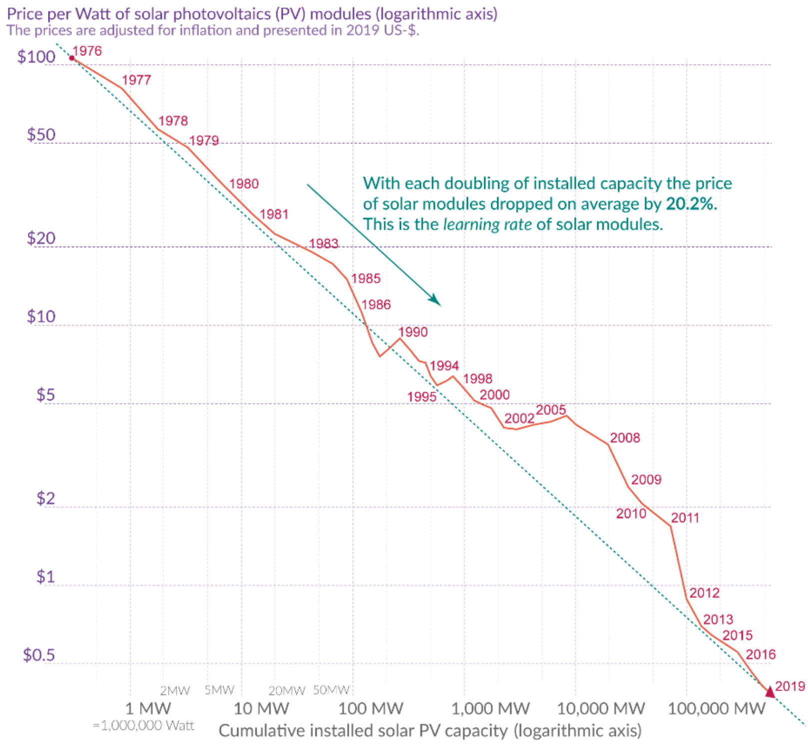

Figure 2.10: Evolution of price per watt in function of installed PV capacity, in the year range 1976-2019 [21] and [22]

More deployment means falling prices, which means more deployment. This increase in deployment for solar technology was possible due to government subsidies and mandates, which helped drove down the prices. In the year 2020, the price per watt registered the lowest ever for photovoltaic modules, having reach the price point of $0.17 per watt, as it is possible to verify in the figure 2.11.

Figure 2.11: Evolution of price per watt over the year range 2008-2020 [23]

In figure 2.12 is presented the levelized cost of energy (LCOE) for solar PV, by country, between the year 2010 and 2019. LCOE is an economic indicator that evaluates the total cost of an energetic system, being defined as the ratio between all lifetime costs of the system (operation, maintenance, construction, taxes, insurance, and other financial obligations of the project) and the expected total energy produced by the system. This is a valuable indicator when comparing different situations, because having lower LCOE values resembles a lower energy cost, which means a more profitable investment. It is possible to analyse the progression of the cost and check that in majority of the cases the prices decrease significantly, year by year. Countries like Vietnam, Turkey or Netherlands are only listed in the graph after 2015, which helps to confirm the constant appearance of new countries in the solar PV market.

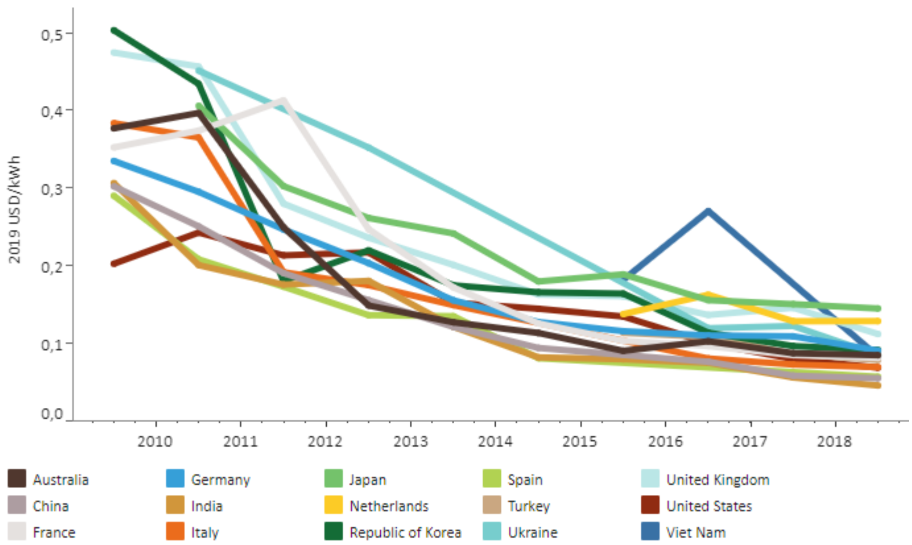

Figure 2.12: Weighted-average LCOE of newly commissioned utility-scale solar PV by country, 2010-2019 [16]

Relatively to the market's influence, China and India are the world's producers offering lower prices, being India the leading country, with the lowest module cost. In 2019, the average module cost in China was around 0.046 €/kWh and in India was around 0.038 €/kWh. In Europe, the country with the lowest module cost is Spain, that in 2019, registered 0.048€/kWh. In contrast, countries like Japan, South Africa or Canada, present a higher module cost (see figure 2.13).

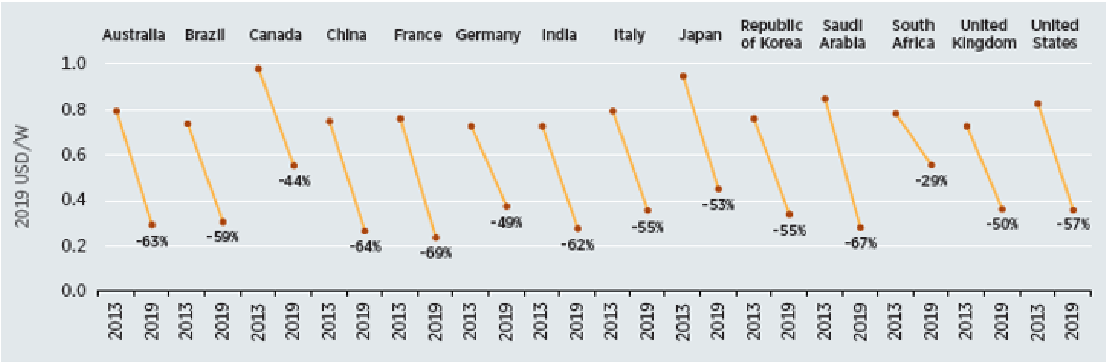

Figure 2.13: Average yearly module prices by market, 2013-2019
Source: IRENA Renewables Database

2.4.5 Legal context in Portugal

In Portugal, the solar photovoltaic production is regulated by the decree-law n.º 162/2019 [24], published on October 2019 and entered into force on 1st of January of 2020. The previous legislation only contained individual production and self-consumption, but now it is possible to create a community of various individuals, establish production and have a collective self-consumption between them, this community is denominated as CER (comunidades de energia renovável in Portuguese).

The Law differentiates solar photovoltaic production in two types of regimes: UPP (Unidade de Produção Pequena, in Portuguese) and UPAC (Unidade de Produção para Autoconsumo, in Portuguese).

UPP is defined as a small production unit that delivers all the energy produced to the public grid (Rede Elétrica de Serviço Público – RESP, in Portugal), there is no self-consumption in these type of production units, and it is limited to 250 kW in the connection power.

UPAC is defined as a production unit that has the purpose of producing energy to be self-consumed in the installation, having the possibility to sell the remaining energy, that was not consumed, to the RESP. The producer can decide if the unit is connected or not to the RESP. If it is connected, RESP will provide the necessary energy, when the production unit cannot produce the energy needed by the installation.

In the case study the regime applied is UPAC, so to better understand the subject, it will be presented important information about this regime of production.
In UPAC regime the following conditions must be met:

$$Connection\ Power_{(UPAC)} \leq Contracted\ Power \quad (1)$$

$$Installed\ Power_{(UPAC)} \leq 2 \times Connection\ Power_{(UPAC)} \quad (2)$$

Where:

- Connection Power is the nominal output power that can be sold to RESP;
- Contracted Power is the maximum power that the installation can receive;
- Installed Power is the peak power of the equipment producing energy;

Depending on the installed power, the producer has duties that has to fulfil, according to the decree-law n.º 162/2019 [24]:

- Installed Power $\leq$ 350 W – The producer doesn't require any type of registration or communication;
- 350 W $<$ Installed Power $\leq$ 30 kW – The producer needs to communicate it to the regulatory authority, that in Portugal is Direção-Geral de Energia e Geologia (DGEG);
- 30 kW $<$ Installed Power $\leq$ 1 MW – The producer needs to register the installation in DGEG and obtain an exploration certificate;
- Installed Power $>$ 1 MW – The producer must obtain a certificate of exploration as well as an electricity production license;

It is also important to notice that there no limit to number of solar panels installed and each producer can sell the remaining energy with a variable price accorded between the energy buyer and the producer.

Chapter 3

Case Study: SIBS Forward Payment Solutions

SIBS Payment Solutions is a Portuguese company that provides financial, modern, and secure services, in the sector of payments, to more than 300 million users in a global scale. This company gathers all the bank operation in Portugal, including the entire debit card system, the network, the local payment machines, and the automated teller machines (ATM's). Moreover, they have created digital payment platforms like MBWay and MBnet, providing different alternatives to their users, always investing in innovation. In addition to Portugal, their field of action includes several countries in Europe and Africa, like Angola, Poland, Romania, Mozambique.

To support this broad field of action, SIBS has different infrastructures, serving powerful datacentres, which implicate a substantial energy consumption. This is where this dissertation is inserted. The aim is to decrease energy consumption by performing a case study of one of their buildings.

3.1 Building description

The case study's objective is to promote energy efficiency measures to SIBS II Alfragide, one of SIBS' building, located in Estrada Casal do Canas, Amadora (see figure 3.1). This building was constructed in 2006. However, it was only occupied and completely remodelled by SIBS in 2008. It has 6.000 m² of available area, being constituted by 5 floors, distributed has the following:

- Floor -3: Wearhouse and parking;
- Floor -2: Meeting rooms, scanners room, sanitary installations, meals room, technical areas and common areas;
- Floor -1: Meeting rooms, sanitary installations, open space offices, meals room, technical areas, datacentres' room and common areas;
- Floor 0: Meeting rooms, show room, technical areas, open space offices, sanitary installations, and common areas;
- Floor 1: Cafeteria, sanitary installations, technical areas, and common areas;

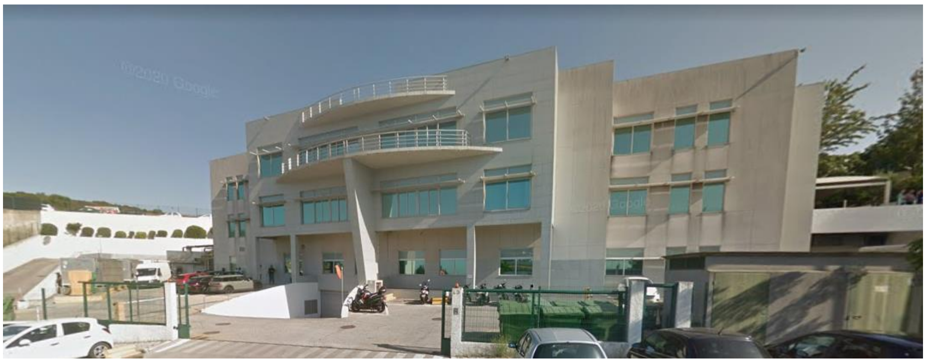

Figure 3.1: Front façade of the building

Source: *Google Maps*

According to the Portuguese legislation (Decree-law n.º 118/2013 [25]), the building is located in a climatic zone I1, V1, and has a hot-summer Mediterranean climate, according to Köppen climate classification system.

The exact location of the building is 38 º 736' N latitude and 9 º 232' W longitude. The front façade is the south façade and the angle that it makes with the south direction is approximately 11º West. With these values, it was possible to obtain the exact location of the building and thus determine the incident radiation. These data were obtained using the *PVGIS* software for each month of the year. The table 3.1 shows the values obtained [26]:

Table 3.1 Average monthly sum of global horizontal irradiation per square meter in the building's location [26]

Month	**G** $[kWh/m^2]$
January	116.2
February	129.6
March	168.3
April	185.4
May	207.3
June	207.5
July	226.4
August	224.6
September	196.2
October	155.1
November	118.3
December	112.9

The building is very populated, receiving daily 800 workers, from security staff, office staff to maintenance staff, creating an elevated energy demand.

The progress of the work was carried out normally, however due to strict confidential agreements with the company, so that restricted the access to some useful information. Nevertheless, this case study is focussed on the promotion of two energy efficiency measures to the building, aiming to decrease the energy consumption of the building, and consequently the money spent on electricity by the company. These promoted measures were:

- The replacement of the installed luminaries for LED luminaries, on the open space offices (see figure 3.2);
- The installation of photovoltaic modules on the roof;

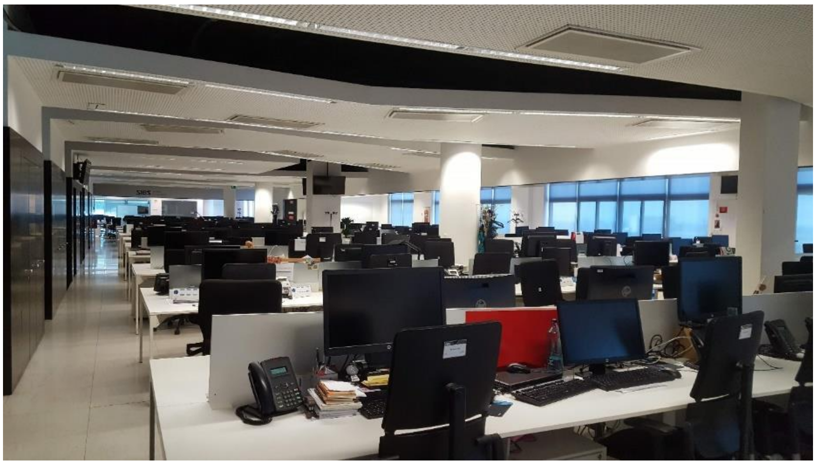

Figure 3.2: Picture of one of the open space offices

On the next chapters, the methodology used on the promotion of the proposed measures will be approached, as well as the energetic and economic studies needed to verify if the measures are viable or not to the company.

3.2 Principal energy consuming systems

In the year of 2019, SIBS registered, in this building, an annual energy consumption of 1.58 GWh, distributed as it is shown in figure 3.3, obtained with the *WiseMetering* online platform [27]. The months with the highest values of energy consumption were August and September. This might be due to the increase in HVAC utilization caused by the high temperatures outside. From April to July, the consumption decreased, despite being summertime and the utilisation of the HVAC still be high. This decrease is justified by the fact that during this months, part of the workers is on holidays. This high demand of energy is justified by the elevated population of the building and the various energy consuming systems installed in it, which will be presented in this section.

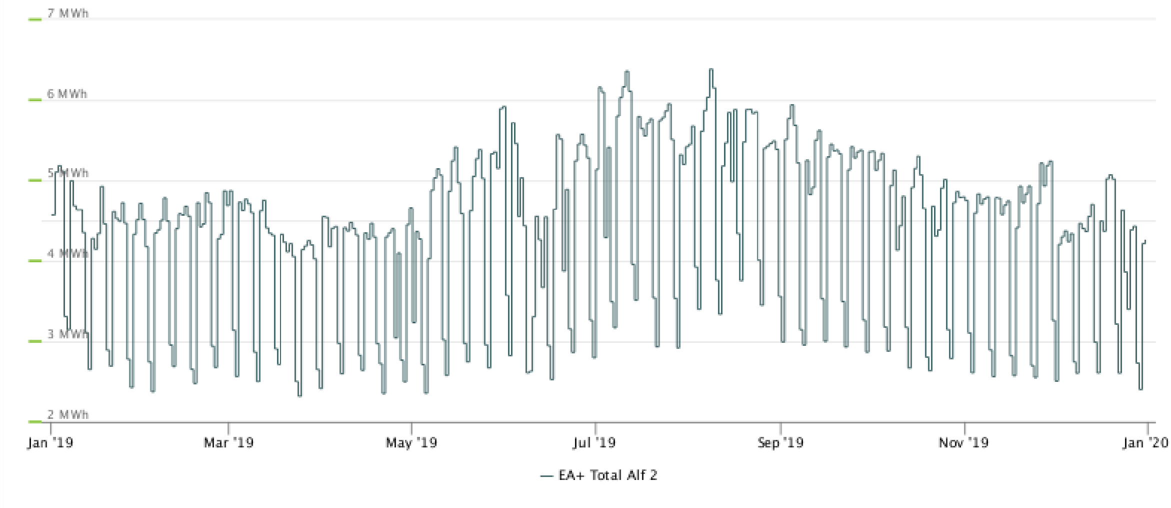

Figure 3.3: Energy consumption monthly distribution for the year 2019 [27]

3.2.1 Thermal power station

To produce cooled and heated water, in this building, there is installed a thermal power station, located in the exterior of the -2 floor (see figure 3.4). This thermal power station is constituted by two chillers, one of which is equipped with a four-tube heat pump and the other one is a “just cold” chiller capable of free-cooling. The principal characteristics of these equipment are listed in the table 3.2.

The production of cooled and heated water is destined to:

- the air handling units (AHU);
- the induction units (IU) of the offices, open spaces, and cafeterias from floor -2 to floor 1;
- the precision air handling units in the warehouses;
- the duct fan coil units in the open spaces;

The heat pump has the capacity to produce chilled water, hot water and, simultaneously, chilled water and hot water, through independent circuits (4-pipe system). It, also, has two semi-hermetic screw compressors.

The “just cold” chiller, with free cooling, has the capacity to produce cold water, suitable for systems without glycol mixed water, with an additional coil for pre-cooling the water when the outside temperatures are low. It, also, has four hermetic scroll compressors.

Table 3.2: Thermal equipment characteristics

Equipment	Brand	Model	Cooling Power [kW]	Heating Power [kW]	Refrigerant	EER	COP
Heat pump	Climaveneta	ERACS – Q/SL 1962	-	418	R134a	-	3.58
Chiller	Climaveneta	NECS-FC-NG/SL 1204	377	385	R410a	3.3	-

Figure 3.4: thermal power station on the exterior of floor -2

According to the needs of the installation, the production of chilled water and hot water is done mainly by the heat pump, but in case of a greater consumption of cold water, the production will switch to the "just cold" chiller. There is a temperature probe place on the return to the equipment, which has a reference temperature. In case the temperature at that point reaches 13.5 ºC, the centralized technical management system gives the "just cold" chiller order to start production.

The circulation on the heat pump is made at a fixed flow rate in the primary circuit, through two hydraulic modules (hot water and chilled water), while in the secondary circuit the distribution of the fluid is promoted by two electric pumps (hot water and chilled water) with a speed controller, operating in variable flow regime.

In the case of the "just cold" chiller, the distribution in the primary circuit is done through a hydraulic module, in a constant flow rate.

3.2.2 Circulation pumps

To meet the heating and cooling needs simultaneously, the distribution of the climatized water is carried out in four tubes. On these tubes, the water needs to be pumped, for it to reach the entire building. So, each circuit consists of electric pumps, and a modulating valve for temperature regulation.

The electric circulation pumps work in variable flow regime to control the pressure differentials and are equipped with two-ways valves, in the terminal station (see figure 3.5).

The system was designed to operate with the following temperatures:

- Cooling → 10 °C / 17 °C (outwards / inwards);
- Heating → 45 °C / 40 °C (outwards / inwards);

Figure 3.5: Pumping terminal station outside floor -2

3.2.3 Air handling units (AHU)

The treatment of fresh air is done through seven AHU's. Three AHU's are located on the roof, and those units acclimatize the kitchen and floors 1 and 0. The other AHU's are located on the floor -2 and acclimatize the remaining areas of the building. All units have heating and cooling batteries, except the one operating in the kitchen, that only has a heating battery. The characteristics and operating parameters of these equipment are synthetized in table 3.3:

Table 3.3: Specifications and operating parameters of the AHU's

	AHU Floor 0	**AHU Floor -1**	**AHU Floor -2a**	**AHU Floor -2b**	**AHU Floor -2c**	**AHU Floor 1**	**AHU Floor 1/ Kitchen (Extract fan)**
Heating Power [kW]	100	130	17	20	125	35	-
Cooling Power [kW]	200	230	17	20	125	35	-
Recuperation Power [kW]	70	230	-	-	50	-	-

Affected Area	Floor 0	Complete Floor	"Abertura de contas" area	Cafeteria	Scanner Room	Canteen	Kitchen
Set Point Maximum Temperature [°C]	-	32	-	-	24	-	-
Set Point Base [°C]	20.5	20.5	21	20	21	23	23
Set Point Minimum Temperature [°C]	-	18	-	-	24	-	-
Set point Relative Humidity	60%	65%	-	63%	65%	60%	-
Operating Time	24h/24h	Mon-Fri 6 am - 3 am	Mon-Fri 6 am - 00 pm	Mon-Fri 7 am - 00 pm	Mon-Fri 6h30 am - 3 am	Mon-Fri 7 am - 9 pm	Mon-Fri 7 am -4 pm

The AHU from floor 1 has a hot and cold battery and has a group of pumps associated to each of the exchangers. The kitchen is equipped with an extract fan that is turned on, to compensate the flow rate of the AHU.

The AHU's from floor 0 and -1 are equipped with heat recovery systems. Allowing the new air to heat / cool, before passing through the hot / cold batteries, respectively.

The floor -2 has three different AHU's, due to the diversity of rooms in this floor, and so the higher and different demand for air renovation. The AHU Floor -2c is specifically used for the scanner room to avoid overheating in this room, where there are machines constantly running, thus this AHU's is limited to a maximum temperature.

The working schedules of the AHU's are not completely fixed and can be changed and adapted to the work needs of the users of the facility.

3.2.4 Induction Units (IU)

The thermal conditions in the spaces are controlled mostly through the induction units, Swegon's Parasol model, with heating / cooling capacity of 1.20 kW. There are controllers associated with the IU's strategically placed by room or zone, which allow local adjustment up to a maximum variation of 1°C in relation to the setpoint defined for the climatic season. The temperature setpoints are:

- Winter - 21°C

- Summer - 24°C

In each group of IU's there is a modulating valve that varies the opening according to the needs in the space and depending on the dew point in the piping passages, in order to avoid condensation.

The pumps used for the circulation of heated / cooled water are centrifugal and have been dimensioned to overcome the loss of loads in the pipes, valves and other accessories. The pumping systems are divided in two, the primary and the secondary. They are closed systems, hydraulically isolated, where water circulates in a loop. The primary pumping system pumps water to the Chillers, while the secondary pumps the water to the terminal equipment, equipped with 2-way valves.

In the primary circuit, the flow rate is fixed, ensuring the proper functioning of the equipment, and avoiding the triggering of the safety systems by a sudden decrease in flow. In the secondary circuits, the pumps allow the flow to vary, depending on the consumption needs of the installation.

3.2.5 Fans and fan coil units

The Scanners room and the Open Spaces are equipped with duct fan coils, embedded in the ceiling. These are equipped with a three-way valve system and only allow water to pass through, either hot or cold water.

The temperature can be adjusted locally up to +/- 2.5 ºC in relation to the defined setpoint value. The sanitary facilities are equipped with helicocentrifugal extraction fans, being permanently in operation. The equipment installed are summarised in the table 3.4.

Table 3.4: Specifications of the equipment installed

Quantity	**Brand**	**Model**	**Electric Power [W]**
2	S&P	TH-1300	170
4	S&P	TH500/150	50
1	S&P	TH-2000	255
2	S&P	TH500/150	50

3.2.4 Illumination

The type of luminaries used in the workspaces is mostly fluorescent, with electronic ballasts, differing only on the length and power. The circulation areas are equipped with LED strips, installed in the ceiling crown mouldings.

3.2.5 Solar water heating system

Additionally, to heat water for the sanitary installations, for the kitchen, and the showers for the maintenance staff, a solar water heating system is installed on the roof. This system integrates four flat solar collectors, an inertia tank, to store temporarily the excess water from the heating system, and hydraulic and control components.

3.3 Energy prices

The current contract of energy distribution, signed with the energetic company, integrating a tetra-hourly price rate, following the prices stated on the table 3.5 and the legal hourly periods from Monday to Friday, stated on the table 3.6

Table 3.5: Electricity prices

Period	Price [€/kWh]
Peak	0.049
Full	0.04690
Empty	0.04158
Super-Empty	0.04111

Table 3.6: Legal hourly periods from Monday to Friday [28]

Period	Summer time	Winter time
Peak	09:15 – 12:15 h	09:30 – 12:00 h / 18:30 – 21:00 h
Full	07:00 – 09:15 h / 12:15 – 00:00 h	07:00 – 09:30 h / 12:00 – 18:30 h / 21:00 – 00:00 h
Empty	00:00 – 02:00 h / 06:00 – 07:00 h	00:00 – 02:00 h / 06:00 – 07:00 h
Super-Empty	02:00 – 06:00 h	02:00 – 06:00 h

3.4 Financial indicators

To assess the economic viability of a certain investment, some specific tools and indicators of financial analyses should be used. In this work, the proposed investments will be evaluated using three financial measurement tools – the net present value (NPV), the payback period (PP) and the internal rate of return (IRR). These tools will assure the quality in the investment's decision. In this section, a brief review of this indicators will be done.

3.4.1 Net present value (NPV)

NPV is a forecast of the cash flow generated by the project over its economic life. It is considered one of the best indicators to evaluate projects, because it considers the lifetime of the equipment, the risk of investment and the monetary savings. It is calculated through [29]:

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \tag{3}$$

Where:

R_t	Net cash flow during a single period t, in [€];
i	Discount rate, in [%];
t	Time period for which the NPV is obtained;
n	Number of years of the project;

If the NPV is:

- Less than zero - indicates that the project is not feasible because the generated cash flows do not cover the initial investment nor return the payback required by the investors;
- Equal to zero - The project is economically viable, as cash flows cover the complete initial investments and the investors receive the required return, however the profit is null and thus there is a possibility that the project may become unfeasible;
- Higher than zero - The project is economically viable, because cash flows cover the complete initial investments, investors receive the required remuneration and profit is generated. So, a project is only considered for investment if its NPV is positive.

3.4.2 Payback Period (PP)

The payback period of a project indicates the number of years that it takes to obtain the return of the initial investment. It is calculated through the following equation [29]:

$$\sum_{t=1}^{n} R_t = I_0 \rightarrow Payback\ Period = n \tag{4}$$

Where:

R_t	Net cash flow of the year t, in [€];
I_0	Initial investment, in [€];
n	Number of years;

3.4.3 Internal rate of return (IRR)

The Internal Rate of Return (IRR) is the rate of return that makes the NPV equal to zero. By this criterion, a project will only be economically viable if the discount rate is inferior to the IRR. The IRR is calculated through the following equation [29]:

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+IRR)^t} = 0 \tag{5}$$

3.4.4 Conversion to toe and emissions of CO_2

The conversion value used in this dissertation, from kWh of electric energy to tonnes of oil equivalent (toe) and the emission factor of CO_2 associated with the consumption of electricity were taken from the legislation nº 17313/2008 from Direção-Geral de Energia e Geologia (DGEG). The conversion factors are [30]:

$$1\ kWh = 215 \times 10^{-6}\ toe \tag{6}$$

$$1kWh = 0.47\ kg\ CO_2 \tag{7}$$

Chapter 4

Illumination replacement project

This chapter aims to present the different phases related to the replacement of the existent luminaries with LED based luminaries, in the open spaces. To this end, it will be presented the methodology used on the project conception, having first a brief review of contents, as well as the legal context in Portugal.

One of the objectives of this work is to study the energy and cost savings of changing the lamps installed with LED type lamps. LED based luminaires are an attractive alternative comparing to the ones already installed because they present properties such as:

- Long lifetime;
- Flexible design;
- Dimmability;
- Almost negligible heat transfer in the light beam;
- More energy efficient luminaires.

On the other hand, LED type lamps are more expensive than the halogenic lamps, which means the replacement of the lamps would imply an investment by the company, for that reason it is necessary to evaluate the project on a financial side, to see in how much time and if the investment will be worth it. Another aspect to take in consideration is if the LED type lamps provide the acceptable level of illuminance referred previously in this section.

4.1 Content revision:

To better compare the different types of lamps and do an adequate decision, it is important to clarify some contents that might influence the decision.

4.1.1 Luminous flux:

It is defined as a measure of the perceived power of light, i.e., the total quantity of visible light emitted by a light source per unit time, weighted according to the human eye's sensitivity to wavelengths of light. The measuring unit is $lumen\ (lm)$.

4.1.2 Illuminance:

Illuminance is the total luminous flux of light incident per unit area, in other words, the measure of how much the incident light illuminates aa certain surface. The measuring unit is lux, i.e., lm/m^2 . This value is calculated by:

$$I = \frac{L_l C_u L_{LF}}{A_l} \qquad (8)$$

Where:

I	Illuminance, in [lux];
L_l	Luminous flux per lamp, in [lm];
C_u	Coefficient of utilization;
L_{LF}	Light loss factor;
A_l	Area per lamp, in [m^2].

4.1.3 Luminous efficacy:

Luminous efficacy evaluates the ability of a light source to produce visible light from electric power. It is the ratio between luminous flux and power, measured in lm/W.

4.1.4 Photometric code:

The photometric code is a six digit code that displays the most relevant quality parameters of an LED lamp. As an example, using letters instead of numbers, to clarify the meaning of each digit, the code: ABC/DEF represents:

- A – represents the colour rendering index (CRI);
- BC – represent the colour temperature in kelvins divided by 1000, i.e., if the digits were 65, the correspondent colour temperature would be 6500 °K;
- DE – represents the initial and maintained chromaticity respectively;
- F – represents the maintained luminous flux;

4.1.5 Colour rendering index (CRI):

The colour rendering index is a quantitative measure of the ability of a light source to accurately reproduce the colours of the object it illuminates, in comparison with an ideal light source, the sun light. CRI is evaluated on a numerical scale where a higher number represents a higher ability, with 100 being the highest. The colour rendering value intervals are expressed in table 4.1. Also, an illustrative explanation of the CRI is shown in figure 4.1.

Table 4.1: CRI interval values [31]

Digit in the photometric code	CRI range	Colour rendering properties
6	57-66	Poor
7	67-76	Moderate
8	77-86	Good
9	87-100	Excellent

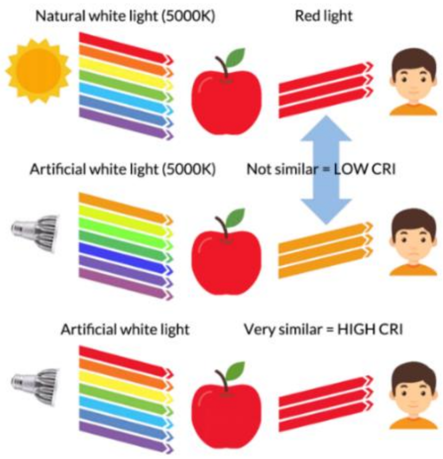

Figure 4.1: Illustration of the CRI evaluation [32]

4.1.6 Colour temperature:

Evaluation of Colour temperature is a way to describe the light appearance provided by a light bulb. It is measured in degrees of Kelvin (K) on a scale from 1,000 to 10,000. Being divided in three main groups:

- Below 3000 K – Warm Whites;
- From 3000 K to 4500 K – Cool Whites;
- Above 4500 K – Cool Daylight;

4.1.7 Initial and maintained chromaticity:

The digits in the photometric code indicate the values correspondent to the initial and maintained chromaticity, to find corresponding deviation number of MacAdam ellipse. The MacAdam ellipses refer to the region on a chromaticity diagram that contains all colours which are indistinguishable, to the average human eye, from the colour at the centre of the ellipse. The size of those ellipses represents different colour variation, and those values are expressed in the table 4.2. It is important to refer that the maintained value is measured at 25% of the rated lifetime up to a maximum of 6.000 hours.

Table 4.2: Colour variation categories [31]

Size of MacAdam ellipse, centred on the rated colour target	Colour Variation category	
	Initial	Maintained
3-step	3	3
5-step	5	5
7-step	7	7
>7-step	7+	7+

4.1.8 Maintained luminous flux:

This parameter expresses the lumen reduction in the luminous flux. It is important to refer that the maintained luminous flux is measured at 25% of the rated lifetime up to a maximum of 6.000 hours, and the value classification for the photometric code is shown in the table 4.3.

Table 4.3 Lumen maintenance percentages [31]

Lumen maintenance [%]	Digit in the photometric code
≥ 90	9
≥ 80	8
≥ 70	7

4.2 Portugal legal context:

It is relevant to mention that over time norms and legislation were created, to minimize the negative impact of using lamps that are not adequate. In Europe, the workspaces' lighting has to follow the European Standard (EN 12464-1) [33]. In this norm, all the rules and recommendations are summarised, but the most important ones are the minimum illuminance values for the task in practice and the minimum CRI accepted value from the light source, these values are listed in the table 4.4.

Table 4.4: Minimum illuminance values for the task in practice and the minimum CRI accepted value from the light source [33]

Type of interior, task or activity	Illuminance [lux]	CRI
Filing, copying, etc	300	80
Writing, typing, reading, data processing	500	80
Technical drawing	750	80
CAD work stations	500	80

Conference and meeting rooms	500	80
Reception desk	300	80
Archives	200	80

For this case study, the workers have a typical office job, listed in the table 4.4 as writing, typing, reading and data processing, thus the required value of illuminance is 500 lux and a CRI of 80.

Portugal's legislation on the matter (Decree 17-A/2016) [34] regulates that the values presented in EN 12464-1 (table 4.4) cannot be exceeded in more than 30%. Also, it regulates maximum values for lighting power density (LPD), those values are represented in table 4.5, being only listed the most relevant scenarios. The LPD is the lighting load of a certain area expressed in W/m^2 and it is calculated as:

$$LPD = \frac{(P_t \cdot F_o \cdot F_D) + P_c}{A} \tag{9}$$

And to simplify and standardize the values, the following calculation as to be done:

$$\frac{LPD}{100\ lux} = \frac{LPD}{I_m} \cdot 100 \quad [W/m^2/100lux] \tag{10}$$

Where:

LPD	Lighting power density, in $[W/m^2]$;
P_t	Total power of the installed luminaries' systems, in $[W]$;
F_o	Occupancy control factor;
F_D	Control factor for availability of natural light;
P_c	total power of the control equipment for the luminaires in operation, in $[W]$;
A	Useful interior area, in $[m^2]$;
I_m	Maintained average illuminance, in $[lux]$;

Table 4.5: maximum values for lighting power density (LPD) [34]

Type of interior, task or activity	**LPD** $[\boldsymbol{W/m^2/100lux}]$
Office space with more than 6 people	2.1
Individual office with 1 to 6 people	2.4
Classrooms, reading rooms, libraries, support rooms meetings, auditoriums	2.4

The offices from the case study are open spaces with a lot of people working at the same time, so they fit in the category “Office space with more than 6 people” from the table 4.5, needing to have a maximum LPD of 2.4 $W/m^2/100lux$.

4.3 Methodology:

In this work, illumination will only be analysed in the open space areas, since in an open space office, illumination is one of the most energy consuming parameters. Most of the time, natural light is not enough to achieve the value of illumination needed to work properly without health implications to the workers. These areas have the most concentration of people working at the same time in the building, so the lights must always be turned on.

The procedure used to perform this analysis, on an energy standpoint, was the following:

1. Inquiry of the installed luminaries and current energy consumption;
2. Survey of the LED market to choose the models with an equivalent, or approximated, luminous flux to the lamps that will be replaced;
3. Selection of two brands with different models suggested;
4. Calculation of the power reduction and respective energy consumption for each lamp;
5. Choice of the most beneficial combination of lamps.

4.3.1 Installed luminaries

The lamps installed in these spaces are T5 fluorescent, differing only on the length and power. Fluorescent lamps are classified according to their wattage, shape, and diameter. The “T” in T5 indicates that the bulb is tubular shaped, while the “5” denotes that it has a diameter of five eights of an inch. The other common lamps are the larger T8 and T12. Between These types of fluorescent lamps, the most energy efficient is the T5, having also a higher selling price then the rest.

In table 4.6 and figure 4.2, are presented the properties of the types of lamp installed in the open spaces, as provided by the manufacturer:

Table 4.6: Properties of the installed lamps, provided by the Manufacturer [35]

Installed lamps properties					
Designation	**Type of lamp**	**Unitary Power [W]**	**Unitary Illumination Intensity [lm]**	**Length A [mm]**	**Length B [mm]**
1	OD-3882 1 T5 HF	21	1900	880	450
2	OD-3882 1 T5 HF	28	2600	1180	800
3	OD-3882 1 T5 HF	35	3300	1480	800

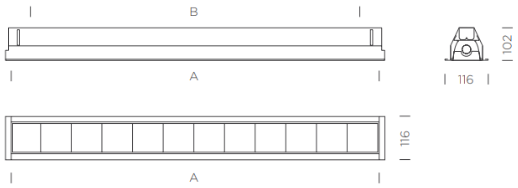

Figure 4.2: Lamp dimensions, provided by the manufacturer [35]

4.3.2 Space description

The six open space areas analysed are located in floor 0 and -1. These areas are descripted in the table 4.7 according to the numeration of the highlighted in brown areas presented in the figure 4.3:

Table 4.7: Description of the open space office

Designation	Area [m^2]	Location
1	563.58	Floor 0
2	468.43	Floor 0
3	316.65	Floor 0
4	595.08	Floor -1
5	438.22	Floor -1
6	317.06	Floor -1

Figure 4.3: On the left: the blueprint of the floor 0. On the right: the blueprint of the floor -1

The distribution of the installed luminaries per open space is shown in the table 4.8:

Table 4.8: Luminaries distribution per open space

	Open Space 1	Open Space 2	Open Space 3	Open Space 4	Open Space 5	Open Space 6
Quantity of lamps 1	12	12	8	12	12	12
Quantity of lamps 2	8	4	4	4	4	4
Quantity of lamps 3	156	134	92	136	134	116

4.3.3 Proposed Lamps

After surveying the LED market, two brands were selected and from those brands, some alternative models were proposed. The proposed lamps were chosen considering the need to have an equivalent, or approximated, luminous flux and approximated length to the lamps already installed. First, LED T5 compatible with the already installed electronic ballast were investigated, and those models are presented below, on the table 4.9:

Table 4.9: Properties of the proposed T5 lamps, as provided by the manufacturers [36] and [37]

	OSRAM T5			Philips T5		
Lamps	Type 1 Alternative	Type 2 Alternative	Type 3 Alternative	Type 1 Alternative	Type 2 Alternative	Type 3 Alternative
Model	ST5HE-UN 10 W/865	ST5HE-UN 17 W/865	ST5HO-UN 26 W/840	Master LEDtube HF 1200mm HE 16.5W 865 T5	Master LEDtube HF 1200mm HE 16.5W 865 T6	Master LEDtube HF 1500mm HE 20W 865 T5
Luminous flux [lm]	1500	2600	4000	2500	2500	3000
Length [mm]	849	1149	1449	1200	1200	1500
Power [W]	10	17	26	16.5	16.5	20
Efficacy [lm/w]	150	152.94	153.85	151.52	151.52	150.00
Lifetime [hours]	60000	60000	60000	50000	50000	50000
CRI	83	83	83	83	83	83
Colour temperature [K]	6500	6500	4000	6500	6500	6500

All the proposed lamps have an energy class A++. For the type 1 and 2 Philips alternatives, it was proposed the same lamp, because it was the model that fitted the most the specifications of both types. However, to install it in the installations for the type 1 lamps would have to be changed, because the length of the proposed model is bigger than the one already installed. The T5 models proposed are very cost demanding because they are the most efficient type of tubular LED, and that might not make the project feasible.

However, to propose a more feasible improvement, LED T8 models were also investigated. Since they are also more energy efficient than the installed lamps and less cost demanding than the T5, they may signify a better investment for the company. It is important to clarify that using T8 lamps, instead of T5 lamps, would imply the replacement of the electronic ballasts. This replacement would involve in a larger investment, although this type of cost will not be considered in the present dissertation. The suggested T8 models are presented in the table 4.10:

Table 4.10: Properties of the proposed T8 lamps, as provided by the manufacturers [38] and [39]

	OSRAM T8			**Philips T8**		
Lamps	Type 1 Alternative	Type 2 Alternative	Type 3 Alternative	Type 1 Alternative	Type 2 Alternative	Type 3 Alternative
Model	ST8A-EM 11.3 W/6500K 900 mm	ST8AU-EM 15.1 W/6500K 1200 mm	ST8AU-EM 22.4 W/6500K 1500 mm	MASTER LEDtube 900mm HO 12W 865 T8 1	MAS LEDtube VLE UN 1200mm UO 16W865 T8	MASTER LEDtube 1500mm HO 18.2W 865 T8
Luminous flux [lm]	1700	2500	3700	1575	2500	3100
Length [mm]	900	1200	1500	900	1200	1500
Power [W]	11.3	15.1	22.4	12	16	18.2
Efficacy [lm/w]	150.44	165,56	165.18	131.25	156.25	170.33
Lifetime [hours]	50000	60000	60000	50000	50000	60000
CRI	83	83	83	83	83	83
Colour temperature [K]	6500	6500	6500	6500	6500	6500

4.4 Energetic and economic study

An energetic and economic study was performed on *Microsoft Excel* software, comparing the specifications of the proposed lamps with the current scenario, as well as the application of the financial indicators to assess the viability of the investment, as explained before in this dissertation. This study in its extent is presented on table 4.11.

The current situation presents an annual energy consumption of 122884.61 kWh, obtained by the sum of the energy consumption of the three types of lamps installed, producing a total annual electricity cost of 5794.62€. To simplify the calculations, it was assumed a 16 h hours daily usage, since the lamps are usually turned on around 6 am and turned off around 10 pm, varying by 2 hours some other days. Also, it was assumed that each month had 22 working days and using the energy prices stated in the chapter 3 of this dissertation.

The obtained consumption represents 7.78% of the total electricity consumption of the building registered in 2019. A 7.78% share might not seem very significant, but when taken into context, the importance of it reasonably increases. Since this building has a lot of energy consuming systems, that make it reach high annual energy consumption numbers, this share just for the illumination in six open space offices might be higher than expected.

The financial indicators have an important role in analysing the results. Even though, the diminishing in energy consumption is a crucial part in this project, the economic factor is what makes it feasible for the company. As predicted, in section 4.3.3, the LED T8 models present a more attractive alternative to this situation, comparing to the LED T5 models. This is because the T5 models are more cost demanding, implying a large investment, obtaining higher payback periods, in most cases higher than the lifetime period of the lamp, negative IRR's and NPV's. This indicates, that investing in the LED T5 models, would not be a viable investment and the company would lose money. Since the initial investment is very high, due to the lamps' price, the replacement will only be worth it, if the proposed lamps produce significant annual energy savings, otherwise the payback period will be too high and the financial indicators will turn out to be negative, because the produced savings are not big enough to compensate the initial investment.

It is important to refer that the NPV was calculated using the lamp lifetime as the time period and a discount rate of 5%. The indicators should only be compared between models of the same type, since the quantity of lamps needed for the different types varies and that influences the initial investment needed. This is the factor, on par with the monetary savings, that most influences the results.

The selected alternatives for the three types of lamps installed are highlighted in blue on the table 4.11 and are:

- Type 1 alternative – OSRAM T8;
- Type 2 alternative – OSRAM T8;
- Type 3 alternative – Philips T8.

These models were the ones that provided the best balance between energy and monetary savings, being the ones with the lowest payback period and the highest NPV's and IRR's. The chosen models imply a payback period of around 8 years, which can be somewhat high for a luminaire investment. However, the average lifetime of this lamps is 14,2 years, the payback would be achieved in 56% of the time of the investment.

The new scenario would need an initial investment of 22395.6€ and have an annual energy consumption of 64073.01 kWh, implying an annual cost of 3021.36€. This investment would produce a reduction in annual energy consumption of 58811.6 kWh, lowering the 7.78% share of the luminaries of these 6 open spaces in the total consumption of the building, to 4.06%, returning 2773.26€ in annual savings.

4.5 Generated savings

The energetic savings produced by the replacement of the luminaries were estimated for the lifetime of the lamps and calculated considering the legislation nº 17313/2008. The results obtained are summarised in the table 4.12:

Table 4.12: Summary of the energetic and emissions savings

	Energetic Savings [toe]	**Reduction in CO_2 emissions [kg CO_2]**
In the first year	12.64	27641.45
Lifetime (8 years)	101.16	221131.62

Table 4.11: Energetic and economic study performed on *Microsoft Excel*

	Current Scenario			OSRAM						Philips					
				T5 Alternatives			T8 Alternatives			T5 Alternatives			T8 Alternatives		
	Type 1	Type 2	Type 3	Type 1	Type 2	Type 3	Type 1	Type 2	Type 3	Type 1	Type 2	Type 3	Type 1	Type 2	Type 3
Luminous flux [lm]	1900	2600	3300	1500	2600	4000	1700	2500	3700	2500	2500	3000	1575	2500	3100
Power [W]	21	28	35	10	17	26	11.3	15.1	22.4	16.5	16.5	20	12	16	18.2
Efficacy [lm/w]	90.48	92.86	94.29	150	152.94	153.85	150.44	165.56	165.18	151.52	151.52	150	131.25	156.25	170.33
Colour Temperature [K]	-	-	-	6500	6500	4000	6500	6500	6500	6500	6500	6500	6500	6500	6500
Lifetime [hours]	-	-	-	60000	60000	60000	50000	60000	60000	50000	50000	50000	50000	50000	60000
Usage [hours/day]	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Lifetime [years]	-	-	-	14.2	14.2	14.2	11.84	14.2	14.2	11.84	11.84	11.84	11.84	11.84	14.2
Retail Price [€/unit]	-	-	-	33.1	35.5	38.3	15.4	20.5	23.9	31.75	31.75	35.28	18.22	19.99	27.05
Quantity	68	28	768	68	28	768	68	28	768	68	28	768	68	28	768
Total Annual Consumption [kWh/year]	6031.87	3311.62	113541.1	2872.32	2010.62	84344.83	3245.72	1785.91	72666.32	4739.33	1951.49	64880.64	3446.78	1892.35	59041.38
Annual Cost in Electricity [€/year]	284.43	156.16	5354.03	135.44	94.81	3977.28	153.05	84.21	3426.58	223.48	92.02	3059.45	162.53	89.23	2784.1
Annual Savings in Electricity [€/year]	-	-	-	148.99	61.35	1376.75	131.38	71.95	1927.45	60.95	64.14	2294.58	121.9	66.93	2569.93
PP [years]	-	-	-	15.11	16.2	21.37	7.97	7.98	9.52	35.42	13.86	11.81	10.16	8.36	8.08
NPV [€]	-	-	-	-879.11	-429.19	- 16 739.51	14.65	88.36	-609.35	- 1 666.33	-395.31	- 8 549.19	-253.71	-18.79	2 886.69
IRR	-	-	-	-2%	-3%	-6%	5%	7%	4%	-15%	-4%	-1%	1%	4%	7%

Chapter 5

Solar photovoltaic project

This chapter aims to present the different phases in the integration of photovoltaic modules on the roof of the SIBS's building in study. To this end, it will be presented the methodology used, the important calculation and design tools used in the technical phase of the project conception.

This project will be divided in three phases: geometric study of the area, selection of the modules and sizing of the system. The methodology applied will be presented in the next sections as well as a brief content revision to better understand the project.

5.1 Content Revision:

5.1.1 Solar radiation

The sun is an inexhaustible source of light and energy and sunlight is by far the largest and most accessible source of energy received by earth. The total amount of solar energy that reaches the Earth is far more than the world's current and anticipated energy requirements. If properly harnessed, this diffused source has the potential to satisfy all future energy needs. However, the intensity of this radiation is quite low at the Earth's surface, since some of that radiation is reflected. The emitted radiation by the sun can be categorized as such (see figure 5.1):

- Direct Radiation: consisting of all incident rays that hit the Earth's surface directly without being absorbed or dispersed;
- Diffuse Radiation: portion of light that is received indirectly, after diffracting on clouds, fogs, suspended dust and other obstacles that may be present in the atmosphere;
- Reflected Radiation: portion of radiation reflected by the earth's surface into space

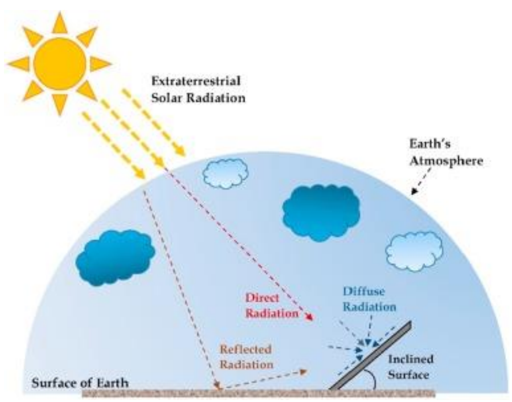

Figure 5.1: Illustration of the different categories of solar radiation [40]

The average radiation intensity perceived at the earth surface is denominated the solar constant (E_0) and it its value is: $E_0 = 1367\ W/m^2$. However, in good climatic conditions, in a horizontal plane, and independently of the location, the intensity of the solar radiation reaching the Earth's surface totals an approximate value of 1000 W/m^2 at noon.

In terms of solar irradiation, in Europe, Portugal, due to its geographical location, has a great advantage in comparison to other countries, especially the northern ones, having great availability of solar radiation. Presenting a range of 2500 and 3000 hours of sun annually, reaching average annual values of solar intensity of 1500 kWh/m^2 in the north and 2000 kWh/m^2 in the south [41].

A country with excellent solar radiation levels, must take advantage, with the available technology, of this radiation for applications, in order to decrease the national energy consumption and, consequently, dependence on fossil fossils.

5.1.2 Solar incidence Angle

The energy produced by the photovoltaic modules is related to the incident radiation. In order to get the most out of this radiant flow that reaches the surface, it is essential to define the most suitable inclination and orientation parameters of the PV modules for greater electrical production. Therefore, knowing the incidence angle of the sun's rays is crucial to quantify the energy coming from the Sun. To do this, it is necessary to know the geographic factors of the location, such as latitude, hour angle, solar declination, angle of the surface in relation to the horizontal plane and the direction in which modules will be installed (see Figure 5.2). It is clear that the different positions of the Earth in relation to the Sun will vary the incidence angle. In that sense, the equation that allows the calculation of the incidence angle is shown below:

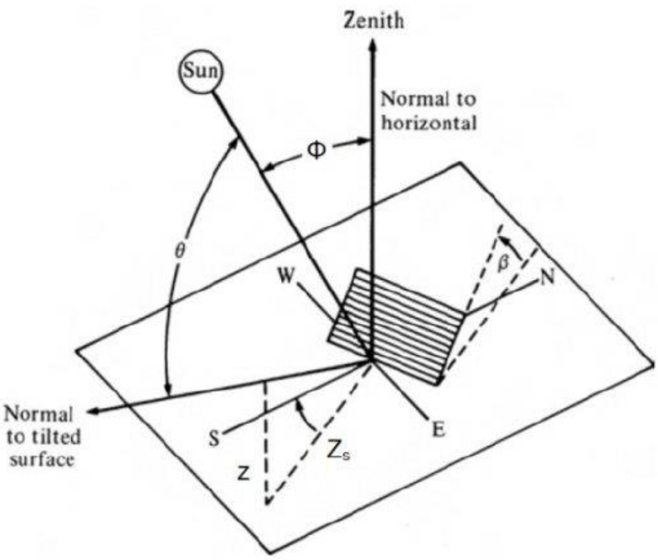

Figure 5.2: Representation of the relevant angles in a PV module [42]

$$\begin{aligned} cos(\theta) = {} & sin(L)\, sin(\delta)\, cos(\beta) - cos(L)\, sin(\delta)\, sin(\beta)\, cos(Z_s) \\ & + cos(L)\, cos(\delta)\, cos(h)\, cos(\beta) \\ & + sin(L) cos(\delta)\, cos(h) sin(\beta)\, cos(Z_s) \\ & + cos(\delta)\, sin(h)\, sin(\beta)\, sin(Z_s) \end{aligned} \tag{11}$$

Where:

θ	Angle of incidence: the angle between solar beam and surface normal, in [º];
L	Local latitude: values at north of the equator are positive and those at south are negative, in [º].
δ	Declination angle: The angle between the Sun's direction and the equatorial plane
β	Module's tilt angle: angle between the surface and a horizontal plane, in [º];
Φ	Solar zenith angle: The angle between the solar beam and the normal to the horizontal plane, in [º];
h	Hour angle: the angle through which the Earth has rotated since solar noon. It is calculated as $h = 15°(time\ in\ hours, since\ solar\ noon)$. The hour angle is positive in the evening and negative in the morning, in [º];
Z_s	Surface azimuth angle: angle between the north-south line and the projection of the normal to the surface on a horizontal plane (positive west of south, and negative east of south), in [º];

In the Northern hemisphere, the orientation that maximizes the amount of radiation captured by a surface coincides with the geographical south. In Portugal, the optimal requirements for maximizing the solar installation are: the south direction and a tilt angle of 35 ° [43].

5.1.3 Photovoltaic cells and photovoltaic effect

The photovoltaic cells are the basis of the photovoltaic technology. Inside these cells, the photovoltaic effect happens, the mechanism that converts sunlight to voltage or electric current. The PV cells are constituted of semiconductor materials. Those are materials with intermediate characteristics between a conductor and an insulator, and usually are silicon, gallium arsenide, cadmium telluride or copper indium selenide. The most common material is the crystalline Silicon, being used in 95% of the modules present in the market.

Each cell has two layers of different material, a positive layer, and a negative layer (type p material and type n material), creating an electromagnetic field. By joining layers n and p of the semiconductors, a transition region is formed called junction p-n. In this junction, surplus electrons diffuse from the semiconductor n to the semiconductor p creating an electric field. When the semiconductor is exposed to sun light, the electrons absorb the photons. This energy increase breaks the connection between the electrons and these move to the conduction band being conducted through the electric field to the layer n and the gaps created flow to the layer p, creating a potential difference. This potential difference is called the photovoltaic effect and it is illustrated in the figure 5.3.

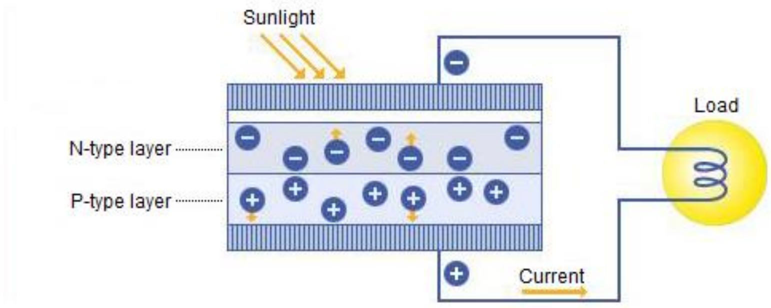

Figure 5.3: Representation of the Photovoltaic Effect [44]

The PV cells are divided into three main categories, differing from the type of materials and manufacturing used. These categories are:

- Monocrystalline;
- Polycrystalline;
- Thin-film.

The **monocrystalline cells** are manufactured with monocrystalline silicon, being the most used material in the composition of photovoltaic cells, being the oldest technology, its reliability, durability, and longevity have made them remain until today. Monocrystalline cells were the first to be made from a block of pure crystallized silicon, in a single crystal, they present a uniform colour, indicating high purity silicon and typically rounded corners. The uniformity of the molecular structure resulting from the use of a single crystal uniformity is ideal to enhance the photovoltaic effect, and hence improve its efficiency, being the type of PV cell with the highest efficiency. However, the need of using pure crystals in its production, results in high consumption and waste of material. Naturally, these factors increase the production costs of the monocrystalline cell. The higher efficiency of monocrystalline solar cells means that they require less space to reach a given power capacity. So, monocrystalline solar modules will usually have a higher power output rating than either polycrystalline or thin film modules.

The **polycrystalline cells** are produced in a faster and more economical way, these cells are manufactured like the monocrystalline ones, by placing a seed crystal into molten silica. However, instead of pulling out the silicon seed crystal, the whole vat of silicon cools. This cooling process causes multiple crystals to form. This manufacturing process is cheaper and produces less material waste, however due to the combination of various crystals, the molecular structure presents some discontinuities that difficult the movement of the electrons, which reduces the output power and hence the efficiency of the cell. These cells are also sensitive to high temperatures, decreasing the cell efficiency significantly with an increase in temperature.

The **thin-film cells** are completely different from the crystalline ones, being more lightweight and flexible. This type of cell is manufactured by depositing one or more thin layers of photovoltaic material on a substrate, its atoms' organization is no longer regular as in a crystal. For this, semiconductor materials are used that have a sunlight absorption capacity superior to mono and polycrystalline cells, like amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and dye-sensitized solar cells (DSC). Since the manufacturing process requires less materials and energy, the production costs are smaller than the other types of cells. However, despite the low cost and other advantages associated with higher flexibility, higher temperature tolerance and lower shading sensitivity, its performance is lower compared to the crystalline cell technology. Nevertheless, due to their advantages, thin-film cells have been the subject of several investigations as a future alternative to silicon.

The range of efficiency for each technology is summarised in the following table:

Table 5.1: Efficiency ranges of the three types of cells [45]

Technology	Efficiency
Monocrystalline	17 to 22%
Polycrystalline	15 to 17%
Thin-film	10 to 13%

5.1.4 Types and constitution of photovoltaic systems

Usually, the Photovoltaic systems are mainly constituted by the following elements:

- **PV modules** connected in parallel and/or in series;
- **Inverter** device that transforms direct current into alternating current;
- **AC and DC cabling**;
- **Batteries and power regulators**;

Photovoltaic energy installations, can be divided into three categories, based on their generalized applications. The categories for the exploitation of decentralized energy production are:

- **Stand-alone systems**, isolated or autonomous systems with or without energy storage;
- **Hybrid systems,** connected with more than one energy source in addition to photovoltaic;
- **Grid-connected systems**.

In stand-alone systems, the energy produced equals the location's energy needs. In these types of systems, the dimensioning of the PV module is made based on the month in which the minor solar radiation is verified. Usually, this type of device involves the use of batteries to store electricity to ensure the continuous feeding of the consumptions, in the periods that solar radiation is not available.

If the photovoltaic system is connected to another power source the system is denominated as hybrid. They are systems disconnected from the conventional network and use various forms of electricity generation, such as wind turbines, cogenerating systems, photovoltaic modules, among others. The various forms of production make it complex to optimize the energy use.

The main difference in the stand-alone systems and the grid-connected systems is the temporality of energy supply, i.e., whenever the photovoltaic production is not enough to meet the energy needs, the demand is met by the energy coming from the public grid. The energy produced can either be consumed by the installation itself or be sold to the public grid.

5.1.5 Characteristic curve

To properly dimension a production system, it is of utmost importance the identification of the cells' I-V characteristic curves, according to the manufacturers' data. These curves show the current and voltage (I-V) characteristics of a particular photovoltaic cell, module or array giving a detailed description of its solar energy conversion ability and efficiency.

To find these curves, it is important to understand some cell's electrical parameters, such as:

- Nominal power (P_{MPP}), in [W];
- Nominal current (I_{MPP}), in [A];
- Nominal voltage (V_{MPP}), in [V];
- Short circuit current (I_{sc}), in [A];
- Open circuit voltage (V_{OC}), in [V];

Solar Cell I-V Characteristics Curves are essentially a graphical representation of a solar cell or module's operation, summarizing the relationship between current and voltage under the current irradiance and temperature conditions. I-V curves provide the requisite details to optimize a solar system so that it can run as close as possible to its optimum peak power point (MPP). The below graph (see figure 5.4) shows the current-voltage (I-V) characteristics of a typical silicon PV cell operating under normal conditions.

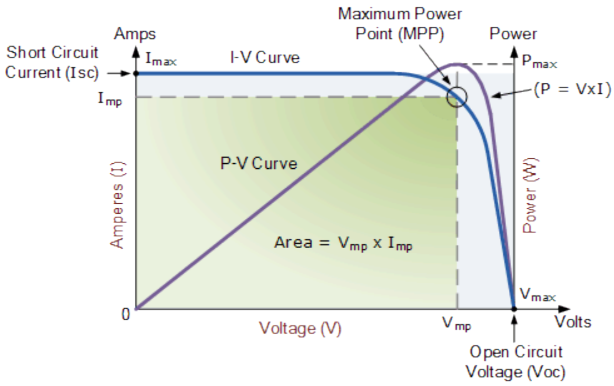

Figure 5.4: Characteristic curve of a solar cell [46]

The PV modules can be connected in either series or parallel combinations to increase the voltage or current of the photovoltaic array, respectively. Figure 5.5 shows that the voltage increases when connected in a series combination, and that the current increases when connected in parallel. The electrical power in Watts, generated by these different photovoltaic combinations will still be the product of the voltage times the current.

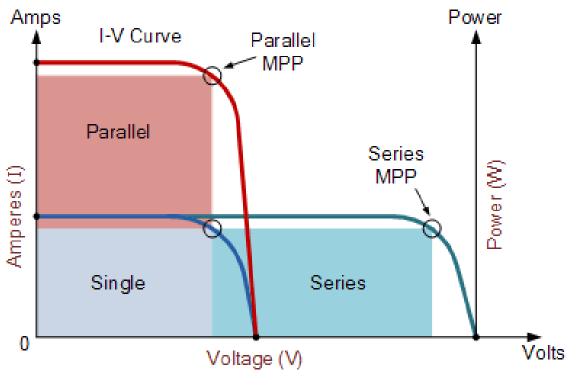

Figure 5.5: Effect of connecting the modules in series or in parallel [46]

5.2 Geometric study of the area

Before determining the optimal geometric displacement of the PV panels, it is necessary to calculate the available area on the roof. For that, a satellite view of the building, obtained on Google Maps, was used to sketch the area available and later approximate that sketch to geometrical figures. Using the scale provided in the image, it was possible to dimension the geometrical figures and then calculate the total area available, as exemplified in figure 5.6.

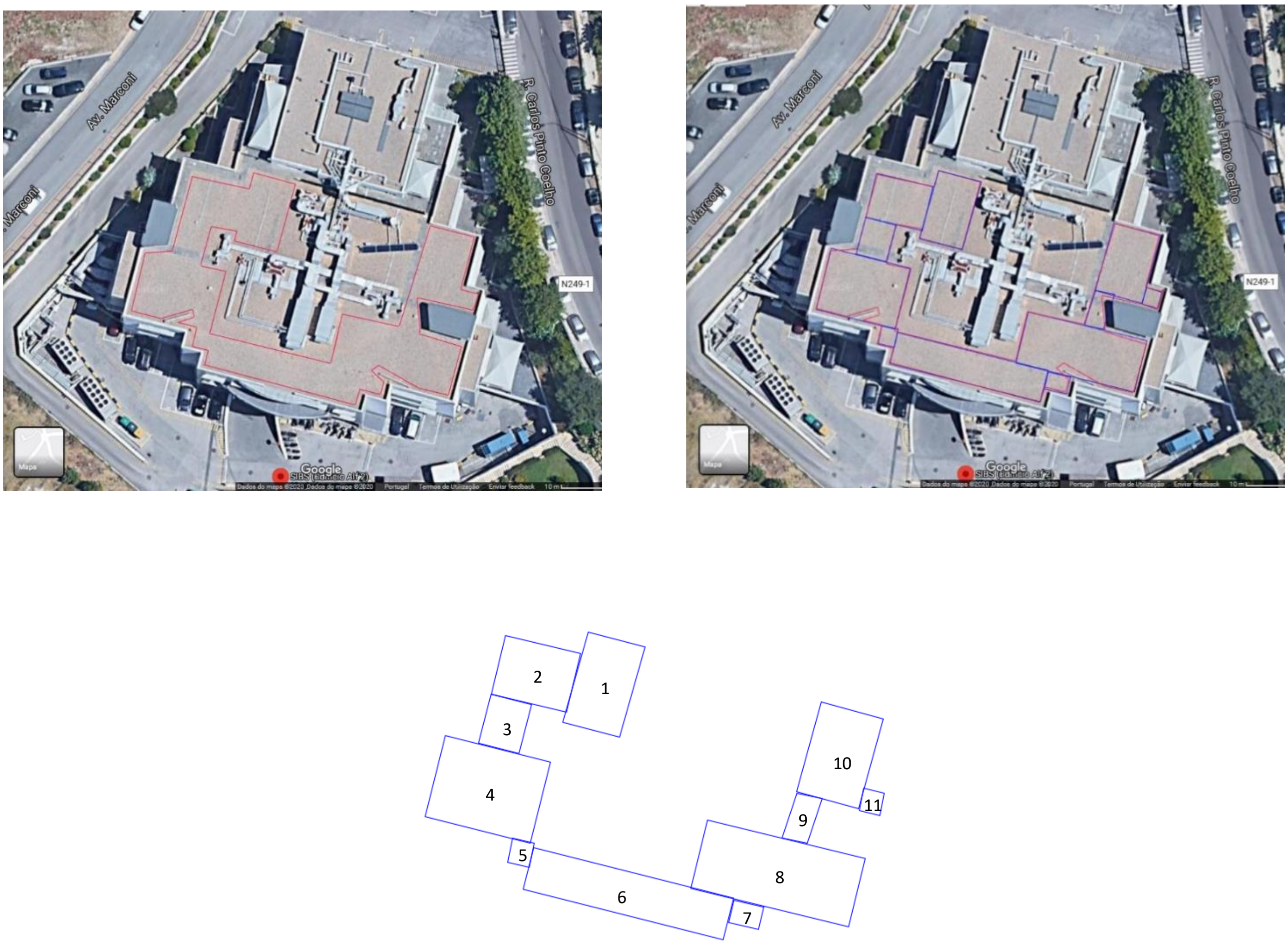

Figure 5.6: Geometrical approximation of the available area

$$A = \sum_{i=1}^{11} A_i = A_1 + A_2 + A_3 + A_4 + A_5 + A_6 + A_7 + A_8 + A_9 + A_{10} + A_{11} \tag{12}$$

Image scale: 1.8 cm : 10 m

Measuring all the geometries and converting the values in cm to m, through:

$$\begin{matrix} 1.8\ cm \rightarrow 10\ m \\ x\ (cm) \rightarrow x(m) \end{matrix} \Leftrightarrow x(m) = \frac{10 \times x(cm)}{1.8}$$

It results:

$$A = 662.96\ m^2$$

The value obtained has some errors associated to it. Errors in the precision of the sketch created and in the measuring of the geometrical figures, however it is precise enough to make a dimension of the PV system.

5.3 Determination of system losses

This kind of electrical systems have several types of energy losses throughout the energy path, which makes the total efficiency of the system not optimal. Some of these loss factors are not possible to be avoided because they are part of the specifications of the various equipment in the system. However, other losses can be reduced or even eliminated if there is a correct periodic maintenance. The main causes of energy losses are:

- Decrease of the efficiency of the modules over their useful life;
- Inverter efficiency;
- Effect of temperature and irradiation on energy production;
- Losses in cabling;
- Shading;

The efficiency values of the modules and inverter were obtained through data provided by the manufacturer.

5.3.1 Modules

Adding to the energy losses caused by the decrease of efficiency of the modules over their useful life, there is another loss factor in the formation of the modules. In theory, the modules are constituted by cells with similar characteristic curves, however, the characteristic curve changes from cell to cell and that may cause mismatch losses between characteristic curves. To minimise this mismatch losses, the modules used should be all from the same type.

5.3.2 Shading

In certain situations, this factor can be one of the largest physical conditioning variables of a PV system installation, since it directly affects the efficiency of the system. Direct radiation from the sun arises from a certain angle of incidence in relation to a plane installation, causing shade when an object is struck. The larger the height of the object and the inclination of it, assuming it ranges from 0º to 90º, the greater will be the shadow generated. If the panels installed are covered in shadow, the efficiency of the system drops substantially. So, this factor must be assessed during the study of the available area, on the dimensioning phase.

To assess the shading produced by the panels and other objects, the "worst case scenario" should be considered, which is, for the Northern Hemisphere, when the winter solstice occurs, in which the solar radiation has the lowest angle in relation to the ground. Using trigonometry, one can calculate the shadow generated by any object. The procedure to calculate the distance between panels is presented below, being illustrated in the figure 5.7:

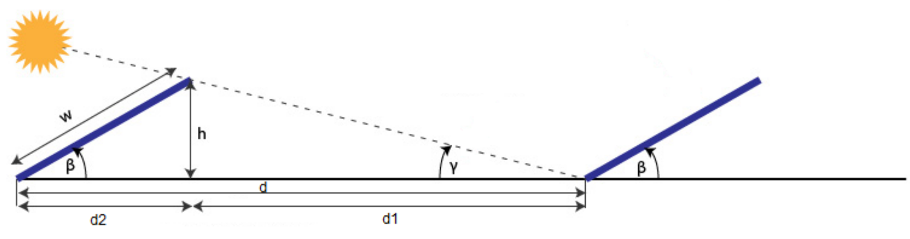

Figure 5.7: Representation of the shading generated by the modules
Source: [47]

Where:

w	PV module's width;
h	Height of the module's most elevate zone;
β	Module's tilt angle, in [º];
γ	Incidence angle of the sun on a flat surface;
d	Total distance between modules;
d1	Shading distance generated beyond the module itself;
d2	Shading distance generated to the module itself.

The unknown variable that its intendent to determine is the total distance between modules (d), that is the sum between d1 and d2. The following equations summarise the process of calculating the parameters necessary to calculate d:

$$h = sin\ (\beta) \times w \tag{13}$$

$$d1 = \frac{h}{tan(\gamma)} \tag{14}$$

$$d2 = \frac{h}{\tan\ (\beta)} \tag{15}$$

$$d = d1 + d2 \tag{16}$$

Regarding the shading over the modules, since there are no buildings nearby, the only aspect to take in consideration is the walls on the boarders of the roof and the different systems installed on the roof.

Following the procedure used to calculate the distance between the modules, it is possible to calculate the shading effect caused by the boarder walls, with its due changes.

On way of minimising the shading effect caused by the boarder walls would be the installation of elevation structures for the modules. Since by elevating the module, the difference in height between the modules and the walls will be reduced. It would require an additional investment, but an elevating structure would not only minimise the shading created by the boarder walls but would also allow an air passage creating natural ventilation preventing overheating and consequently reduction in the performance. Nevertheless, in this dissertation this option will not be considered and instead it will be calculated the minimum distance between the modules and the wall for which the module is not shaded. Being the modules only installed beyond that distance.

Following the procedure, considering that it happens in winter solstice, the following values were assumed:

- Building's latitude: Amadora 38º 74';
- Walls's tilt in relation to the roof (β): 90º;
- Walls height: 0.7 m;
- Solar declination: 23º 27'.

Using those values, the results are:

- h = 0.7 m;
- d1 = 1.63 m;
- d2 = 0 m;
- d = 1.63 m

Thus, the modules must be placed 1.63 m from the boarder walls.

5.4 Inverter's sizing

The main role of the inverter in the photovoltaic system is to invert the electric energy generated by the modules, from direct current (DC) to alternating current (AC). Its secondary role is to guarantee the security of the system and to generate data on the energy production over time, to monitor the performance of the respective system.

The number of inverters used in the project depends on the estimated system power and the type of system selected. As a general convention, the dimensioning of the inverter is done, using a ratio between the power of the photovoltaic system and the inverter power equal to 1. However, if there are deviations, they must fit the following power intervals for the correct functioning of the system [43]:

$$0.7 \times P_{PV} < P_{INV,DC} < 1.2 \times P_{PV} \tag{17}$$

$$\frac{P_{PV}}{1.25} < P_{INV,AC} < \frac{P_{PV}}{0.83} \tag{18}$$

5.4.1 Determination of input voltages

The voltage amplitude in the inverter derives from the sum of the individual voltages of the modules connected in series. As the voltage of the module and the overall voltage of the photovoltaic generator depend on the temperature, the intense winter and summer operating conditions are decisive in the dimensioning process.

To properly dimension the inverter, it is very important to bear in mind that the PV system voltages must not exceed the operating voltage and maximum voltage allowed by the inverter manufacturer. Thus, it is necessary to determine the number of photovoltaic modules that can be connected in series and parallel.

5.4.1.1 Maximum number of photovoltaic modules connected in series:

To calculate the maximum number of modules (n_{max}) connected in series, the following equation is used:

$$n_{max} = \frac{V_{Max,INV}}{V_{OC(Module\ at\ Tmin)}} \tag{19}$$

Where:

$V_{Max,INV}$	Inverter's maximum allowable voltage, in [V];
$V_{OC(Module\ at\ Tmin)}$	Module's open circuit voltage at the minimum temperature of operation, in [V].

The module's open circuit voltage is usually calculated considering a minimum temperature of −10 ºC. This value is not always provided by the manufacturer, in its place is the voltage variation (ΔV) in % or in mV. Thus, when that happens, the open circuit voltage is calculated using the following equations, the first one is used for ΔV in %, and the second for ΔV in mV :

$$V_{\ OC(Module\ at\ -10°C)} = (1 - \frac{35°C \times \Delta V}{100}) \times V_{OC(STC)} \tag{20}$$

$$V_{\ OC(Module\ at\ -10°C)} = -35°C \times \Delta V \tag{21}$$

Where:

ΔV	Variation of module's voltage as a function of temperature in$°C$, in [V];
$V_{OC(STC)}$	Module's open circuit voltage under standard test conditions. Value provided by the manufacturer, in [V].

If none of these data is provided, it is possible to use the following approximation:

$$V_{\ OC(Module\ at\ -10°C)} = 1.14 \times V_{OC(STC)} \tag{22}$$

5.4.1.2 Minimum number of photovoltaic modules connected in series:

It is important to consider the maximum and minimum temperature values at which the modules are subject to, as temperature variation significantly affects the module voltage. In the summer, due to the high solar radiation levels and the temperature that it is subjected to, a photovoltaic system will have a voltage at its terminals lower than the voltage at standard test conditions (STC). If the generator's operating voltage falls below the inverter's maximum power point (MPP) voltage, the overall system efficiency will be compromised and, in the worst case, may cause the shutdown of the inverter. Thus, for its correct dimensioning, one must not only consider the minimum temperature to which the modules are subject, but also consider their maximum temperature reached in summer.

The minimum number of modules that can be installed in series can be calculated with the following equation, assuming, as a general rule, a maximum temperature of 70 ºC:

$$n_{min} = \frac{V_{INV(MPP)}}{V_{Module\ at\ 70°C\ (MPP)}} \tag{23}$$

Where:

$V_{INV(MPP)}$	Value provided by the manufacturer that represents the minimum operating voltage of the inverter, in [V];
$V_{Module\ at\ 70°C\ (MPP)}$	Module's voltage at the maximum power point at 70 ºC, in [V].

Sometimes, the module's MPP voltage at 70 ºC is not provided by the manufacturer, so it must be calculated using the following equations, the first one is used for ΔV in %, and the second for ΔV in mV:

$$V_{Module\ at\ 70°C\ (MPP)} = (1 + \frac{45°C \times \Delta V}{100}) \times V_{MPP(STC)} \tag{24}$$

$$V_{Module\ at\ 70°C\ (MPP)} = V_{MPP(STC)} + 45°C \times \Delta V \tag{25}$$

If none of these data is provided, it is possible to use the following approximation:

$$V_{Module\ at\ 70°C\ (MPP)} = 0.82 \times V_{OC(STC)} \tag{26}$$

5.4.2 Determination of the number of modules connected in parallel

To complete the dimensioning, it is necessary to determine the number of rows by verifying if at some point the photovoltaic generator's current exceeds the maximum limit of the inverter's input current [43]. So, the maximum number of rows (N) is determined by the next equation, used only for a single maximum power point tracking (MPPT) controller:

$$N \leq \frac{I_{INV\ max}}{I_n} \tag{27}$$

Where:

$I_{INV\ max}$	Inverter's maximum current input, in [A];
I_n	Maximum current in row n, in [A].

Nowadays, inverters with more than one MPPT controller exist in the market. These controllers allow the subdivision of rows by the existing controllers. It is a very useful type of system, as this subdivision prevents the system from being affected by the poor performance of one or more solar panels in cases of shading or malfunctioning. The number of rows can then be determine using the following equation [43]:

$$N \leq \frac{I_{MPPT\ max}}{I_n} \tag{28}$$

Where:

$I_{INV\ max}$	Inverter's maximum input current for each MPPT controller, in [A];

5.4.3 Limits Validation

After the determination of number of modules connected in series and in parallel, it is important to verify if the inverter limits are respected, to assure the correct functioning of the system. Those limitations are:

- $V_{MPP\ (Module\ at\ -10°C)} > V_{MPP,\min\ INV}$;

- $V_{MPP\ (Module\ at\ -10°C)} < V_{MPP,\max\ INV}$;
- $V_{OC\ (Module\ at\ -10°C)} < V_{\max\ INV}$;
- $I_{MPP} < I_{\max\ INV}$;
- $I_{SC\ (module)} < I_{\max,\ SC\,INV}$;

Where:

$V_{MPP,\ INV}$	Interval of voltage input of the MPPT controller(s) provided by the manufacturer in [V];
$I_{\max\ INV}$	Maximum current input of the controller(s) in the MPP, in [A];
$I_{SC\ (module)}$	Module's short circuit (SC) current, in [A];
$I_{\max,\ SC\,INV}$	Controller(s) maximum short circuit input current, in [A].

5.5 Cable's sizing

The entire cabling system must comply with the requirements because it is the energy conductors that allow the system to work and produce energy in an efficient way. All the necessary cables will not be identified, but the most important ones are as follows:

- Row cabling;
- Direct current cabling;
- Alternating current cabling.

5.5.1 Direct current (DC) cables

To correctly do the dimensioning of these cables, three essential criteria must be respected:

When sizing cables, three essential criteria must be observed:

- Compliance with the cable's nominal voltage limit, given by the manufacturer;
- Compliance with the cable's maximum allowable current limit, given by the manufacturer;
- Minimization of losses.

5.5.1.1 Cable's nominal voltage

Usually, the open circuit voltage of the photovoltaic systems at the minimum operation temperature ($V_{OC(PV\ at\ Tmin\,°C)}$) does not exceed the standard cable's nominal voltage ($V_{nominal\ DC\ Cable}$) that sits between 300 and 1000 V. Nevertheless, this verification must be made, and it is summarised in this equation:

$$V_{nominal\ DC\ Cable} > V_{OC(PV\ at\ Tmin\ °C)} \tag{29}$$

5.5.1.2 Cable's maximum allowable current

The cable's cross section area is sized according to the maximum current flowing through the cable. Having to determine the maximum permissible cable current and subsequently calculate the losses associated with it. According to the European standard IEC 60364-7-712, the value of the maximum current intensity ($I_{\max cable}$) for which the cable is dimensioned is given by the following equation:

$$I_{\max cable} = 1.25 \times I_{SC\ PV} \tag{30}$$

Where:

$I_{SC\ PV}$	Photovoltaic system's short circuit current, in [A];

After this, it is necessary to select the cable's cross area considering that the calculated maximum current intensity cannot exceed the values of current intensity set by the manufacturer.

5.5.1.3 Minimization of losses

The process of selecting the cross-section area has to consider the necessity of reducing as much as possible the losses by Joule effect, taking into account that the larger its section is, the smaller will be the losses. The German norm VDE 0100 – 712 suggests that the energy losses in the DC cables should not be higher than 1% comparing to the reference STC. The calculation of the section is made through the following equation [43]:

$$S_{DC} = \frac{2 \times L_{DC} \times I_{cable}}{Losses \times V_{MPP} \times \kappa} \tag{31}$$

Where:

S_{DC}	Cable's cross-sectional area, in [mm^2];
L_{DC}	Length of the cable in the row, in [m];
I_{cable}	Current that flows through the DC cable, in [A];
$Losses$	Value that represents the losses by Joule effect, in [%];
V_{MPP}	Nominal voltage of the row, in [V];
κ	Electrical conductivity of the conductive material, in [$m\ /\ \Omega\ mm^2$].

5.5.2 Alternating current (AC) cables

This part of the design depends on the installed power, having values of installed power higher than 5 kWp, the system must have a three-phase installation.

5.5.2.1 Calculation of the cable cross-section area for a three-phase installation

The calculation of the cable cross-sectional area for a three-phase installation is obtained by the following equation. The power factor was assumed to be unitary:

$$S_{AC} = \frac{\sqrt{3} \times L_{AC} \times I_{n,AC} \times cos\varphi}{3\% \times V_n \times \kappa} \tag{32}$$

Where:

S_{AC}	Cable's cross-sectional area, in [mm^2];
L_{AC}	Length of the cable from the inverter to the low voltage distribution board, in [m];
$I_{n,AC}$	Nominal current output of the inverter, in [A];
V_n	Nominal voltage of the grid, in [V];
κ	Electrical conductivity of the conductive material, in [m / Ω mm^2].

5.5.2.2 Losses

For the calculation of the cross-section area of the AC cable, a maximum voltage drop (Energy losses) of 3% is assumed. These losses can be estimated through the following equation:

$$P_{AC} = \frac{\sqrt{3} \times L_{AC} \times {I_{n,AC}}^2 \times cos\varphi}{S_{AC} \times \kappa} \tag{33}$$

Where:

P_{AC}	Energy losses in the AC cable for a three-phase system, in [W];
L_{AC}	Length of the cable from the inverter to the low voltage distribution board, in [m];
$I_{n,AC}$	Nominal current output of the inverter, in [A];
S_{AC}	Cable's cross-sectional area, in [mm^2];
κ	Electrical conductivity of the conductive material, in [m / Ω mm^2].

5.6 Production of energy in a photovoltaic system

The real energy produced by the system can be estimated using the following equation:

$$E_{PV} = G \times d_{month} \times A_{installed} \times \frac{\eta_{module}}{100} \times \eta_{system} \tag{34}$$

$$\eta_{system} = \frac{\eta_{inv}}{100} \times \frac{\eta_{rel}}{100} \times (1 - \frac{Losses_{T,I}}{100}) \times (1 - \frac{Losses_{S}}{100}) \times (1 - \frac{Losses_{DC}}{100}) \times (1 - \frac{Losses_{AC}}{100}) \quad (35)$$

Where:

E_{PV}	Energy that the photovoltaic system produces monthly, in [kWh / $month$];
G	Solar radiation on a surface at 90 ° of inclination, in [kWh / $(m^2. day)$];
d_{month}	Number of days related to the month which the quantity of energy produced is being calculated;
$A_{installed}$	Area occupied by the PV modules, in [m^2];
η_{module}	Module's efficiency under STC, in [%];
η_{system}	Systems efficiency;
η_{inv}	Inverter's efficiency, in [%];
η_{rel}	Annual efficiency related to the power losses in the module, in [%];
$Losses$	Energy losses related to the effect of temperature, radiation, shading, and in the DC and AC cables, in [%].

5.7 Module selection and area distribution

The used modules in this project were selected according to:

1. The type of material: monocrystalline or polycrystalline;
2. Module's power and efficiency;
3. Module's temperature coefficient;
4. Module's price.

The choice of the right module starts very much from the customer's energy needs, but also from the expertise of the project's responsible engineer, especially in terms of selecting the perfect brand. Obviously, the characteristics of each brand differ in price, but in general, the higher the capacity, the higher the cost for the same module area. After a brief market search, one of the manufacturers brands that stood out was the Hanwha Q.cells. This brand is one of the most popular and recognised manufacturers in the photovoltaic industry in Europe, and the average price of their pv modules is generally lower comparing to other modules with similar specification from other renowned brands.

After deciding the module's manufacturer, the objective was to find its module that fitted the most the needs of this project. The decision fell up on the module Q.PEAK DUO-G7 335. This module is a monocrystalline module and fills all the needed requirements. It was chosen based on the MPP power and the high efficiency it presents, comparing with other modules of this brand. The complete specifications of the selected module are presented in the table 5.2 [48]:

Table 5.2: Module specifications

Q.PEAK DUO-G7 335 Specifications	
Length [mm]	1685
Width [mm]	1000
Thickness [mm]	32
Weight [kg]	18.7
Power at MPP (P_{MPP}) [W_p]	335
Short Circuit Current (I_{SC}) [A]	10.21
Open Circuit Voltage (U_{OC}) [V]	40.89
Current at MPP [A]	9.72
Voltage at MPP [V]	34.47
Efficiency [%]	19.9
NMOT [ºC]	43
α (I_{SC}) [%/K]	0.04
β (U_{OC}) [%/K]	-0.27
γ (P_{MPP}) [%/K]	-0.35
Maximum System Voltage [V]	1000
Operating Temperature [ºC]	−40 to 85

To simplify the study of the different configurations of the PV arrays on the roof of the building, the *SolidWorks* software was used. Using the real module dimensions with the appropriate scale, considering the shading distances already discussed before, the layout of the modules was studied. This tool proved to be very useful because it not only allowed to verify with precision which areas available for placing the panels, as well as maximizing their occupation on the roof.

Two alternatives were developed, the first which has the modules tilted with the ideal inclination for Portugal (35º) and a second one, which has the modules tilted with a small and not ideal inclination (15º) but having less shading distance between the modules, this alternative has more PV modules installed than the other. Both alternatives were studied to understand which one was the best for the company needs.

Alternative 1:

The figure 5.8 represents the geometry study performed, where the blue rectangles represent the modules, having 126 modules represented. Following the procedure, considered in section 5.3.2, to calculate the minimum distance between modules, the needed values for the procedure are presented below:

- Building's latitude: Amadora 38º 74';

- Module's tilt (β): 35º;
- Module width: 1 m;
- Solar declination: 23º 27'.

Using those values, the results are:

- d1 = 1.33 m;
- d2 = 0.82 m;
- d = 2.15 m;

Thus, the modules must be placed 2.15 m from each other.

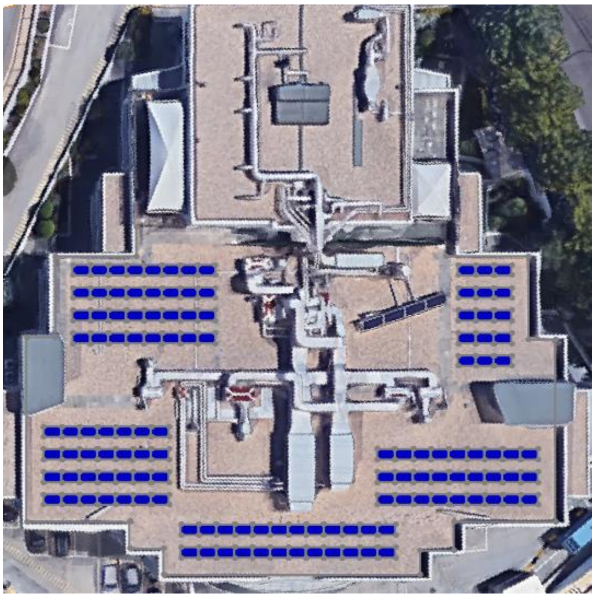

Figure 5.8: Initial displacement of the PV modules

However, after inputting the proposed PV arrays on Sunny Design, the decision of removing the 5 rows of 3 modules, placed on the upper left corner was taken. With these rows the design became too complex and the search for the appropriate inverter to use became very extensive. Thus, the final layout of the PV modules is represented on the figure 5.9. It was proposed the utilization of 111 modules on this project, tilted 35º and placed facing to the wall on the roof, having an 11º azimuth angle. The choice of orienting the modules this way instead of placing them facing the optimal orientation, south, was done due to geometrical reasons, having the rows of modules parallel to the wall allows for more modules to be installed.

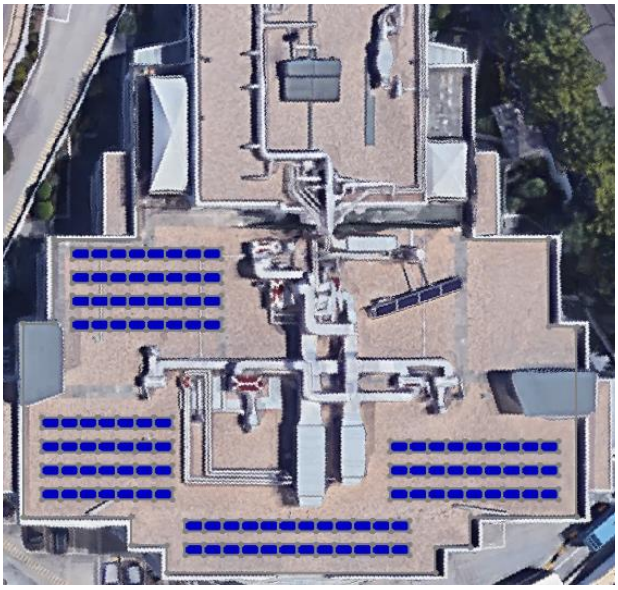

Figure 5.9: Alternative 1 - Selected layout for the PV modules

Alternative 2:

The figure 5.10 represents the geometry study performed, where the blue rectangles represent the modules. For this alternative, it was proposed the utilization of 147 modules on this project, tilted 15º and just like the previous alternative, they were placed facing to the wall on the roof, having an 11º azimuth angle. This geometry allows the system to have more modules installed, since the shading distance were reduced amongst the modules. However, the tilt angle of modules is not ideal, which will affect the modules' efficiency and performance, nevertheless it is expected that this alternative produces more energy since it enables the installation of more power. Just like in alternative 1, following the same procedure, to calculate the minimum distance between modules, the needed values for the procedure are presented below:

- Building's latitude: Amadora 38º 74';
- Module's tilt (β): 15º;
- Module width: 1 m;
- Solar declination: 23º 27'.

Using those values, the results are:

- d1 = 0.60 m;
- d2 = 0.97 m;
- d = 1.57 m;

Thus, the modules must be placed 1.57 m from each other.

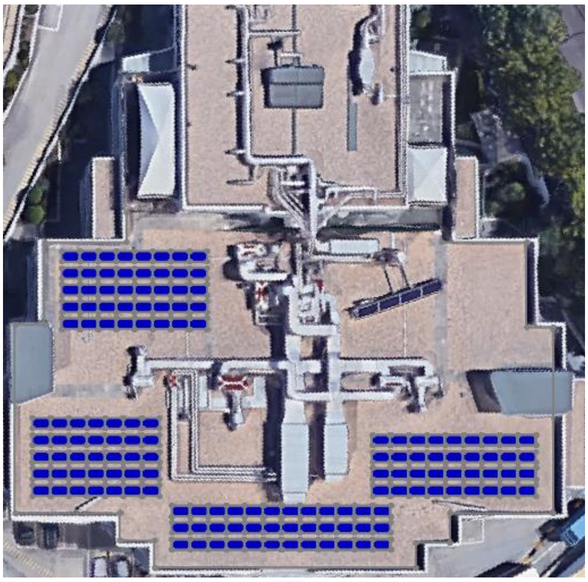

Figure 5.10: Alternative 2 - Selected layout for the PV modules

5.8 Selected inverter

The selection of inverters was focused on high-quality modular equipment, thoroughly established in the market. Brands such as Kaco, Fronius, ABB, Kostal, Siemens and SMA have been taken into consideration. SMA was the best match for the mapped photovoltaic system among all the brands of inverters examined, since it provided the PV system with more acceptable power values. One of the advantages of choosing an SMA inverter is the provided software *Sunny Design* that supports the planning of the project.

After inputting the chosen PV modules and the different PV arrays created, the software supports the search of the most suitable inverter, providing automatic designs and suggestions to the user.

Alternative 1:

The decision of using two inverters was made and the selected inverters' model was the SMA STP 20000TL-30. At first sight, this does not appear to be the most economical solution since having a single central inverter would minimise the costs. However, less energy would be generated, because there would be an increase in the current produced in the system and therefore, larger losses would be felt in the cables due to the joule effect. The complete specifications of the selected inverter are presented in the table 5.3 [49]:

Table 5.3: Alternative 1 - Inverter specifications

SMA STP 20000TL-30 Specifications	
Length [mm]	264

Height [mm]	682
Width [mm]	661
Weight [kg]	61
Rated Power DC [kW]	20.44
Rated Power AC [kW]	20
MPP Voltage [V]	320 to 800
Max Input Current DC	33
Nº of inputs DC	2
Operating temperature range [ºC]	-25 to 60
Efficiency [%]	98

<u>Alternative 2:</u>

For this system, it was used four inverters, the selected model was the SMA STP 15000TL-30. Just like, the previous alternative, the use of four inverters might not be the best solution economically, but during the dimension phase on the software used, it was the best solution found, meeting all the needed criteria. The complete specifications of the selected inverter are presented in the table 5.4 [49]:

Table 5.4: Alternative 2 - Inverter specifications

SMA STP 15000TL-30 Specifications	
Length [mm]	264
Height [mm]	682
Width [mm]	661
Weight [kg]	61
Rated Power DC [kW]	15.33
Rated Power AC [kW]	15
MPP Voltage [V]	240 to 800
Max Input Current DC	33
Nº of inputs DC	2
Operating temperature range [ºC]	-25 to 60
Efficiency [%]	98

5.9 Energetic and economic study

<u>Alternative 1:</u>

After performing the simulation to the dimensioned system on *Sunny Design*, it was time to analyse the results. The most relevant results are summarised in the table 5.5:

Table 5.5: Alternative 1 - Simulation results

Simulation Results	
Total number of PV modules	111
Peak Power [kWp]	37.19
Total number of PV Inverters	2
Nominal AC power of the PV inverters [kW]	40
AC active power [kW]	40
Active power ratio [%]	107.6
First year energy production [kWh]	64198
Performance ratio [%]	88.1
Specific energy production [kWh/kWp]	1726
Production in 25 years [kWh]	1505129.84

The number of modules chosen represents a system with 37.19 kWp of peak power. Clearly, this system is not dimensioned to fulfil the complete energy demand of the building, that consumes around 1.58 GWh per year. This kind of production would be impossible to satisfy with the available area, nevertheless, the system was optimised to fulfil the energy demand as much as possible. The performed simulation predicted a production of 64198 kWh in the first year, this value represents a 4.06% of the total annual energy consumption of 2019. In terms of production per month, as shown in the graph in the figure 5.11 below, it appears that for the summer months the production values are in between 6000 kWh and 7200 kWh and for the winter months in between 3000 kWh and 5000 kWh. This makes sense, since the solar irradiation is greater in the summer, enabling more energy production.

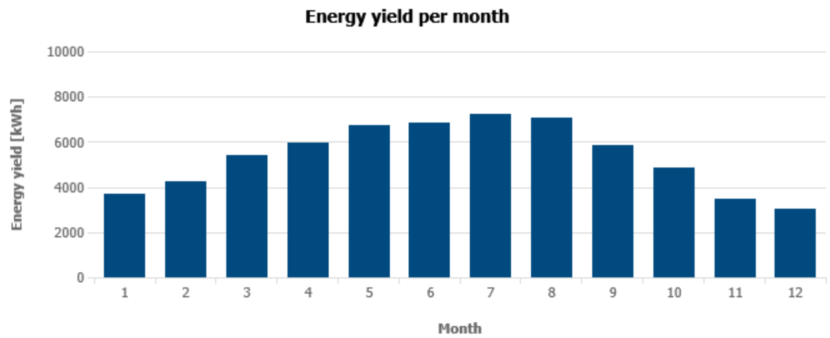

Figure 5.11: Alternative 1 - Energy production distribution by month [50]

To assess the total viability of the project, the energy results are not enough. The economic study is crucial to determine if the project is viable or not to the company. In that sense, the economic study was performed using the *Microsoft Excel* software, and the results are in the table 5.6. It is known that the annual production of the modules will decrease with time. The modules will suffer erosion and will worn out, making its efficiency lower. According to the manufacturer, the module will suffer a maximum of 0.54% degradation per year in efficiency, conserving at least 85% of nominal power up to 25 years. The decay in efficiency per year was considered in the economic study.

Table 5.6: Alternative 1 - Economic Study [51] and [52]

Economic Study	
Module's price [€/unit]	128.85
Inverter's price [€/unit]	2519
Total project investment (111 modules + 2 inverters) [€]	19340.35
First year total production [kWh]	64198
First year total savings in electricity [€]	2937.7
PP [years]	7.02
NPV	20 010.18 €
IRR	14%

Alternative 2:

After performing the simulation to the dimensioned system on *Sunny Design*, it was time to analyse the results. The most relevant results are summarised in the table 5.7:

Table 5.7: Alternative 2 – Simulation results

Simulation Results	
Total number of PV modules	147
Peak Power [kWp]	48.91
Total number of PV Inverters	4
Nominal AC power of the PV inverters [kW]	60
AC active power [kW]	60
Active power ratio [%]	122.7
First year energy production [kWh]	83459
Performance ratio [%]	88.8
Specific energy production [kWh/kWp]	1706
Production in 25 years [kWh]	1956706.30

The number of modules chosen represents a system with 48.91 kWp of peak power, a value greater than the previous alternative. Clearly, this system is dimensioned to produce more power than the alternative 1 however it is still not dimensioned to fulfil the complete energy demand of the building. The performed simulation predicted a production of 83459 kWh in the first year, this value represents a 5.28% of the total annual energy consumption of 2019. In terms of production per month, as shown in the graph in the figure 5.12 below, just like the previous alternative, the production is greater in the summer, ranging from 7500 kWh and 10100 kWh and for the winter months in between 3000 kWh and 6000 kWh. The main difference between the two alternatives relies on the summer months production, since in the winter, the production values range around the same values for both systems. On an energy standpoint, the second alternative might seem better than the alternative 1, due to having more power installed, the system produces more energy, representing a bigger share in the total annual energy consumption

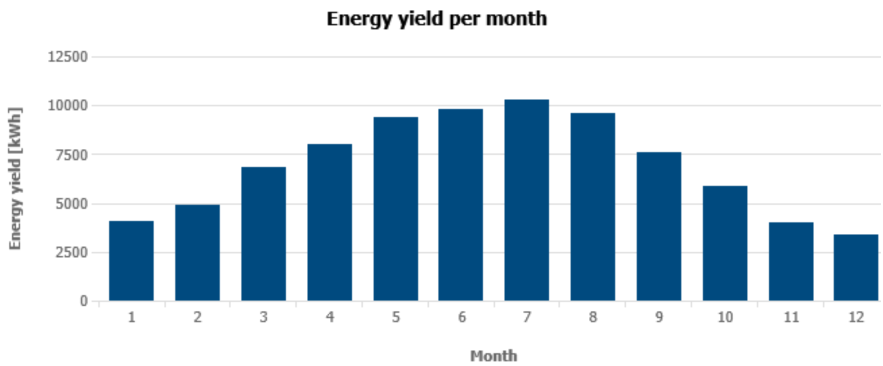

Figure 5.12: Alternative 2 - Energy production distribution by month [50]

Just like in the previous alternative, to assess the total viability of the project, the energy results are not enough. The economic study is crucial to determine if the project is viable or not to the company. In that sense, the economic study was performed using the *Microsoft Excel* software, and the results are in the table 5.8.

Table 5.8: Alternative 2 – Economic study [51] and [53]

Economic Study	
Module's price [€/unit]	128.85
Inverter's price [€/unit]	2345
Total project investment (147 modules + 4 inverters) [€]	28320.95
First year total production [kWh]	83459
First year total savings in electricity [€]	3819.08
PP [years]	7.91
NPV	22 835.67 €
IRR	12%

5.10 Results analysis

The results show a viable investment for the company for both alternatives. It is important to refer that the NPV was calculated using the modules lifetime as the time period and a discount rate of 5%.

On the alternative 1, the payback period achieved was 7.02 years, which, considering the 25 years as the average lifetime of the modules, represents a return in the investment in only 28% of the time of the investment. The NPV returned a 20010.18€ of profit after 25 years. The IRR achieved was 14% for the same number of years.

On the alternative 2, the payback period achieved was 7.91 years, which, considering the 25 years as the average lifetime of the modules, represents a return in the investment in only 31.6% of the time of the investment, being higher than the first alternative, but still low considering the complete time period of the investment. The NPV returned a 22835.67€ of profit after 25 years. The IRR achieved was 12% for the same number of years.

The estimation of the installation costs of the PV system on the roof of the building presents some difficulties, since it is necessary that specialised technical teams visit the building to check all the conditions of the site. For this reason, the cost associated with the installation of this system were not considered.

The alternative 2 presents a greater investment. Having more modules and inverters installed, the investment costs are considerably higher than the ones for the alternative 1, both differing on around 9000€. However, this alternative represents more savings, producing more 30% on both energy and monetary savings than the first alternative.

Just by looking at the financial indicators, the alternative 2 has a higher payback period, a lower IRR and a higher NPV, this higher NPV means that the company would have more 2825.49€ of profit, than the first alternative, at the end of the lifetime of the modules. The margin between the two alternatives is not considerable enough to make this alternative more viable than the first, since the other two indicators favour the first alternative.

There are two favourable viewpoints that the company can consider. The first, assessing the problem with the intend of generating more energy savings and less emissions, the alternative 2 is the one to consider. The second, with the intend of having a more economically viable solution, the alternative 1 is the one to consider.

5.11 Generated savings

The energetic savings produced by the PV system were estimated for the lifetime of the modules and calculated considering the legislation nº 17313/2008. The results obtained are summarised in the table 5.9:

Table 5.9: Summary of the energetic and emissions savings

	Alternative 1		Alternative 2	
	Energetic Savings [toe]	**Reduction in CO_2 emissions [kg CO_2]**	**Energetic Savings [toe]**	**Reduction in CO_2 emissions [kg CO_2]**
In the first year	13.80	30173.06	17.94	39225.73
Lifetime (25 years)	323.60	707411.03	420.69	919651.97

According to the *PORDATA* database in 2018, in Portugal:

- The production of electricity coming from Photovoltaic technology was 87000 toe [54];
- The emission of CO_2 per capita was 5000 kg CO_2 / habitant [55];

Comparing this data with the results obtained, one can see that using the alternative 1, the saving in emissions of the first year are enough to cover the CO_2 emissions of 6 people and the lifetime energy production represents 0.37% of the total national production, but if using the alternative 2, the annual saving in emissions would be enough to cover the CO_2 emissions of 7 people and the lifetime energy production represents 0.48% of the total national production.

Chapter 6

COVID-19 effect on energy efficiency

In 2020, the world faced a health and economic crisis, the coronavirus disease 2019 (COVID-19) pandemic, caused by the outbreak of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). This outbreak was declared, by the World Health Organization, a public health emergency of International concern on the 30th of January 2020, and a pandemic on the 11th of March 2020.

This virus spreads mainly through the air in the dispersion of droplets when people breathe, cough, sneeze, or speak or it might also be spread via contaminated surfaces. Being the mouth, nose and eyes the canals of transmission. The symptoms vary from person to person, being identified as the main symptoms: fever, dry cough, tiredness, and loss of sensations. In some case, people are asymptomatic.

When COVID-19 pandemic spread in Europe, governments imposed unprecedented confinement measures and remote work with mostly unknown repercussions on contemporary societies. The pandemic affected all sectors, especially the economy. Companies had to close and reduce severely their productivity. This led to the closure of some businesses because of the impactful financial hit.

This subject is relevant for this dissertation because companies are facing times of adaptation having to follow the recommendations placed by the world health organization. Some of these recommendations imply an increase of energy consumption, so it is important to study ways of following the recommendations in a more energy efficient way to not significantly increase the annual cost of electricity.

6.1 Regulations

The main regulations implemented by Direção Geral de Saúde (DGS) focuses on the blocking of the dissemination of the virus through the purity of the air, meaning filtering and introducing new air to the spaces as much as possible. The result is an inevitable increase in energy consumption, due to the HVAC system. Some service buildings might have windows in their spaces that allow cross ventilation and thus reduce the energy consumption, maintaining the entry of fresh air and good air quality.

In relation to ventilation, some advocate the use of natural ventilation only, but when having buildings with a high occupancy rate, the needs for fresh air flow are not met and, therefore, it is needed a mechanical ventilation. However, HVAC systems are known to play an active role in pathogen dissemination, if not adequately maintained and operated. When the building has more than one air handling unit, the communication zones between the units must be closed. There is some risk of taking the virus from one place to another, but if the volume is increased at which the virus is distributed, the concentration gets lower.

The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) and Federation of European Heating, Ventilation and Air Conditioning Association (REHVA) published a guidance document for HVAC users and operators for the operation optimization during the COVID-19 outbreak [56]. The use of higher supply air flow and exhaust ventilation and fixation of a lower CO_2 set point (400 ppm) are emphasized in these measures. It is also advisable for offices equipped with split units or windows unit air conditioning to force regular natural ventilation. REHVA stresses that the exhaust system in washrooms should always be turned on because the chance of aerosolization due to flushing could increase the risk. Also, the recirculation mode should not be used during the pandemic time to assure complete renovations of air, which implicates an increase in energy consumption.

Other important parameters in the virus control strategies are temperature and humidity, being the required temperature and humidity to stop the dissemination equal to 34 ºC and 60-80% respectively. Unfortunately, these values are not within the comfort levels of the occupant, which means these parameters cannot used as a control strategy in the work environment.

6.2 Particle spread

In specific indoor environments that are confined to lower ventilation rates, lack of dedicated return air channel, insufficient pressure, the risk of infection through airborne virus-laden aerosols may be higher.

If two people are in an indoor environment, even if far apart from each other, there are always draughts, whether of thermal origin or by the existence of ventilation, which causes particles to spread in space. A recent study suggested that aerosolized SARS-CoV2 remains viable in the air with a half-life in the order of 1 h in a laboratory-controlled environment [57]. However, due to variations in temperature, relative humidity and UV penetration, the half-life in ambient conditions can vary. In addition, research from the earlier SARS CoV-1 outbreak concluded that the HVAC system was a virus transmission pathway [58].

The small size of coronavirus particles (aerosols) enables them to stay airborne and potentially travel long distances through duct airflow. Aerosols are associated with the droplets that come out of people’s breath when they cough, speak or sneeze, and their size is less than 10 micrometres of diameter. These drops quickly lose the liquid phase and only the nucleus remains, which is the solid residue, allowing it to remain in suspension. Comparing two droplets, one of 10 micrometres of diameter and another of 100, the droplet of 100 is 10 times bigger in terms of linear dimension but it is 1000 times bigger in terms of volume. The capacity to transport viral load of a 100 micrometre droplet is much greater than the carrying capacity of a 10 micrometre particle. However, the 100 micrometre particle will fall within a certain distance from the person that expelled it, while the 10 micrometre particle stays in suspension in the air. Larger particles, when emitted, are more likely to bring viral load, but on the receiving side, smaller particles are more likely to be inhaled.

Further research is required to ascertain the contribution of this particles as a potential route of spread and its importance compared to other routes of transmission, mainly direct contact via large droplets. Efficient concentration, viability, size and lifetime of the virus in the air particulate matter are the essential missing variables. Another critical aspect that must be addressed is the biological and chemical composition of the virus-laden aerosols in the air.

6.3 Influence in the energy consumption of the SIBS' building

In this specific case, SIBS was affected greatly. In Portugal, alike some countries in Europe, during the first months of the spread of the virus, a lot of companies had to close and have their personnel work from home. SIBS was no exception, changing the occupancy rate of 800 people daily to only 160 people. This affected the logistic and organization, having to adapt as best as possible. Due to the decrease of people working in the building, the energy consumption of the building in the year 2020, decreased comparing to 2019 registered consumptions. The figure 6.1 shows the comparison of the consumption values of the year 2019 and 2020. These values were obtained using the same time period, starting at January 1st, until December 21st of the respective year. Comparing the consumption for that time period, the year 2019 registered a consumption of 1.54 GWh and the year 2020 registered a consumption of 1.40 GWh, indicating a 9.1% of decrease.

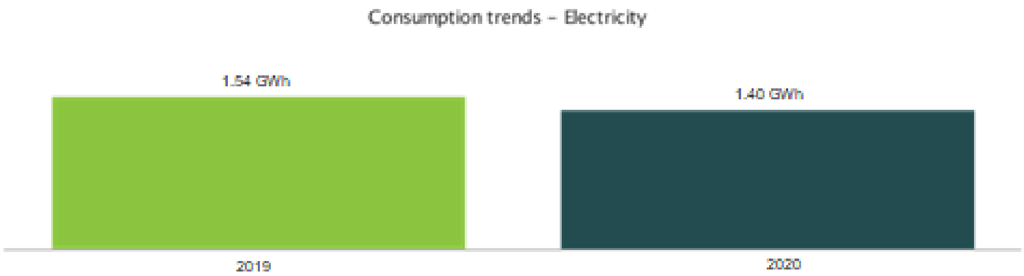

Figure 6.1: Energy consumption of the SIBS's building in the years of 2019 and 2020, until the day December 21st

The decrease in consumption is easily justified by the decrease of occupancy rate. This means, less energy consumption equipment turned on. In 2020, the HVAC system consumption share was 50.87%, representing a consumption of 713.28 MWh, while in 2019, the HVAC system consumed 740.25 MWh, representing a 48.03% share. The increase of the HVAC system share was expected due to the implemented regulations, that obligate the increase in ventilation on the different spaces in the building, also having less energy consuming systems, due to having less occupation, the share in the total consumption had to increase. However, the consumption itself of the HVAC system decreased, what was not expected. This can also be justified due to the decrease of the occupation rate since less spaces in the building were occupied meaning they did not need to be climatized. The lack of spaces needed to be climatized helped to balance the consumption of the HVAC system, even though the ventilation increased in the climatized spaces.

Comparing the consumption of the months of march until July of 2020 (see figures 6.2), when the regulations started to be implemented, with the same months of 2019 (see figure 6.3), in 2020 the HVAC system consumed 286.78 MWh, representing a 52.35% share, while in 2019, the same system consumed 284.38 MWh, representing a 47.16% share. Thus, in those months, in 2020 the system consumed more energy than in 2019 even with less people in the building.

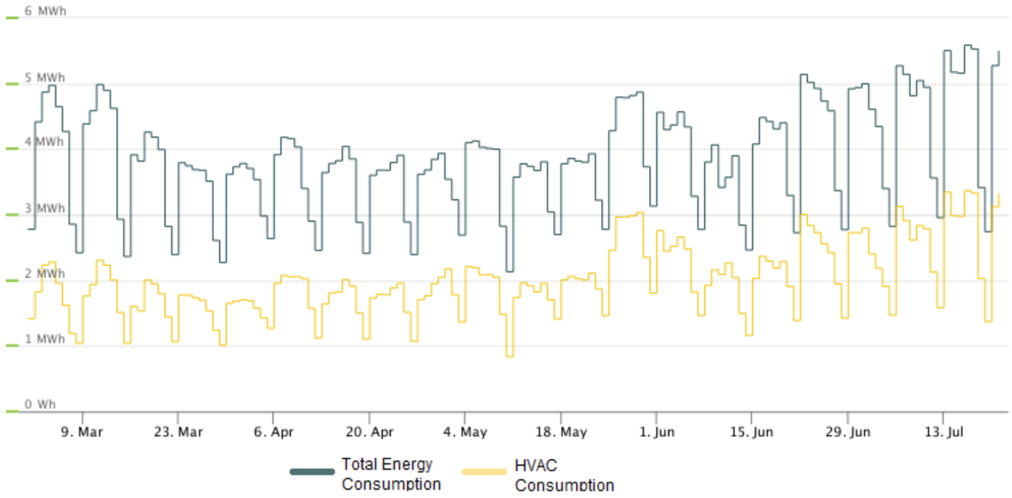

Figure 6.2: Total consumption and HVAC system consumption from March to July 2020

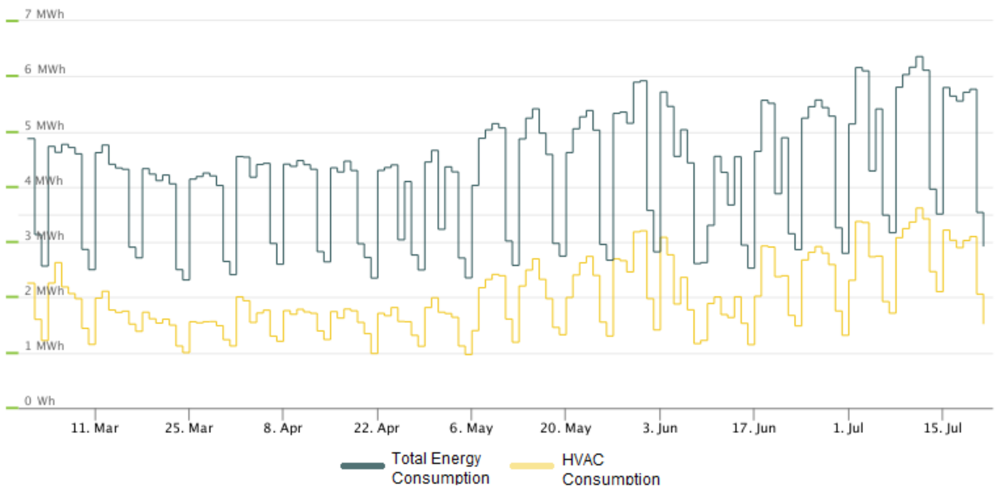

Figure 6.3: Total consumption and HVAC system consumption from March to July 2019

When looking at the consumption of energy per person, it has increased substantially from one year to another, since the consumption values are of the same order of magnitude, having only 20% of the usual occupancy rate. Even though the effect of COVID-19 haven not been felt on the total numbers of energy consumption in 2020, one can predict that if the occupation rate had not decreased, and the ventilation still increased as it was regulated, the energy consumption of the building would increase substantially.

Chapter 7

Conclusions and future work

7.1 Conclusions

Buildings are in a process of transformation, shifting from being major energy consumers to more sustainable systems capable of generating, storing, and providing energy. Aligned with the strong political incentive in terms of legislation, which promotes investment in systems and equipment less harmful to the environment, especially in the sector of photovoltaics, and with the new technological advances registered in recent years in the same vein, it has been make it more and more advantageous for both public entities and institutions, to invest in this kind of technologies in order to amortize the increasing energy demand that today's world requires.

With all the knowledge acquired before, during and after the internship, it was possible to promote two energy efficiency measures to the building in study, designing functional, balanced, efficient and financially viable options for the company, even with the limitations found throughout the project. Realizing which are the best options for each of the various steps was a challenge that, in the end, was successfully overcome.

The proposed measures were the replacement of the current luminaries with more energy efficient ones and the installation of a photovoltaic system on the roof of the building. An energetic and technical analysis was performed to both projects. From the technical analysis, the main results to point out are the following:

- The proposed luminaries lowered the share of energy spent with the lighting of the studied six open space offices from 7.78% to 4.06% generating 58811.6 kWh in annual savings;
- Two alternatives were proposed for the photovoltaic system. A more efficient one with 111 modules distributed through the rooftop of the building, having an installed power of 37.19 kWp, producing in the first year of operation 64198 kWh. The second alternative although less efficient, had more power installed, with 48.91 kWp, having 147 modules in the system.

Regarding the economic analysis, carried out with the software *Microsoft Excel*, the main results to point out are the following:

- The analyses to new luminaries were carried out comparing each type of lamp used. The generated NPV’s range in between 14.65€ to 2886.69€, producing IRR’s between 5% to 7%, having an average of 8 years of payback period for each type of lamp;
- The PV systems proposed generated NPV’s of 20010.18€ and 22835.67€ respectively, and IRR’s ranging from 12 to 14%, having a payback period of less than 8 years.

In this way, if both measures are applied, there is potential of decreasing the annual energy demand of the building in 9%, generating annual energy saving of around 142270.6 kWh, making the company save around 6592.34€ a year. Also, it would reduce the CO_2 emissions in 9%, generating a 66867.18 kg reduction.

To finish the work, a study was carried out to understand the influence of the COVID-19 pandemic in the energy consumption of the building. For that a comparison between 2019 and 2020 energy consumption values was done. It was verified that the energy consumed per person increased in 2020 because, even though, the occupancy rate of the building decreased 5 times, the required space ventilation increased. This did not change the total energy consumption of the building, having registered similar values of consumption to the previous year, however the personnel in the building were comparatively much less.

7.2 Future work

To really utilize the proposed measures in this dissertation, would be important to contact the different suppliers directly, in this case OSRAM, Philips and Hanwha, to determine the bulk price of the required equipment, since in this case study only the singular price for each was considered. Also, specialized technicians in the installation of PV modules in buildings should visit the facilities to properly assess all the costs in the project and give a concrete budget for the investment.

Another measure that should be considered in the future is the installation of PV modules vertically in the south façade of the building. Since there are no other buildings around that generate shading on this façade, the potential of energy production of these implementation could be high. Looking at the façade, it can be predicted the installation of around 60 to 80 more modules, what would imply a considerable increase in energy production and consequently in energy and monetary savings. Also, if the company is not interested in installing PV modules on the façade, since it could ruin the aesthetic of the building, the installation of PV modules on the exterior spaces near the parking lots should be considered. Once again, it would increase the potential energy and monetary savings for the company.

Bibliography

[1] “2020 climate & energy package | Climate Action.” https://ec.europa.eu/clima/policies/strategies/2020_en (accessed Oct. 26, 2020).

[2] “2030 climate & energy framework | Climate Action.” https://ec.europa.eu/clima/policies/strategies/2030_en (accessed Oct. 26, 2020).

[3] “2050 long-term strategy | Climate Action.” https://ec.europa.eu/clima/policies/strategies/2050_en (accessed Oct. 26, 2020).

[4] “Energy performance of buildings directive | Energy.” https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en#facts-and-figures (accessed Oct. 27, 2020).

[5] S. C. M. Hui, *Energy benchmarking for buildings and plant engineering*. 2010.

[6] A. C. de Oliveira Veloso, R. V. Gonçalves de Souza, and F. N. dos Santos, “Energy benchmarking for office building towers in mild temperate climate,” *Energy Build.*, vol. 222, pp. 12–14, 2020, doi: 10.1016/j.enbuild.2020.110059.

[7] X. Sun, Z. Gou, and S. S. Y. Lau, “Cost-effectiveness of active and passive design strategies for existing building retrofits in tropical climate: Case study of a zero energy building,” *J. Clean. Prod.*, vol. 183, pp. 35–45, 2018, doi: 10.1016/j.jclepro.2018.02.137.

[8] W. R. A. Ryckaert *et al.*, “Performance of LED linear replacement lamps*,” *Light Eng.*, vol. 20, no. 1, pp. 129–139, 2012.

[9] L. Xu, Y. Pan, Y. Yao, D. Cai, Z. Huang, and N. Linder, “Lighting energy efficiency in offices under different control strategies,” *Energy Build.*, vol. 138, pp. 127–139, 2017, doi: 10.1016/j.enbuild.2016.12.006.

[10] N. Luewarasirikul, “A Study of Electrical Energy Saving in Office,” *Procedia - Soc. Behav. Sci.*, vol. 197, no. February, pp. 1203–1208, 2015, doi: 10.1016/j.sbspro.2015.07.379.

[11] A. Capozzoli, M. S. Piscitelli, A. Gorrino, I. Ballarini, and V. Corrado, “Data analytics for occupancy pattern learning to reduce the energy consumption of HVAC systems in office buildings,” *Sustain. Cities Soc.*, vol. 35, no. August, pp. 191–208, 2017, doi: 10.1016/j.scs.2017.07.016.

[12] H. Thermoregulation, “Chapter 8: Thermal comfort,” *ASHRAE Handb.*, no. Gagge 1937, 2001.

[13] S. S. Shahzad, J. Brennan, D. Theodossopoulos, B. Hughes, and J. K. Calautit, “Energy Efficiency and User Comfort in the Workplace: Norwegian Cellular vs. British Open Plan Workplaces,” *Energy Procedia*, vol. 75, pp. 807–812, 2015, doi: 10.1016/j.egypro.2015.07.135.

[14] S. Salimi and A. Hammad, “Optimizing energy consumption and occupants comfort in open-plan offices using local control based on occupancy dynamic data,” *Build. Environ.*, vol. 176, no. March, p. 106818, 2020, doi: 10.1016/j.buildenv.2020.106818.

[15] J. Jurasz and P. E. Campana, “The potential of photovoltaic systems to reduce energy costs for office buildings in time-dependent and peak-load-dependent tariffs,” *Sustain. Cities Soc.*, vol. 44, no. July 2018, pp. 871–879, 2019, doi: 10.1016/j.scs.2018.10.048.

[16] “Solar energy.” https://www.irena.org/solar (accessed Oct. 06, 2020).

[17] “EU solar boom: over 100% solar market increase in 2019 – SolarPower Europe.” https://www.solarpowereurope.org/eu-solar-boom-over-100-solar-market-increase-in-

2019/ (accessed Oct. 06, 2020).

[18] “REN - Publicações.” https://www.ren.pt/pt-PT/media/publicacoes/ (accessed Oct. 31, 2020).

[19] “Energia - Principais números.” https://www.dgeg.gov.pt/pt/estatistica/energia/publicacoes/energia-principais-numeros/ (accessed Oct. 31, 2020).

[20] “Energia em números.” https://www.dgeg.gov.pt/pt/estatistica/energia/publicacoes/energia-em-numeros/ (accessed Oct. 31, 2020).

[21] “Why did renewables become so cheap so fast? And what can we do to use this global opportunity for green growth? - Our World in Data.” https://ourworldindata.org/cheap-renewables-growth?fbclid=IwAR1U5wZyY_2--MziGWN4pFJZ8qUNPGw1agxwQT1ISCX_u-aU2veRiDPLVCk (accessed Dec. 16, 2020).

[22] “Solar PV module prices.” https://ourworldindata.org/grapher/solar-pv-prices (accessed Dec. 16, 2020).

[23] “Long read: UNSW’s Martin Green sets out solar’s accelerating technological development – pv magazine Australia.” https://www.pv-magazine-australia.com/2018/05/27/long-read-unsws-martin-green-sets-out-solars-accelerating-technological-development/ (accessed Dec. 16, 2020).

[24] República Portuguesa, “Diário da República: Decreto-Lei n.º 162/2019 de 25 de outubro,” pp. 45–62, 2019.

[25] Despacho nº 15793-F, “Zonamento Climático,” *Diário da República*, vol. 2.ª série, no. 234, pp. 26–31, 2013.

[26] “Photovoltaic Geographical Information System (PVGIS) | EU Science Hub.” https://ec.europa.eu/jrc/en/pvgis (accessed Dec. 03, 2020).

[27] “WiseMetering | A Sua Solução de Gestão Energética.” https://www.wisemetering.com/ (accessed Dec. 03, 2020).

[28] “Períodos horários.” https://www.ceve.pt/tarifarios/periodos-horarios (accessed Dec. 03, 2020).

[29] I. Superior, “Notes to support the discipline of Project Management , of the Integrated MSc in Mechanical Engineering INDEX,” 2017.

[30] D.-G. de E. e Geologia, “Despacho nº17313, 2ªSérie - n.122,” *Diário da Répulica*, pp. 27912–27913, 2008.

[31] Celma and A. Pears, “Apples & Pears , a CELMA guiding paper : Why standardisation of performance criteria for LED luminaires is important,” pp. 1–12, 2011.

[32] “What is CRI? The ultimate guide to the Color Rendering Index | Waveform Lighting.” https://www.waveformlighting.com/tech/what-is-cri-color-rendering-index (accessed Nov. 13, 2020).

[33] Technical Committee CEN/TC 169 “Light and Lighting,” “Light and lighting - Lighting of work places - Part 1 : Indoor work,” *Eur. Stand.*, vol. 3, pp. 1–43, 2002, doi: http://www.din.de.

[34] “Portaria 17-A/2016, 2016-02-04 - DRE.” https://dre.pt/web/guest/pesquisa/-/search/73441202/details/normal?q=Portaria+n.º 349-D%2F2013 (accessed Nov. 15, 2020).

[35] “Catálogos | Lledo.” https://www.lledoblogportugal.com/catalogos-2/ (accessed Nov. 13, 2020).

[36] “SubstiTUBE T5 UN | OSRAM DS.” https://www.osram.com/ecat/SubstiTUBE T5 UN-LED tubes-Lamps-Digital Systems/com/en/GPS01_3234447/PP_EUROPE_Europe_ErP/ (accessed Nov. 24, 2020).

[37] “MASTER tubo LED InstantFit equipamentos eletrônicos T5 Tubos LED - Philips.” https://www.lighting.philips.pt/prof/lampadas-e-tubos-led/tubos-led/master-tubo-led-instantfit-equipamentos-eletronicos-t5 (accessed Nov. 24, 2020).

[38] “SubstiTUBE T8 UN | OSRAM DS.” https://www.osram.pt/ecat/SubstiTUBE T8 UN-Tubos de LED-Lâmpadas-Digital Systems/pt/pt/GPS01_3124682/ (accessed Dec. 04, 2020).

[39] “MASTER tubo LED Universal T8 Tubos LED - Philips.” https://www.lighting.philips.pt/prof/lampadas-e-tubos-led/tubos-led/master-tubo-led-universal-t8 (accessed Dec. 04, 2020).

[40] B. Jamil and E. Bellos, “Development of empirical models for estimation of global solar radiation exergy in India,” *J. Clean. Prod.*, vol. 207, pp. 1–16, Jan. 2019, doi: 10.1016/j.jclepro.2018.09.246.

[41] A. Cavaco, H. Silva, P. Canhoto, S. Neves, J. Neto, and M. Collares Pereira, “Radiação Solar Global em Portugal e a sua variabilidade, mensal e anual,” p. 32, 2016, [Online]. Available: http://www.ipes.pt/ipes/wp-content/uploads/2017/10/Radiação-Solar-Global-em-Portugal-e-a-sua-variabilidade.pdf.

[42] A. Al-Khazzar, “A comprehensive solar angles simulation and calculation using Matlab,” *Int. J. ENERGY Environ.*, vol. 6, pp. 367–376, Jun. 2015.

[43] “Comissão Europeia – Projeto GREENPRO. Energia Fotovoltaica – Manual sobre tecnologias, projeto e instalação. Janeiro, 2004.” https://www.portal-energia.com/downloads/guia-tecnico-manual-energia-fotovoltaica.pdf (accessed Nov. 19, 2020).

[44] “Energyland - Solar Photovoltaic.” https://www.emsd.gov.hk/energyland/en/energy/renewable/solar_photovoltaic.html (accessed Dec. 18, 2020).

[45] L. Ahmad, N. Khordehgah, J. Malinauskaite, and H. Jouhara, “Recent advances and applications of solar photovoltaics and thermal technologies,” *Energy*, vol. 207, p. 118254, 2020, doi: 10.1016/j.energy.2020.118254.

[46] “Solar Cell I-V Characteristic | Alternative Energy Tutorials.” https://www.alternative-energy-tutorials.com/energy-articles/solar-cell-i-v-characteristic.html (accessed Dec. 15, 2020).

[47] “Solar Photovoltaics | Impact of shading.” http://www.greenrhinoenergy.com/solar/performance/shading.php (accessed Dec. 04, 2020).

[48] “Q.PEAK DUO-G7 : Q.PEAK DUO G7 Series : SOLAR PANELS : PRODUCTS : Q CELLS.” https://www.q-cells.com/en/main/products/solar_panels/G7/G7_series01.html (accessed Dec. 01, 2020).

[49] “SUNNY TRIPOWER 15000TL / 20000TL / 25000TL | SMA Solar.” https://www.sma.de/en/products/solarinverters/sunny-tripower-15000tl-20000tl-25000tl.html (accessed Dec. 01, 2020).

[50] “SUNNY DESIGN.” https://www.sunnydesignweb.com/sdweb/#/ (accessed Dec. 04,

2020).

[51] “Q Cells Q.PEAK DUO-G7 335 Wp Solar Panel - inutec solarcenter international gmbh.” https://www.inutec-int.com/us/qpeak-duo-g7.html (accessed Dec. 03, 2020).

[52] “SMA Sunny Tripower 20000TL-30 | SMA STP 20000TL-30 inverter | Europe Solar Store.” https://www.europe-solarstore.com/sma-sunny-tripower-20000tl-30.html (accessed Dec. 03, 2020).

[53] “SMA Sunny Tripower 15000TL-30 | SMA STP 15000TL-30 inverter | Europe Solar Store.” https://www.europe-solarstore.com/sma-sunny-tripower-15000tl-30.html (accessed Dec. 18, 2020).

[54] “PORDATA - Energias renováveis no balanço energético.” https://www.pordata.pt/Portugal/Energias+renováveis+no+balanço+energético-1128-9124 (accessed Dec. 03, 2020).

[55] “PORDATA - Emissões de gases por habitante.” https://www.pordata.pt/Portugal/Emissões+de+gases+por+habitante-1256 (accessed Dec. 03, 2020).

[56] Ashrae, “ASHRAE Position Document on Infectious Aerosols,” 2020. Accessed: Dec. 23, 2020. [Online]. Available: www.ashrae.org.

[57] G. Kampf, D. Todt, S. Pfaender, and E. Steinmann, “Persistence of coronaviruses on inanimate surfaces and their inactivation with biocidal agents,” 2020, doi: 10.1016/j.jhin.2020.01.022.

[58] T. F. Booth *et al.*, “Detection of Airborne Severe Acute Respiratory Syndrome (SARS) Coronavirus and Environmental Contamination in SARS Outbreak Units,” 2005. Accessed: Dec. 23, 2020. [Online]. Available: https://academic.oup.com/jid/article/191/9/1472/862003.

Appendix A

Inverter Designs

A.1 Alternative 1

Inverter designs

Project: SIBS	**Location: Portugal / Amadora**
Project number:	**Ambient temperature:**
	Annual extreme low temperature: 4 °C
	Average high Temperature: 24 °C
Subproject Projecto parcial 1	Annual extreme high temperature: 38 °C

1 x SMA STP 20000TL-30 (PV system section 1)

Peak power:	17.09 kWp
Total number of PV modules:	51
Number of PV inverters:	1
Max. DC power (cos φ = 1):	20.44 kW
Max. AC active power (cos φ = 1):	20.00 kW
Grid voltage:	220V (220V / 380V)
Nominal power ratio:	120 %
Dimensioning factor:	85.4 %
Displacement power factor cos φ:	1
Full load hours:	1487.2 h

SMA STP 20000TL-30

PV design data

Input A: 2
24 x Hanwha Q.Cells GmbH Q.PEAK DUO-G7 335 (06/2019), Azimuth angle: 11 °, Tilt angle: 30 °, Mounting type: Ground mount

Input B: 3
27 x Hanwha Q.Cells GmbH Q.PEAK DUO-G7 335 (06/2019), Azimuth angle: 11 °, Tilt angle: 30 °, Mounting type: Ground mount

	Input A:	**Input B:**
Number of strings:	2	3
PV modules:	12	9
Peak power (input):	8.04 kWp	9.05 kWp
Typical PV voltage:	✓ 394 V	✓ 295 V
Min. PV voltage:	370 V	277 V
Min. DC voltage (Grid voltage 220 V):	150 V	150 V
Max. PV voltage:	✓ 519 V	✓ 389 V
Max. DC voltage:	1000 V	1000 V
Max. MPP current of PV array:	✓ 19.4 A	✓ 29.2 A
Max. operating input current per MPPT:	33 A	33 A
Max. input short-circuit current per MPPT:	43 A	43 A
Photovoltaic Output Circuit Current:	✓ 20.4 A	✓ 30.6 A

Inverter designs

Project: SIBS
Project number:

Subproject Projecto parcial 1

Location: Portugal / Amadora
Ambient temperature:
Annual extreme low temperature: 4 °C
Average high Temperature: 24 °C
Annual extreme high temperature: 38 °C

1 x SMA STP 20000TL-30 (PV system section 2)

Peak power:	20.10 kWp
Total number of PV modules:	60
Number of PV inverters:	1
Max. DC power (cos φ = 1):	20.44 kW
Max. AC active power (cos φ = 1):	20.00 kW
Grid voltage:	220V (220V / 380V)
Nominal power ratio:	102 %
Dimensioning factor:	100.5 %
Displacement power factor cos φ:	1
Full load hours:	1722.7 h

SMA STP 20000TL-30

PV design data

Input A: 1
32 x Hanwha Q.Cells GmbH Q.PEAK DUO-G7 335 (06/2019), Azimuth angle: 11 °, Tilt angle: 30 °, Mounting type: Ground mount

Input B: 2
28 x Hanwha Q.Cells GmbH Q.PEAK DUO-G7 335 (06/2019), Azimuth angle: 11 °, Tilt angle: 30 °, Mounting type: Ground mount

	Input A:	Input B:
Number of strings:	4	4
PV modules:	8	7
Peak power (input):	10.72 kWp	9.38 kWp
Typical PV voltage:	263 V	230 V
Min. PV voltage:	247 V	216 V
Min. DC voltage (Grid voltage 220 V):	150 V	150 V
Max. PV voltage:	346 V	303 V
Max. DC voltage:	1000 V	1000 V
Max. MPP current of PV array:	38.9 A	38.9 A
Max. operating input current per MPPT:	33 A	33 A
Max. input short-circuit current per MPPT:	43 A	43 A
Photovoltaic Output Circuit Current:	40.8 A	40.8 A

A.2 Alternative 2

Inverter designs

Project: SIBS
Project number:

Subproject Projecto parcial 1

Location: Portugal / Amadora
Ambient temperature:
Annual extreme low temperature: 4 °C
Average high Temperature: 24 °C
Annual extreme high temperature: 38 °C

2 x SMA STP 15000TL-30 (PV system section 1)

Peak power:	23.45 kWp
Total number of PV modules:	70
Number of PV inverters:	2
Max. DC power (cos φ = 1):	15.33 kW
Max. AC active power (cos φ = 1):	15.00 kW
Grid voltage:	220V (220V / 380V)
Nominal power ratio:	131 %
Dimensioning factor:	78.2 %
Displacement power factor cos φ:	1
Full load hours:	1337.6 h

SMA STP 15000TL-30

PV design data

Input A: 1
17 x Hanwha Q.Cells GmbH Q.PEAK DUO-G7 335 (06/2019), Azimuth angle: 11 °, Tilt angle: 15 °, Mounting type: Ground mount

Input B: PV array 1
18 x Hanwha Q.Cells GmbH Q.PEAK DUO-G7 335 (06/2019), Azimuth angle: 11 °, Tilt angle: 15 °, Mounting type: Ground mount

	Input A:	Input B:
Number of strings:	1	2
PV modules:	17	9
Peak power (input):	5.70 kWp	6.03 kWp
Typical PV voltage:	558 V	295 V
Min. PV voltage:	524 V	277 V
Min. DC voltage (Grid voltage 220 V):	150 V	150 V
Max. PV voltage:	735 V	389 V
Max. DC voltage:	1000 V	1000 V
Max. MPP current of PV array:	9.7 A	19.4 A
Max. operating input current per MPPT:	33 A	33 A
Max. input short-circuit current per MPPT:	43 A	43 A
Photovoltaic Output Circuit Current:	10.2 A	20.4 A

Inverter designs

Project: SIBS
Project number:

Subproject Projecto parcial 1

Location: Portugal / Amadora
Ambient temperature:
Annual extreme low temperature: 4 °C
Average high Temperature: 24 °C
Annual extreme high temperature: 38 °C

2 x SMA STP 15000TL-30 (PV system section 2)

Peak power:	25.46 kWp
Total number of PV modules:	76
Number of PV inverters:	2
Max. DC power (cos φ = 1):	15.33 kW
Max. AC active power (cos φ = 1):	15.00 kW
Grid voltage:	220V (220V / 380V)
Nominal power ratio:	120 %
Dimensioning factor:	84.9 %
Displacement power factor cos φ:	1
Full load hours:	1444.3 h

SMA STP 15000TL-30

PV design data

Input A: 1
20 x Hanwha Q.Cells GmbH Q.PEAK DUO-G7 335 (06/2019), Azimuth angle: 11 °, Tilt angle: 15 °, Mounting type: Ground mount

Input B: PV array 1
18 x Hanwha Q.Cells GmbH Q.PEAK DUO-G7 335 (06/2019), Azimuth angle: 11 °, Tilt angle: 15 °, Mounting type: Ground mount

	Input A:	**Input B:**
Number of strings:	2	2
PV modules:	10	9
Peak power (input):	6.70 kWp	6.03 kWp
Typical PV voltage:	✓ 328 V	✓ 295 V
Min. PV voltage:	308 V	277 V
Min. DC voltage (Grid voltage 220 V):	150 V	150 V
Max. PV voltage:	✓ 433 V	✓ 389 V
Max. DC voltage:	1000 V	1000 V
Max. MPP current of PV array:	✓ 19.4 A	✓ 19.4 A
Max. operating input current per MPPT:	33 A	33 A
Max. input short-circuit current per MPPT:	43 A	43 A
Photovoltaic Output Circuit Current:	✓ 20.4 A	✓ 20.4 A