MASTERS IN MANAGEMENT (MIM)

MASTERS FINAL WORK

PROJECT

A PATH TO SUSTAINABLE ENERGY:
A SOLAR POWER INITIATIVE FOR ISEG

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Lastly, I would like to dedicate this work to my mom, who used to tell me "Whatever you decide to do in life, make sure it makes you happy". Thank you for all the learnings, you made me who I am, and this is for you.

ABSTRACT

This project explores the importance of transitioning to renewable energy sources, due to the strong environmental impacts of industrialization and fossil fuel consumption. Within ISEG's framework, several initiatives implemented in recent years reflect a holistic approach to sustainability, covering waste management, community awareness, academic integration, and carbon emissions inventory (ISEG, 2023). The university is committed to promoting strategies that can help mitigate climate change, including the integration of renewable energy technologies within the campus, to align with both Portuguese and United Nations 2030 sustainability goals.

With this in mind, the main purpose of this study is to propose the adoption of photovoltaic (PV) panels at ISEG, due to their cost-effectiveness and promising forecasts that have positioned this technology as a key energy source of the future. To achieve this objective, the study employed secondary data research methodologies, including a thorough literature review, ongoing discussions with ISEG's staff, and the analysis of historical data. Additionally, the technical and economic viability was examined, identifying the main drivers and potential drawbacks of this technology.

Furthermore, two scenarios were analyzed to simulate the number of panels needed to achieve a minimum of 10% renewable energy production by 2030, as stipulated by the Portuguese Energy Efficiency Program in Public Administration (ECO.AP). The results revealed that ISEG has the rooftop infrastructure and geographical location to even surpass this target by strategically deploying solar panels in underutilized areas across the campus.

In this context, the solar PV initiative not only contributes to reducing the university's carbon footprint and optimizing its energy efficiency but also fosters an environmental stewardship culture focused on promoting sustainable practices within the entire ISEG's academic community.

Keywords: Renewable Energy, Solar Photovoltaic Panels, Sustainability, ECO.AP, Carbon Footprint, Energy Efficiency, Environmental Stewardship

RESUME

Este projeto explora a importância da transição para fontes de energia renovável, devido aos fortes impactos ambientais da industrialização e do consumo de combustíveis fósseis. Dentro do contexto do ISEG, diversas iniciativas implementadas nos últimos anos refletem uma abordagem holística à sustentabilidade, abrangendo gestão de resíduos, conscientização comunitária, integração acadêmica e inventário de emissões de carbono (ISEG, 2023). A universidade está comprometida em promover estratégias que possam ajudar a mitigar as mudanças climáticas, incluindo a integração de tecnologias de energia renovável no campus, para alinhar com os objetivos de sustentabilidade de Portugal e das Nações Unidas para 2030.

Com isso em mente, o principal objetivo deste estudo é propor a adoção de painéis fotovoltaicos (PV) no ISEG, devido à sua eficácia econômica e previsões promissoras que têm posicionado essa tecnologia como uma fonte de energia chave do futuro. Para alcançar este objetivo, o estudo empregou metodologias de pesquisa de dado secundários, incluindo uma revisão abrangente da literatura, discussões em curso com a equipe do ISEG e análise de dados históricos. Adicionalmente, a viabilidade técnica e econômica foi examinada, identificando os principais impulsionadores e potenciais desvantagens dessa tecnologia.

Além disso, foram analisados dois cenários para simular o número de painéis necessários para alcançar um mínimo de 10% de produção da energia renovável até 2030, conforme estipulado pelo Programa de Eficiência Energética na Administração Pública (ECO.AP). Os resultados revelam que o ISEG possui a infraestrutura de telhado e a localização geográfica para para ultrapassar este objetivo, através da instalação estratégica de painéis solares em áreas subutilizadas do campus.

Neste contexto, a iniciativa solar fotovoltaica não só contribui para reduzir a pegada de carbono da universidade e otimizar a sua eficiência energética, mas também fomenta uma cultura de gestão ambiental centrada na promoção de práticas sustentáveis em toda a comunidade académica do ISEG.

Palabras-chave: Energia Renovável, Painéis Fotovoltaicos Solares, Sustentabilidade, ECO.AP, Pegada de Carbono, Eficiência Energética, Gestão Ambiental

ABBREVIATIONS (IF APPLICABLE)

°C: Degree Celsius

ADENE: in English *Agency for Energy*

AC: Alternating Current

AI: Artificial Intelligence

CAPEX: Capital Expenditures

CdTe: Cadmium Telluride

CHP: Combined heat-and-power

CO2: Carbon dioxide

CO2e: Carbon dioxide emissions

COP: Conference of the Parties

CSP: Concentrated Solar Power

DC: Direct Current

DNI: Direct Normal Irradiation

ECEEE: European Council for an Energy-Efficient Economy

ECO.AP: Energy Efficiency Program in Public Administration in English

EDP: in Portuguese *Energias de Portugal*

EJ: Exajoule

ESMAP: Energy Sector Management Assistance Program

EU: European Union

EUR: Euros

Fraunhofer ISE: Fraunhofer Institute for Solar Energy Systems

GHI: Global Horizontal Irradiance

GHG: Greenhouse Gas Emissions

GW: Gigawatt

IEA: International Energy Agency

IEA-PVPS: International Energy Agency – Photovoltaic Power Systems Programme

IPCC: Intergovernmental Panel on Climate Change

IRENA: International Renewable Energy Agency

J: Joule

kW: Kilowatt

kWh: Kilowatt-hour

kWh/m^2: Kilowatt-hour per square meter

kWp: Kilowatt-peak

LCOE: Levelized Cost of Electricity

m^2: Square meter

MW: Megawatt

NPV: Net Present Value

O&M: Operation and Maintenance

PNEC: National Energy and Climate Plan in English

P_{max}: Maximum Power Output

PV: Photovoltaic

PVOUT: Photovoltaic Power Output

REN: *Redes Energéticas Nacionais* in Portuguese

RES: Renewable Energy Sources

ROI: Return on Investment

SDG: Sustainable Development Goal

UN: United Nations

UNFCC: United Nations Framework Convention on Climate Change

USD: US dollar

VAT: Value Added Tax

W: Watt

W_p: Watt-peak

WEEE: Waste Electrical and Electronic Equipment directive

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1. INTRODUCTION

1.1 Contextualization

Over the years, there has been an important debate concerning global warming and the urgent need to reinforce initiatives to mitigate its impacts. As escalating temperatures and unprecedented weather phenomena continue to manifest, there is an increasing necessity for countries to collectively transition towards more sustainable and clean energy sources (Schleussner et al., 2016). Within this context, the Paris Agreement, an international treaty signed in 2015 by 196 nations, aims to limit the temperature increase to 1.5°C and achieve the peak and subsequent reduction of greenhouse gas (GHG) emissions by no later than 2030 (United Nations Framework Convention on Climate Change [UNFCCC], 2015). During the same year, the United Nations (UN, 2015) established a 2030 agenda consisting of 17 Sustainable Development Goals (SDGs), which demand a series of substantial socioeconomic modifications and serve as an international call to action to address diverse challenges including poverty, health, education, inequality, and environmental conservation.

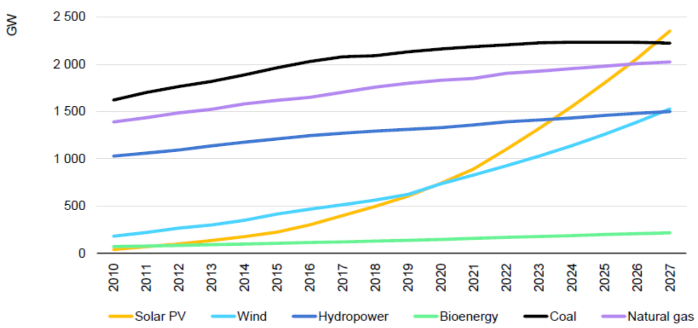
In view of this alarming panorama, it is imperative to emphasize that carbon dioxide (CO2) emissions, commonly recognized as 'carbon footprints', are the primary contributors to the GHG effect, also known as global warming. These emissions have risen by 50% over the past two centuries due to human activities, mainly driven by the exponential growth in population, industrialization, deforestation, and the combustion of fossil fuels to generate electricity. These activities have resulted in elevated levels of air pollution, presenting imminent risks to both human populations and ecosystems (Yu et al., 2023; Picano et al., 2023; Cao et al., 2016; Pacesila et al., 2016), such as biodiversity loss, human health diseases, heat-related mortality, and damage to urban infrastructure (Intergovernmental Panel on Climate Change [IPCC], 2023). Moreover, according to Ge et al. (2022), China is the largest contributor to global GHG emissions (measured in CO2e per capita), accounting for 26.4% of the total emissions in 2019, next to the United States, India, and the European Union at 12.5%, 7.06% and 7.03%, respectively. In addition, the International Energy Agency (IEA, 2022a) identified the power sector as the economic activity with the highest carbon emissions impact over the past 4 years, followed by other sectors such as transportation, industrial processes, and buildings (Ge et al., 2022). Consequently, Pell et al. (2021) explain that one of the biggest challenges of transitioning to cleaner energy is related to the high initial costs of both manufacturing materials and grid integration. Nevertheless, Zhang et al. (2021) stress the value of this transition, particularly in the post-COVID-19 pandemic era, due to the positive effects that green innovation has on promoting low-carbon development. Furthermore, as a potential solution to minimize global warming and achieve The Paris Agreement targets, Makešová & Valentová (2021) highlight the significance of implementing robust policies to encourage the development of renewable energy sources (RES), considering technical, financial, social, and environmental aspects. An example of this is the European Commission's 'Energy Union Plan', established in 2015 with three primary objectives focusing not only on promoting sustainability but also on ensuring a secure energy supply for all European citizens and enhancing competitiveness through advancing research (European Council for an Energy-Efficient Economy [ECEEE], 2023). In addition, in 2019 the 'European Green Deal' was established to tackle environmental and climate challenges to make Europe a resource-efficient economy and a pioneer in having net-zero emissions by 2050 (Miłek et al., 2022). For instance, in 2022, Europe held 23% of renewable energy, with Sweden (66%), Finland (47.9%), and Latvia (43.3%) emerging as the leading clean energy producers (European Commission, 2023).

Every year, the Conference of the Parties, often abbreviated as COP, is organized to approve international treaties, and promote initiatives in favor of addressing climate change. According to the latest conference, COP28 et al. (2023), the fundamental strategies to fulfill the 1.5°C target by 2030 require "tripling renewable power and doubling energy efficiency" (p. 17). Thus, investing in clean energy technologies is crucial to secure a resilient infrastructure for future generations and minimize dependency on fossil fuels such as coal, oil, and natural gas (Yu et al., 2023), which have been identified as significant contributors to the escalation of environmental damage (Martins et al., 2019). In this context, Russia plays a significant role as a major exporter of fossil fuels due to the increasing concerns about energy security after the invasion of Ukraine in February 2022. This event underscored the urgent need to adopt renewable energy sources and encourage a circular economy. In response, the European Commission launched the 'REPowerEU plan' to cease reliance on Russian fossil fuels by 2027 (IEA, 2022b).

Moreover, a variety of renewable energy technologies have been incorporated in various contexts, including solar, wind, geothermal, hydro, and bioenergy. Nonetheless, the viability and effectiveness of each technology relies on several factors, such as the area of implementation, weather conditions, and the specific geographic context (Cao et al., 2016; Qazi et al., 2019; Østergaard et al., 2022). Additionally, the economic aspect holds significant relevance as it determines the capability to implement such infrastructures, considering that, not all countries have the financial resources to embark on these initiatives (Muwanga et al., 2023). According to the IEA (2019), Europe as well as other industrialized nations have shown a greater willingness to adopt green energy technologies in comparison to less developed nations, due to the absence of regulations, laws, and economic incentives. As a case study, Du & Li (2019) categorized countries into groups according to their income distribution. Their analysis indicated that countries with higher incomes display a stronger commitment to lowering carbon emissions and conserving the environment. In this manner, as stated by the IEA (2022b), major economies including China, the United States, India, and the European Union, are actively implementing the necessary reforms not only to address the energy crisis by 2030 but also to curtail their elevated pollution levels.

Furthermore, the IEA (2022b) is projecting an accelerated growth in wind turbines and solar photovoltaic (PV) panels, as part of the energy transition processes. Nevertheless, solar PV has shown a consistent upward trend compared to wind turbines, mainly due to its cost-effectiveness. Also, forecasts indicate that in 2027, solar PV will emerge as the most extensively installed power capacity with more than 2,000 gigawatts (GW), surpassing wind, hydropower, coal, and natural gas, as illustrated in Figure 1.

Figure 1: Cumulative power capacity by technology, 2010-2027



Source: IEA (2022b).

In addition, according to the IEA Photovoltaic Power Systems Programme (IEA-PVPS, 2019) during the mid-2000s, Europe's high energy demand for solar PV also led to a significant expansion of the global PV industry and opened the opportunity for Chinese manufacturers to enter the market. This resulted in China emerging as a leading player in the production and consumption of PV panels across the globe while also reaching a maturity level and driving consistent price reductions for customers.

Similarly, Victoria et al. (2021) underscored that solar power has been showing a substantial capacity to emerge as the primary energy substitute for fossil fuels, due to the advanced stage of its technological innovation. The authors stated that compared with other RES, solar PV technology faces minimal constraints in terms of components, land utilization, and integration with the power grid and electricity system. Furthermore, Fouad et al. (2020) explained that another key advantage lies in the seamless incorporation of solar PV into the architectural design of rooftop buildings. Additionally, Scognamiglio (2016), explains the flexibility that solar PV panels offer in terms of ecological landscape and emphasizes that, given their prevalent adoption, this technology can be easily integrated as a fundamental element of both urban and rural landscapes. Besides, the energy derived from the sun, known as 'solar radiation', is a free resource that can be accessed by any country. However, its amount fluctuates depending on the geographical location of each region, reaching its minimum levels near the poles, and peaking at its maximum near the equator (Eicke et al., 2022).

Moreover, the Energy Sector Management Assistance Program (ESMAP), in collaboration with the World Bank, aims to enhance economic growth and support low and middle-income countries by implementing renewable energy technologies. In 2017, this program launched the 'Global Solar Atlas' project with the objective of mapping and assessing solar resource availability across the world (ESMAP, 2020; World Bank, 2017). According to ESMAP (2020), the viability of solar energy can be analyzed through metrics such as global horizontal irradiance (GHI), which represents the theoretical potential of solar resources in a specific area, and direct normal irradiation (DNI), that evaluates an approximate surface's exposure to ultraviolet solar radiation. Alternatively, the photovoltaic power output (PVOUT) measured in kWh/kWp illustrates the practical power capacity each PV unit installed can generate, providing a more reliable estimation than GHI and DNI metrics when analyzing the viability of solar PV panels in a specific region, since it considers seasonality factors like air temperature, soiling, terrain horizon, shading, and module orientation. As a result, ESMAP (2020) determined that solar PV has the greatest potential in almost 70% of the global population where the optimal PVOUT is between 3.5 and 4.5 kWh/kWp, specifically in regions such as the Middle East, North Africa, Southern European countries, Australia, the United States, Canada, and South America. For instance, Gonçalves et al. (2020) analyzed the feasibility of implementing solar energy technologies in Portugal. According to their analysis, the country presents a positive suitability, due to its substantial solar irradiation capacity, demonstrating Portugal's promising potential for embracing and adopting solar power solutions.

Additionally, Leal et al. (2019) emphasize the importance for higher education institutions to adopt renewable energy sources to mitigate their carbon footprint, as they can be considered as 'small cities'. Some of the energy uses include lighting, heating, ventilation, and cooling, among others. In this context, the authors conducted extensive research and surveyed 50 universities from different countries, including Portugal. Their findings showed that approximately half of the universities rely on renewable energy, producing between 1% and 20% of their energy on-site. In fact, solar PV emerged as the most prevalent source, representing 70% of energy generation choices within these institutions. In addition, Valls-Val & Bovea (2021) encourage higher education institutions to assume a proactive role in combatting climate change, by constantly developing initiatives to raise environmental consciousness inside the community. Since universities include a wide range of educational populations, different buildings, and green areas, they must develop strategies to monitor and reduce their emissions to facilitate action plans and align with sustainability goals.

In this way, the deployment of renewable energy sources, particularly solar PV technology, presents a practical solution to speed up the energy transition. Furthermore, this approach not only promotes optimization but also streamlines energy infrastructures within societies (ESMAP, 2020).

1.2 Objectives

The main purpose of this project is to analyze the feasibility of implementing solar PV panels at ISEG - Lisbon School of Economics & Management, aiming to meet both Paris Agreement objectives and ECO.AP 2030 energy production target, which seeks to maximize energy efficiency by generating at least 10% of clean energy on-site

(ECO.AP, 2020). Furthermore, the project endeavors to conduct a comparison of solar PV systems with other clean energy technologies and present a comprehensive evaluation of the economic viability, advantages, disadvantages, and potential implications associated with integrating solar PV technology into the institute's energy framework.

1.3 Structure

The project is structured into five chapters: Introduction, Literature Review, Methodology, Project Description, and Conclusions. Each chapter contributes to a comprehensive understanding of energy efficiency, solar power, renewable sources, and the importance of deploying clean energy technologies to mitigate carbon emissions and global warming within ISEG's framework. The 'Introduction' chapter provides context about fossil fuels and their environmental impact, explaining the causes that forced the transition to renewable energy technologies. Also, it explains future trends and positions solar PV as a favorable source for global warming mitigation. The 'Literature Review' chapter outlines the main types of solar energy, emphasizing solar PV technology and its current market. It discusses key aspects of solar PV implementation, as well as its benefits, challenges, and cases related to integrating solar energy into educational campuses. This section highlights the role of institutions in meeting Paris Agreement Targets and includes a comparative analysis with other renewable energy sources within the education context. Later, the 'Methodology' section serves as a roadmap of the data research approaches implemented to achieve the proposed objectives. Furthermore, the 'Project Description' chapter discusses the current panorama of ISEG and the motivation behind the integration of solar PV panels as one of the main renewable energy sources for electricity generation. Additionally, it displays a simulation of the solar PV system, outlining two main scenarios for this integration, key inputs, assumptions, data collected, and a financial analysis to determine the project's viability. In the final chapter, 'Conclusions', the results and main findings of the solar PV initiative for ISEG are examined, alongside its limitations and suggested areas for future research.

2. LITERATURE REVIEW

2.1. Introduction

Nowadays, the most accessible energy source on Earth is solar radiation, and as supportive policies and investments in it increase, so does its economic appeal (Nijsse et al., 2023). In the year 2000, Germany was a pioneer country that launched the first regulatory scheme to guarantee users new incentives and tariffs to make the transition to solar power alternatives (Eicke et al., 2022). Since then, solar energy has been recognized as one of the most eco-friendly energy sources since it plays an important role in mitigating GHG emissions and global warming (Alhamrouni et al., 2020; Sharif et al., 2021; Ang et al., 2022).

According to IEA (2023), the annual energy consumption amounts to 442 EJ. In theory, this could be fulfilled with enough sunshine in less than two hours, especially in regions with high solar irradiance levels (Eicke et al., 2022). Therefore, the sun has the potential to meet all of humanity's energy needs - establishing it as a fundamental and sustainable energy source (Hayat et al., 2019). Notably, there are two kinds of solar technologies: solar PV and concentrated solar power (CSP), also known as 'solar thermal'. The former involves directly converting solar energy through PV cells and is particularly effective for smaller to medium-scale installations. On the other hand, CSP can capture both small and large amounts of solar radiation through mirrors or lenses since they facilitate the conversion of sunlight to produce steam for electricity generation (Ahmadi et al., 2018).

According to Ang et al. (2022) at low temperatures, solar thermal energy is mainly employed in residential settings for water heating and climate control. Conversely, at higher temperature levels, CSP requires collectors to intensify sunlight, especially in industrial-scale power generation settings. For instance, Hayat et al. (2019) mentioned that the textile, culinary, and chemical sectors are among the most common uses. However, they tend to have a more complex structure than PV panels, since they require parabolic troughs, or power towers to focus solar radiation (Hayat et al., 2019; Khan & Arsalan, 2016). In this sense, both PV and CSP methods provide diverse solar solutions that can be adaptable to the specific characteristics of each installation size and energy requirements.

2.3 Solar PV Technology

Solar PV panels consist of many solar cells that are interconnected in series or parallel circuits to increase the amount of voltage generated (Obaideen et al., 2023). These cells are typically made of silicon, which is a semiconductor material that often comprises two layers, one of which generates a positive charge and the other a negative charge, resulting in the creation of an electric current or 'PV effect' when exposed to the sun (Bagher et al., 2015; Ahmed et al., 2022).

Solar PV technologies are considered versatile due to their ability to power residential, commercial, and industrial facilities (Ledmaoui et al., 2023). However, there are some distinctions between these three uses. For instance, commercial settings typically include institutions and business facilities that provide a more flexible installation due to their larger size and available area to fulfill greater energy demands compared to residential settings. Whereas a standard home can contain 60 to 72 cells, commercial solar panels can consist of 96 cells or even more, depending on the energy consumption profile (Zito, 2023). On the contrary, industrial facilities involve installations dedicated to manufacturing, agricultural, or production processes that require an engineering design that can resist challenging environmental conditions, or even a higher energy output and a longer lifespan. These types of facilities can even contribute to enhanced energy self-sufficiency technologies by generating their power without recurring to the main electricity grid (Rodríguez-Martinez & Rodríguez-Monroy, 2021; Akshay, 2023). Thus, solar PV technologies play a key role in capturing and transforming solar radiation into clean electrical energy. It is worth mentioning that the efficiency of this conversion is measured by the panels or module's ability to convert solar irradiance into electricity, which is usually expressed as a percentage (Ledmaoui et al., 2023). Also, when comparing solar panels, it is important to consider the maximum power output 'P_{max}' (measured in watt-peak or W_p) that can be generated under standard irradiation conditions, meaning 25°C per 1000 W/m^2 (Al-Ezzi & Ansari, 2022; del Cañizo et al., 2009). Recent advances in solar technology have shown an increment in the average conversion rate from 15% to more than 22%. This efficiency is primarily influenced by the manufacturing material and the size of the cells, providing an average power output between 250 W to over 420 W. For instance, implementing silicon as a baseline material and increasing the surface area for sunlight absorption, can result in an efficiency rate above 22% and power ratings even higher than 700 W (Svarc, 2024).

Furthermore, a solar PV system includes inverters that transform the direct current (DC) produced by the panel into alternating current (AC), to make it suitable for use in wall outlets (Eicke et al., 2022). In addition, most solar panels consist of two protective layers: a front glass layer that acts as a shield from sun rays' exposition and drastic temperature changes, and a polymer back sheet that offers electrical insulation from the environment, safeguarding the panels from mechanical harm and deterioration from corrosion under standard conditions. Normally, these two layers are supported by an aluminum frame structure that gives inclination and orientation to the panel (Sharma et al., 2022; Buerhop-Lutz et al., 2021). Besides these elements, the installation of solar panels also involves electrical protection devices, transmission lines, control equipment, and transformers to create a 'balanced system'. These components are essential to guarantee a secure operation and regulate voltage levels to improve energy efficiency distribution (Eicke et al., 2022). Oftentimes, solar PV incorporates fixed mounting systems or in some cases, sun-tracking techniques to allow the panels optimal alignment with the sun (Ahmadi et al., 2018).

Moreover, if the solar PV system operates on-grid, it means that the electricity produced on-site interacts with the municipality network or service provider, where any surplus can be fed back to the electrical grid. This practice is called 'net metering' and can result in savings on the electricity bill or even generate additional income depending on the location and regulatory framework. On the other hand, stand-alone PV systems are independent of the grid and rely on energy-storing batteries and backup generators (Obaideen et al., 2023). Usually, these batteries operate through cycles and need to be replaced, on average, every 5 years depending on their normal usage (Rathore et al., 2021). Additionally, the price of the batteries is proportional to the demand, meaning that higher demand leads to increased battery prices, and vice versa (Meral & Dinçer, 2011). The batteries could represent an additional cost of around 9,200 USD alongside operations, maintenance, and repair expenses (Eicke et al., 2022; Brill & Ogletree, 2024). An alternative option known as 'hybrid solar PV' combines both grid-tied and stand-alone PV systems, providing flexibility to the user. Nevertheless, this method comes with higher investment costs due to the requirement of battery banks for backup when needed (Brill & Ogletree, 2024).

The evolution of solar PV technology has been categorized into three generations in the literature, each distinguished by efficiency, types of materials, durability, and overall performance. In the 1950s, the first generation laid the foundation for solar energy with silicon crystal cells as the primary manufacturing material, enabling easy utilization of sunlight energy (Allouhi et al., 2022). By the 1980s, newer technologies emerged with thin-film solar cells, such as amorphous silicon cells that offered increased flexibility and lower costs compared to previous versions (Ahmadi et al., 2018; Allouhi et al., 2022). Moving into the 2000s, third-generation technologies incorporated new resources and styles, including organic materials and polymers, which are generally more affordable and eco-friendlier compared to first-generation options. Additionally, these technologies aim to enhance the efficiency of second-generation PV cells while offering a shorter lifespan due to reduced production costs (Rathore et al., 2021; Obaideen et al., 2023; Hayat et al., 2019). While this stage is still progressing, scientists are exploring innovative alternatives like concentrated solar PV that employ multi-junction cells for higher efficiency rates of up to 40%, which can stand higher temperatures above standard conditions (Jakhar et al., 2016; Hayat et al., 2019). Nonetheless, they usually require larger space than other solar modules, and their manufacturing process tends to be costly, since this technology utilizes several semiconductor materials to improve its performance within larger facilities such as agricultural farms (Obaideen et al., 2023).

The most commercial solar PV technologies are monocrystalline, polycrystalline, and amorphous silicon cells – also known as 'thin-film' cells (Ahmad et al., 2020; Eicke et al., 2022; Fraunhofer ISE, 2023). Monocrystalline PV cells are composed of one crystal structure (Ahmad et al., 2020). They are created by pulling a seed crystal from melted silicon to produce tubular blocks, that can be further sliced into uniform octagonal 'thin wafers' (Tyagi et al., 2013; Hayat et al., 2019). Their cost tends to be higher than other solar cell types due to their purity and high technology implemented (Obaideen et al., 2023), which typically ranges between 1 and 1.50 USD per Watt (Brill & Ogletree, 2024). Despite this, monocrystalline cells have been recognized for their superior performance in converting sunlight into electricity, due to their high-efficiency rates that usually fluctuate between 15% to 20%, as well as their prolonged lifetime of approximately 25 years and up to 40 years under warranty. Additionally, monocrystalline is the most recommended technology for commercial or urban settings, due to the great output and durability they offer (Kang et al., 2019; Ahmad et al., 2020). Notwithstanding, like all solar panels, it is important to consider that both efficiency and durability may decline due to the facility's geographical location, lack of regular maintenance processes, and weather conditions (Eicke et al., 2022; Brill & Ogletree, 2024).

In contrast, polycrystalline solar cells offer a more cost-effective alternative to monocrystalline cells, with prices that fluctuate between 0.90 and 1 USD per Watt, where a variety of fine crystals are utilized during the manufacturing process (Allouhi et al., 2022; Brill & Ogletree, 2024). This method usually involves melting different types of silicon and letting them solidify into big square shapes that are cut into thin wafers. In some cases, silicon ribbons are also cultivated as an alternative process with the main purpose of bypassing the need for block slicing to reduce material waste (El Chaar et al., 2011). Although this method is simpler, they are not as efficient as monocrystalline, resulting in an efficiency rate ranging from 13% to 16% (Eicke et al., 2022) and a lifespan of around 25 years (Prasad, 2021). According to Ahmad et al. (2020), another drawback of polycrystalline solar panels is their high sensitivity to elevated temperatures, which can even shorten their lifespan and reduce their efficiency performance over time.

The third alternative, thin-film solar cells, are recognized for their flexibility and lower production costs. Moreover, they have a more affordable average price compared to monocrystalline or polycrystalline options at around 0.75 and 1.10 USD per Watt. On top of that, unlike the above-mentioned solar technologies, these cells use a non-crystalline form of silicon, allowing them to be deposited into fine layers on flexible substrates such as glass, resulting in significantly reduced material usage. This option makes them lightweight and easy to integrate into various architectural sites, which also facilitates their rooftop installation (Hayat et al., 2019; Rathore et al., 2021; Brill & Ogletree, 2024). When these types of cells are arranged into a solar panel configuration, they can exhibit a good performance in capturing light, under low-illumination scenarios. Nevertheless, the efficiency rate of thin-film cells is lower than its counterparts ranging from 12% to 15% (Allouhi et al., 2022), resulting in a shorter lifespan of around 15 to 20 years, due to the non-crystalline material used during the manufacturing process. This results in decreased durability and accelerated cell degradation compared to crystalline options (Ahmad et al.,2020; Prasad, 2021).

2.4 Benchmarking Solar PV in Other Educational Institutions

Higher Educational Institutions are crucial in society due to their capability to serve as hubs of learning and innovation. Additionally, they have the potential to promote sustainability through the awareness of more eco-friendly practices and the adoption of renewable energy solutions. In addition, they can make a substantial impact on the attainment of SDGs by collaborating with both external and internal stakeholders' communities including faculty, professors, students, and staff (Purcell et al., 2019). The authors Hueske & Guenther (2021) refer to this approach as 'sustainability transformation', as it involves analyzing sustainable practices by their economic and social impact while identifying their barriers and drivers of implementation. The integration of these three concepts is also known as the 'triple bottom line' (de Oliveira et al., 2023).

In recent years, there has been a growing interest in integrating solar PV panels, especially into the urban landscape of university campuses, due to its numerous benefits associated with potential cost savings in electricity bills, reduction of GHG emissions, and flexible implementation (Olivieri et al., 2020). This importance is driven by the recognition of solar PV technology as a renewable energy source that can help achieve institutional sustainability goals while reducing reliance on fossil fuels for electricity generation (Behi et al., 2022). Additionally, institutions can benefit from net-metering incentives, allowing for credits when contributing more electricity than consumed. On the other hand, educational institutions could generate electricity within their facilities and store energy surpluses on battery banks, withdrawing the need to connect the solar system to the electricity grid, and enhancing independence and environmental conservation (Hanus et al., 2019).

Moreover, due to industrialization, it is common for urban areas to have high energy consumption levels. For this reason, these types of areas must become renewable energy producers and improve their electricity infrastructure. One of the most adopted and practical options for buildings is using rooftop PV panels that are connected to the grid (Fakhraian et al., 2021; Fouad et al., 2020). Nonetheless, transitioning to solar energy systems is a process that requires robust planning and significant capital investment. Additionally, to guarantee an optimal solution, it is important to evaluate critical factors, such as rooftop geometry, solar radiation, inclination, implementation costs, social, and environmental constraints, to analyze the energy consumer behavior and further determine if the solar PV system is viable or not (Eicke et al., 2022; Fakhraian et al., 2021).

The significance of this transition relies on the potential that universities possess to become drivers of change by educating the entire community and making alliances with governments and other institutions, in order to promote sustainability, build initiatives, and achieve the SDGs 2030 agenda (Purcell et al., 2019). Furthermore, one of the primary benefits of using renewable energy sources like rooftop PV is the opportunity for a payback period of less than 11 years, which for the case of monocrystalline options, is not even half of their typical 30-year lifespan (Fouad et al., 2020; Olivieri et al., 2020). In addition, as highlighted by Bandeiras et al. (2020), universities can benefit from governmental funds and financial support to speed up the adoption and integration of renewable energy solutions within their premises.

Moreover, when diving into the background of university campuses, it is important to note that energy requirements, demand, and consumption patterns are influenced by factors like building size, occupancy levels, equipment, seasonal variations, and teaching schedules (Leal et al., 2019). For this reason, when choosing the right solar PV panels, it becomes relevant to consider these characteristics along with the available roof area, the type of building, and the setting where the facilities are situated (residential, commercial, or industrial). Additionally, some obstructions such as water tanks and air conditioning units should be considered when designing the placement of solar PV panels, including margins between these devices to allow maintenance and avoid any disruptions. In addition, the accessibility of sunlight and the geographical location of the installation site are essential as they can have a significant impact on the efficiency and performance of the solar PV panels (Meral & Dinçer, 2011; Shi et al., 2022; Khairi et al., 2022; Karanam & Chang, 2023)

For example, Olivieri et al. (2020) analyzed the potential of implementing on-grid solar PV panels at the Polytechnic University of Madrid in Spain. The authors selected the campus *Ciudad Universitaria* (University City in English) as it represents the largest site within this institution with a maximum solar potential of 3.3 MW. Their study focused on eleven buildings that performed similar activities and chose flat rooftops to facilitate the installation. The results indicated a positive Net Present Value (NPV) and a payback period of around 11 years by selecting a monocrystalline solar panel with a lifespan of 30 years, a module efficiency of 22.1%, and a maximum power output of 360 Wp. Based on their findings, this approach could help reduce the university's carbon emissions by 30% and meet 40% of its electricity needs, demonstrating significant progress towards sustainable energy efficiency strategies. Similarly, the authors Haffaf et al. (2021) explained that rooftop PV systems allow university campuses to explode non-utilized areas to incentivize the mitigation of CO2 emissions that buildings have on the environment. In this case, the authors developed a performance analysis related to a monocrystalline grid-connected PV system installed in 2018 at the Institute University of Technology campus in Mulhouse, France. According to their analysis, between 2018 and 2020, a PV module with a maximum power of 300 Wp helped the university avoid approximately 4.17 tonnes of CO2 emissions. Furthermore, their methodology suggested that adding vertical solar tracking techniques to the system could potentialize the amount of clean energy generated by the solar PV panel, highlighting the positive role that solar PV systems have not only within the institute's sustainability framework but also in the environment.

On the other hand, Lee et al. (2016) proposed the expansion of polycrystalline solar PV systems at the University of New Haven in the United States, to analyze both economic and environmental impacts of integrating this technology around the campus. The design criteria for these panels consisted of selecting a PV module with an efficiency rate of 15.5% and a lifetime of 25 years. The results showed that with a maximum solar PV output of 300 Wp, about 8.5% of clean energy production was supplied using the solar system and around 250,000 USD could be saved on annual electricity bills. In the study of Orboiu & Andrei (2020), a simulation of implementing a polycrystalline PV system in a Public Institution in Romania was presented. The authors discussed that a PV module efficiency rate of 16.2% with a lifespan of around 30 years could potentially reduce 604 tonnes of CO2 emissions over the entire period. Additionally, they considered that seasonality factors have a strong influence on this reduction, especially during winter and summer months.

Khairi et al. (2022) evaluated the suitability of installing solar PV systems on the rooftops of eight Public Institutions in Malaysia to contribute to the country's energy sustainability targets. Their investigation conducted a comparison between monocrystalline and polycrystalline solar PV panels, with the main purpose of analyzing both options due to their location and optimal solar radiation. The authors found that monocrystalline options tend to be more expensive but more efficient even under warm weather conditions due to their high tolerance to elevated temperatures in comparison with polycrystalline solar cells. Also, both implementations resulted in reduced electricity bills and the possibility of fulfilling the total energy demands of these institutions.

Al-Otaibi et al. (2015) proposed a PV thin-film alternative for 2 Institutes in Kuwait, a country heavily reliant on oil energy production. The authors simulated the performance of a 150 Wp solar power module with a nominal efficiency rate of 14%, resulting in optimal levels of energy production for both institutions. Furthermore, the authors demonstrated a correlation between the performance and soiling losses, which contributes to the solar degradation cell. To solve this problem, they incorporated an automated cleaning technique to maximize the power output of the entire PV system and prevent any declines in its efficiency. On the other hand, the study conducted by Obeng et al. (2020) brings together the analysis of monocrystalline, polycrystalline, and Cadmium Telluride (CdTe) thin-film cells for implementing solar PV panels at the University of Energy and Natural Resources in Ghana. The results showed that in terms of space, the monocrystalline panels would occupy less area and last longer compared with their counterparts. Moreover, the authors explained that the three scenarios presented a positive NPV and optimal energy production, with thin-film technology emerging as the best choice in terms of power and economic output, meeting over 48% of the campus' electricity needs and the shortest payback period of around 6 years. Nevertheless, CdTe is a hazardous and non-biodegradable material, which represents a significant risk to the environment and human health, particularly during the manufacturing process. Unlike monocrystalline and polycrystalline, recycling thin-film panels requires a more complex treatment (Rathore et al., 2021; IRENA & IEA-PVPS, 2016).

2.5 Drivers of Implementation

The use of solar PV panels in urban universities has gained attention due to their enormous potential to generate renewable energy on-site (Olivieri et al., 2020). This has allowed universities to continue embracing environmental stewardship and align with their sustainability goals. Likewise, green initiatives can generate at the same time positive long-term effects (Bei & Wang, 2023), since it has been demonstrated that solar PV can help reduce both institutional carbon footprints and operational expenses (Zhu et al., 2023; Valls-Val & Bovea, 2021). Furthermore, implementing solar PV panels is a bridge to promote environmental awareness among the academic community to enhance consciousness for future generations (Lee et al., 2016). Besides, they can be integrated into their urban landscape by making use of underutilized spaces to generate renewable energy (Haffaf et al., 2021), as they can be installed in different parts of the campus such as rooftops (Mokhtara et al., 2021), parking lots (Karanam & Chang, 2023), and even facades of urban buildings (Drif et al., 2007).

In addition, Horan et al. (2019) indicated that university campuses can maximize their resources since they provide ideal settings to experiment with low-carbon technologies to generate a positive influence not only within the institution but also on external actors by amplifying their deployment into a broader society. Also, Karanam & Chang (2023) recommended integrating solar PV panel systems in urban university campuses due to the multiple advantages they bring, especially in buildings with higher electricity rates and regions that can benefit from greater solar radiation levels. According to the authors, solar PV systems represent an attractive sustainable cost-saving solution for universities and a financially viable option for transitioning to renewable energy sources. Also, Rathore et al. (2021) explained that rooftop PV panels can be installed without disrupting any operations.

Moreover, following correct end-of-life management, around 1.7 to 8 million tonnes of cumulative PV panel waste can be recycled through the recovery of their main raw materials such as glass, polymer, aluminum, silicon, copper, and other metals like zinc, and nickel (IRENA & IEA-PVPS, 2016). In the European Union, these processes are regulated through the Waste Electrical and Electronic Equipment (WEEE) directive, that comprises guidelines for the collection, handling, and future usability of these devices (Sharma et al., 2018).

Lastly, solar PV panels have gained widespread social acceptance due to their environmental benefits and the awareness among well-informed local communities that encourage sustainable strategies. Over the past century, positive perceptions have resulted in a higher rate of PV installation across the world, reflecting the importance of implementing clean energy sources (Segreto et al., 2020).

2.6 Challenges & Barriers of Implementation

Some of the challenges that universities may face during the implementation could lead to technical constraints, such as limited available space for panel installation and potential shading from nearby buildings and trees (Behi et al., 2022). Furthermore, it is crucial to consider that solar systems rely on sunlight - restricting their usability to daytime hours. In this context, prosumers located in regions with low irradiation levels may encounter problems due to heightened uncertainty levels in power generation or even costly energy storage batteries (Eicke et al., 2022; Crail & Tynan, 2024). Moreover, the electrical performance of solar cells can decrease over time due to dust, soiling, and corrosion, which might be attributed to various causes such as irregular cleaning practices, incorrect installation, manufacturing defects, long-term exposure to harsh UV radiation or environmental conditions like pollution, humidity, and saltwater. These factors can lead to a reduced lifespan and an accelerated deterioration rate (Sangpongsanont et al., 2020; Aboagye et al., 2022; Silva & Sareen, 2021).

On top of that, the authors Chock et al. (2021) noted that solar PV panels can affect wildlife by modifying animals' behavior and posing risks of physical harm, injuries, and mortality, due to the electromagnetic fields emitted during their normal operation. For instance, birds may suffer electrocution, insects can be vulnerable to solar flux, and bats may experience severe trauma. On the other hand, there may be regulatory barriers that involve obtaining the necessary permits and adhering to energy-efficiency building codes (Ahmed et al., 2022), resulting in the inability to install solar PV systems within university campuses. Additionally, financial constraints should be considered as universities need to account not only for high investment expenditures, but also for operation, and maintenance (O&M) costs to ensure a smooth performance and longevity of the solar PV panels (Eicke et al., 2022; ESMAP, 2020). Furthermore, universities can present integration challenges between the solar PV system and the electrical grid. As highlighted by Nwaigwe et al. (2019), this is mainly due to their compatibility and voltage stability that can affect the overall power quality and could lead to grid damage. However, the authors mentioned that in those cases, it may be necessary to renovate the grid infrastructure or adopt energy storage batteries to ensure an effective PV operation. Also, Segreto et al. (2020) discussed how social acceptance can significantly affect the implementation of solar PV panels, due to the fact local communities may have concerns about the impact these technologies will have on the environment, aesthetics, and building design. Following their study, they recommended governments to potentialize awareness campaigns and provide accurate information, to transform this inertia into possible drivers of change.

2.7 Solar PV versus Other Renewable Sources

Beyond solar energy, the leading renewable energy technologies on the market encompass hydropower, wind energy, geothermal energy, and bioenergy (Ang et al., 2022). Notably, hydropower stands out as the primary clean source for electricity generation, representing approximately 83% of the global renewable energy share (Sayed et al., 2021; Schleeter, 2024). On top of that, hydroelectrical plants are known for their high efficiency, often achieving a conversion of up to 90% (Ang et al., 2022). Their growth takes place mainly in China, where the cumulative installed capacity reached 395 GW in 2022 (Blume-Werry & Everts, 2022; Fernández, 2023a). This energy source works through the movement of water and holds the potential to power small (IRENA, 2023a) to large-scale needs, especially when incorporating dams for energy storage (Halkos & Gkampoura, 2020; IRENA, 2023c). However, based on the conducted research, it is less common for universities to implement hydropower given the specific infrastructure requirements involved.

Moreover, wind turbines capture the kinetic energy of wind and transform it into electrical energy (Njiri & Söffker, 2016). Over the years, they have gained recognition worldwide, constituting 7% of the global clean energy mix (Schleeter, 2024) due to their low production costs and smallest carbon emissions (Njiri & Söffker, 2016). At present, there are two main types of wind farms: onshore and offshore. The former involves the installation on land area, whilst the latter is situated near the sea (Ang et al., 2022; Rashad et al., 2017). On the contrary, “bioenergy originates from biological raw materials known as biomass” (Ang et al., 2022, p. 14). This typically comes from grass, plants, solid waste, wood, and crop residues. Furthermore, biomass can be converted into energy through gasification, chemical or combustion processes for some uses that include electricity generation, transportation, heating, and liquid fuels such as biodiesel (Ellabban et al., 2014; Halkos & Gkampoura, 2020; Ang et al., 2022). Nowadays, this source constitutes 7% of the global share, positioning it as one of the most important renewable energy technologies (Schleeter, 2024). Meanwhile, the energy derived from the center of the earth through organic processes is commonly referred to as ‘geothermal energy’ (Halkos & Gkampoura, 2020; Owusu & Asumadu-Sarkodie, 2016), comprising only about 2% of the total renewable energy share (Schleeter, 2024).

Certain higher education institutions have made investments in wind farms, biomass, and geothermal plants, integrating them either within or outside their facilities. One such example is the University of Delaware, which installed an onshore wind plant on its campus to produce renewable energy and provide research opportunities for students and professors (Kukich, 2014). On the other hand, the State University of New York College of Environmental Science and Forestry uses biomass as a fuel to power combined heat-and-power (CHP) systems to produce 20% of the campus's electricity needs (Ackerly, 2016). Alternatively, the University of Aveiro implemented geothermal technology to optimize heating in winter and cooling in summer. This initiative resulted in a 34% reduction in reliance on other energy sources (Pinto et al., 2017). Nevertheless, despite their many benefits, these approaches may also have negative impacts on the environment. For example, hydroelectrical projects can lead to damage and migration of fish populations (Blume-Werry & Everts, 2022), while wind farms are associated with bird strikes and heavy noise pollution (Sayed et al., 2021). In addition, bioenergy production can result in the deterioration and possible deforestation of soil and vegetation areas (Owusu & Asumadu-Sarkodie, 2016), and geothermal energy extraction may contribute to extended land use, contaminated wastewater releases, and gaseous emissions (Sayed et al., 2021).

Although solar energy currently represents less than 1% of global renewable energy (Schleeter, 2024), its potential continues to grow steadily each year, driven primarily by its cost-effectiveness and flexible implementation, especially solar PV, emerging as a promising solution for 2030 energy scenarios (IEA, 2022b). For instance, in 2022, the total installed costs of hydropower stood at approximately 2,881 USD/kW, onshore wind at 1,274 USD/kW, offshore wind at 3,461 USD/kW, bioenergy at 2,162 USD/kW, and geothermal at 3,478 USD/kW (IRENA, 2023b). In comparison, solar PV was recorded at 876 USD/kW, being these costs significantly lower than the other renewable energy technologies. Therefore, this positions solar PV as an important player in the future energy landscape and underscores the commitment of universities to mitigate carbon emissions through environmentally conscious practices. Additionally, as presented during previous sections, monocrystalline emerges as the most recommended type of solar cells, owing to their notable performance, high efficiency, and durability in comparison with polycrystalline and thin-film cells. This makes them a preferred choice for sustainable energy solutions even within university campuses.

3. METHODOLOGY

3.1 Data Research

Secondary data from scientific articles, historical reports, and contemporary sources was reviewed to guide the project's direction and provide contextualization regarding environmental consciousness, the evolution of solar PV technology, and the importance of renewable energy transition, especially within the educational framework. During this process, robust databases such as Scopus and ISEG's online libraries were utilized and further validated through Scimago JR to ensure the quality and reliability of the references consulted. This allowed the author to design the problem statement and find solutions that can be adaptable to the unique restrictions of the campus.

On the other hand, regular meetings were held with members of ISEG's Faculty, including the Vice-president for Sustainability and SDG Project Officer, to gain insights into potential areas for improvement, and analyze the need for implementing renewable energy technologies on campus to reduce carbon emissions by 2030. Furthermore, similar discussions were conducted with the Logistics & Technical Support Specialist from ISEG, who provided engineering expertise and recommended suitable rooftop areas for integrating solar PV systems. In addition, the Faculty and Professional Staff provided access to confidential information for this academic purpose, including ISEG's energy consumption record in Excel named 'Consumos Energéticos – Gabriel Llonde', the Energy Audit Reports conducted by two consulting companies, and an electricity bill from April 2023 to estimate the university monthly expenditures. These sources were crucial inputs for assessing both the economic and technical viability of the project.

3.2 Data Analysis Procedures

Firstly, an examination of PVOUT (amount of energy produced by a solar PV per unit installed capacity) was conducted to assess the feasibility of implementing solar PV panels in Lisbon, using the Global Solar Atlas online platform. This tool provides reliable data related to solar resource availability across the world, as mentioned in the introduction section. Secondly, the Excel file 'Consumos Energéticos – Gabriel Llonde' was used to calculate ISEG's average monthly energy consumption from 2019 to mid-2023. This was done by analyzing the spreadsheet named 'Pot. Ativa e Reat' and using the 'Potência Ativa kW' data from columns C, H, M, and N with the

'AVERAGE' formula in Excel. Also, the peak consumption months were examined to gain insights into ISEG's energy usage patterns. Later, the total average monthly consumption was summed to calculate the annual average consumption, using the 'SUM' formula. Based on this result, the renewable energy production goal was then calculated to align with the ECO.AP 2030 target by multiplying the annual average consumption by 10%. This value was used as a reference to determine the number of solar panels required to fulfill or exceed this goal. Subsequently, the Energy Audit Reports provided to ISEG by the companies *Energias de Portugal* (EDP) and Turn Around Consulting were studied to evaluate their findings and commercial suggestions, compare them with the PV proposal for this project, and provide the best scenario for ISEG. Furthermore, the simulation of the PV panels system within ISEG's framework was designed using the solar software 'HelioScope', which was utilized in the work of Rodríguez-Martinez & Rodríguez-Monroy (2021) to analyze the implementation of rooftop PV systems for self-consumption in Spain. To provide some context, HelioScope is owned by Aurora Solar Inc, an outstanding company based in California that offers real-time design and estimation of PV panels within an area thanks to its user-friendly interface, Google Maps integration, manufacturer database, and production reports to examine PV system capacity per month and year (Grana, 2021; Pressey, 2020). Following the design phase, the project studied a quotation of pricing and installation costs from Galp Solar, to use them as reference points for this project.

Finally, an economic analysis was conducted by examining its cash flows, NPV, Return on Investment (ROI), payback period, and Levelized Costs of Electricity (LCOE), to evaluate the project's viability over the entire lifespan (Obeng et al., 2020; AlAjmi et al., 2016). It is important to note that key assumptions were made throughout this process to facilitate these calculations, which included the monthly average electricity bill, installation costs, governmental subsidies, and distribution of project financing.

4. PROJECT DESCRIPTION

4.1 Problem Statement

Nowadays, Portugal, like many European countries, is navigating the complexity of climate change and the necessity of shifting towards cleaner and sustainable energy alternatives. For instance, within the Portuguese framework, a series of guidelines have been introduced to promote decarbonization activities and diminish reliance on non-renewable resources. A standout initiative in this regard is the Energy Efficiency Program in Public Administration 2030, abbreviated as 'ECO.AP 2030'. This program outlines two key energy-related goals: ensuring that, by 2030, 10% of energy consumption is produced locally using renewable technologies, while simultaneously striving for a 40% reduction in primary energy consumption (ECO.AP, 2020). According to the Portuguese Energy Agency ADENE (2023), there is another significant measure namely the National Energy and Climate Plan 2030 (PNEC 2030), which delineates a strategic pathway and serves as a policy instrument for the incorporation and advancement of renewable energy within the country's electricity production sector, incentivizing the use of both wind and solar energy in the upcoming years. In Portugal, for example, renewable energy production constituted 49% of the total energy mix in 2022. Particularly, wind (25%) and hydro (13%) were the predominant sources, while bioenergy and solar PV only accounted for around (7%) and (5%) of the demand, respectively (Redes Energéticas Nacionais [REN], 2022). This highlights the country's significant efforts in driving energy transition and carbon neutrality (López-Dóriga, 2022). Although wind power is currently the most extensive renewable energy source in the country, Portugal is in a favorable position to take advantage of solar PV due to its location and high levels of solar irradiance throughout the year (Esteves et al., 2019).

Based on the above considerations, energy transition requires immediate action from governments, cities, institutions, and individuals. For instance, to address climate change consequences, the University of Lisbon established an Energy and Water Efficiency Plan in 2022 to promote different strategies throughout the entire academic community (University of Lisbon, 2022). As part of the University of Lisbon, ISEG is committed to taking actions that foster environmental growth by promoting renewable energy sources to become carbon neutral and align with its sustainability strategy for 2030 (ISEG, 2021). This motivation derives from the fact that in 2023, the energy supply was procured from the company Luzboa, where the energy mix constituted 31% renewable and 69% non-renewable (Luzboa, 2023). In this context, the need for proactive implementation of renewable energy sources within the campus becomes extremely necessary, due to the absence of self-consumption technologies.

Furthermore, Yu et al. (2023) explained the strong relationship between the use of renewable energy sources, and the UN's 2030 Agenda by contributing to both 'SDG 7:

Affordable and Clean Energy' and 'SDG 13: Climate Action'. On the one hand, SDG 7 encourages the transition towards sustainable energy and its accessibility in both industrialized and non-industrialized countries by promoting financial subsidies, facilitating supply chains, and fostering efficient and decentralized energy management systems (Elavarasan et al., 2021). On the other hand, SDG 13 promotes urgent action, innovative practices, and environmental awareness across the globe, to incentivize nations to develop and integrate circular economy measures while also addressing climate change and its adverse effects (García-Sánchez et al., 2023).

Considering ISEG's student population, teaching, and non-teaching staff of 5,538 individuals in 2022 (ISEG, 2023) and an expected exponential growth projected by 2030, the adoption of on-grid monocrystalline PV panels emerges as a promising solution for the university due to their advanced technology and superior efficiency rates, compared to other alternatives such as polycrystalline and thin-film systems. Additionally, given ISEG's strategic location in the urban landscape of Lisbon, rooftop PV technologies can be integrated and adapted to the campus, taking into account the unique constraints it may present. It is noteworthy to mention that this proactive approach can significantly contribute to ISEG's mission to mitigate global warming and embrace environmental stewardship, by aligning with SDG 7, SDG 13, ECO.AP 10% self-consumption target and Paris Agreement objectives by 2030.

4.2 Solar Resource Assessment – PVOUT in Lisbon

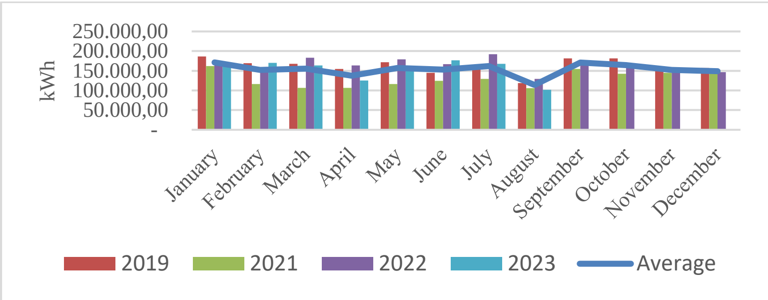
According to ESMAP (2020), an ideal PVOUT falls within the range of 3.5 to 4.5 kWh/kWp per day. The report sourced from the Global Solar Atlas platform indicates that Lisbon is suitable for solar PV implementation due to its optimal PVOUT range, demonstrating its capacity to harness sunlight and generate between 4.15 to 4.52 kWh of electricity per PV unit of installed capacity each day, as illustrated in **Annex 1**.

4.3 Electricity Consumption and Potential PV Production Data

Based on the energy consumption data from 2019, 2021, 2022, and mid-2023 provided by the Professional Staff from ISEG, an analysis of monthly average consumption was calculated. The results showed that the university tends to use more electricity in January (171,283 kWh) and less electricity in August (113,969 kWh), as shown in Figure 2. One primary hypothesis is that students return to classes during

January, while in August they leave for the summer holidays. This leads to a potential analysis to evaluate how solar production will be during these months, considering seasonality and solar irradiance, which will be discussed during the 'Simulation section'. Additionally, the average energy consumption of ISEG was calculated to meet the ECO.AP 2030 target of producing a minimum of 10% of renewable energy. Within this framework, the average consumption per year stands at 1,840,240 kWh, resulting in a goal of generating a minimum of 184,025 kWh on-campus. Moreover, given the modest portion of energy the panels will produce, this project will prioritize the viability of self-consumption and savings on electricity bills, without exploring the option of selling surpluses to the grid.

Figure 2: Monthly Electricity Consumption at ISEG Campus



Source: Author

4.4 Energy Audit Reports vs Description of the Proposed Solar PV

The Energy Audit Reports assessed by EDP and Turn Around Consulting aimed to identify suitable areas and panels for potential PV implementation. In the case of EDP, the company delivered two separate reports: one grouping Library, Francesinhas 1, and Francesinhas 2, and the other focusing on Quelhas 2 and Quelhas 4. They suggested a polycrystalline PV system with a Pmax of 275 Wp, a module efficiency of 16.6%, and a lifespan of 25 years. Meanwhile, Turn Around Consulting recommended the installation of a PV system for Quelhas 6 with a Pmax of 385 Wp and a lifespan between 20 and 25 years. Nevertheless, the literature suggests that the most recommended solar panels in the market are monocrystalline silicon, due to their outstanding performance, durability, and efficiency rate that often exceeds 20% compared with other types of panels, enabling them to harness more sunlight, tolerate high temperatures and withstand drastic weather conditions.

Taking this into account, a simulation using monocrystalline PV technology was performed in HelioScope to analyze the number of panels required to achieve the goal of producing an annual output of 184,025 kWh on-campus by the year 2030. This analysis was based on the monocrystalline PV model studied by Olivieri et al. (2020) at the Polytechnic University of Madrid, considering their significant findings on reducing carbon emissions and meeting more than 10% of their electricity needs.

4.5 Simulation with the HelioScope Software

4.5.1 Technical and Economic Parameters

The simulation provided insights regarding the potential energy production that can be achieved through the implementation of monocrystalline PV panels at ISEG. The primary characteristics of this proposal derived from the work conducted by Olivieri et al. (2020) to design the PV proposal through the HelioScope software. Table 1 outlines the technical and economic parameters according to the authors' research.

Table 1: Technical and Economic Parameters of the PV Proposal

Parameter	Value
Type of panel	Monocrystalline Silicon
PV model	'SPR-X22-360-COM'
Manufacturer	SUNPOWER
Pmax	360 Wp
Panel Efficiency	22.1%
Annual degradation rate	0.5%
Lifespan	30 years
Dimensions	1046 x 1559 mm
O&M Annual cost (% of initial investment)	1
Discount rate	5%

Adapted from: Olivieri et al. (2020)

4.5.2 Suitable Rooftop Areas

As suggested by Olivieri et al. (2020), flat rooftops with small or non-existent inclinations have been chosen to facilitate the PV installation process. In this context, buildings with this specification include the Library, Francesinhas 1, Francesinhas 2, Quelhas 4, and two rooftops from Quelhas 6, as illustrated in Figure 3.

It is important to mention that available areas for PV implementation considered factors such as potential shading from trees, buildings, and the presence of equipment such as heating and air conditioning systems, which are also allocated on the rooftops. Subsequently, the total areas of the selected rooftops were estimated using HelioScope, resulting in a combined area of 3,516 m^2, as detailed in Table 2.

In addition, to provide the best proposal for ISEG, a series of iterations were made in the software to determine the number of panels needed to reach or even exceed the annual energy production target. As a result, two scenarios were evaluated: ‘Scenario 1’ adopted a conservative approach to reach the 10% threshold, and ‘Scenario 2’ pursued a more ambitious approach, focusing on exceeding it.

Figure 3: Suitable Rooftop Areas

Source: Google Maps

Table 2: Estimated Areas per Building

Building	Approximate Area (m2)
Library	443.5
Francesinhas 1	1,223.4
Francesinhas 2	1,271.8
Quelhas 4	255
Quelhas 6.1	236
Quelhas 6.2	87.1
Total	3,516.8

Source: Author

4.5.3 Scenario 1 vs Scenario 2

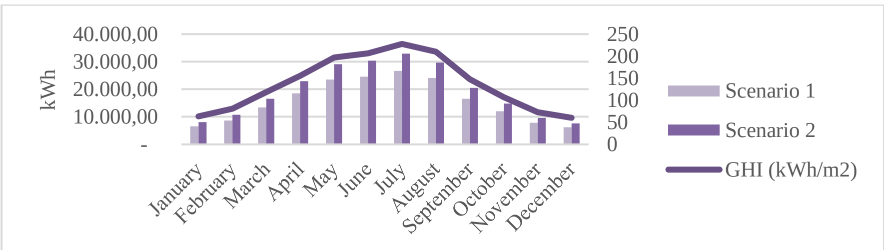
In the first scenario, only 4 buildings were considered for the PV implementation, resulting in 411 modules distributed across Francesinhas 1, Francesinhas 2, Quelhas 4, and one of the Quelhas’ rooftops named Quelhas 6.1. This configuration yielded an annual energy production of 188,712 kWh, equivalent to producing 10.25% of the total average energy consumption, exceeding the target by 0.25%. For the second scenario, all 6 buildings were simulated, resulting in a total of 507 modules and achieving an annual energy production of 232,937 kWh, representing 12.66% of the total average energy consumption, exceeding the goal by 2.66%. The comparison between both scenarios, designed in HelioScope, is illustrated in Figure 4, with the layout from the left indicating Scenario 1, and the layout on the right representing Scenario 2.

Figure 4: Scenario 1 vs Scenario 2

Source: Author

Furthermore, an analysis comparing solar radiation (specifically GHI) with the monthly energy production of both scenarios was conducted, based on the extracted HelioScope reports, as shown in Figure 5. The results demonstrated that lower GHI values corresponded to decreased energy production. In this case, both scenarios displayed a peak energy production level during June, July, and August when there was also a higher GHI, whereas November, December, and January experienced the lowest levels in both production and GHI values. This underscores the significant influence of seasonality on the amount of solar energy that PV panels can convert into electricity. The design and reports for Scenario 1 and Scenario 2 modeled through the HelioScope software can be seen in **Annex 2** and **Annex 3**, respectively.

Figure 5: Energy Production vs GHI



Source: Author

4.6 Main Assumptions

4.6.1 Solar Panels Costs

Since 2022, the Portuguese government introduced legislation to provide a reduced Value Added Tax (VAT) of 6% to encourage more businesses to adopt solar energy solutions, thereby supporting the transition to cleaner energy sources (Galp, 2023). To analyze the potential installation costs per panel, a review of different electricity providers was conducted, identifying Galp Solar as one of the most reliable competitors in the market. This company was selected for having an online simulator that allows medium to large-size companies to calculate the potential PV panel initial investment per panel (including pricing and installation costs), by introducing their location and average monthly electricity bill either in EUR or kWh.

For this study, an electricity bill from April 2023 provided by the Professional Staff from ISEG was used as a reference, assuming an average electricity consumption cost of 35,755 EUR per month. This value, along with the address stated in the electricity bill, 'Rua do Quelhas 6', was then introduced into the Galp Solar Simulator, resulting in a unit price of 291 EUR per panel, as shown in Table 3. For further details, the quote simulation obtained through Galp Solar is presented in **Annex 4**.

Table 3: Estimated Quotation

Electricity Provider	Number of Panels	Initial Investment without VAT (Price + Installation Costs)	Initial Investment with VAT (Price + Installation Costs)
Galp Solar	438	120,138 EUR	127,437 EUR
	1	274.29 EUR	291 EUR

Adapted from: Galp Solar

4.6.2 Electricity Price and Inflation Rate

The electricity bill provided by the Professional Staff indicated that the unit electricity price in 2023 was 0.1892 EUR per month. This charge will serve as a reference for calculating the savings accrued from solar energy production. Additionally, based on the latest data from the European Commission (2024), an estimated inflation rate of 2.3% for 2024 will be considered to further estimate the cash flows throughout the entire project lifecycle.

4.6.3 Financing Mechanisms

Concerning funding methods, the project will align with the Energy and Water Efficiency Plan 2022 of the University of Lisbon. This plan details various governmental mechanisms that will support environmental initiatives within the university and its 18 affiliated schools. Moreover, according to this document, some of the economic incentives that will allow the implementation of these initiatives include the Recovery and Resilience Plan (PRR) named ‘Recover Portugal’, the Environmental Fund, the Energy Consumption Efficiency Promotion Plan (PPEC), the Portugal 2030 and Regional Operational program (University of Lisbon, 2022a).

For this project, it will be assumed that the main governmental subsidy supporting the installation of solar PV panels will be the PRR, due to its focus on promoting renewable energy and decarbonization activities by 2026 (University of Lisbon, 2022a). Furthermore, according to the PRR (2024) database, the University of Lisbon has undergone a budget of 60,015,940 EUR. In this sense, assuming equal payments for each affiliated school, ISEG could expect to receive a fund of 3,334,218.89 EUR for investment in different green initiatives. Bearing this in mind, 2% of this fund will be allocated for the solar initiative and further evaluated for the two simulated scenarios, obtaining in total an incentive of 66,684 EUR.

4.7 Economic Analysis

The literature emphasizes the importance of conducting an economic analysis to assess the viability of implementing solar PV technologies using Excel. In this study, an evaluation criteria proposed by the authors Obeng et al. (2020) will be conducted to analyze and compare financial metrics such as cash flows, NPV, ROI, payback period, and LCOE of the two scenarios simulated to further determine their investment’s worth and define which approach will be the best financial option for ISEG. Additionally, Olivieri et al. (2020) recommended a discount rate of 5% for evaluating medium to large-size installation projects. This input will be considered, assuming the project will have a go-live date in January 2025 and a lifecycle of 30 years.

4.7.1 Cash Flows of the Project

A critical factor in the success of a company is mostly determined by the effective management of cash flows to maintain adequate working capital. In a project context, it represents the estimated costs and revenues for forecasting and controlling a project's financial activities over its lifecycle (Cui et al., 2010). To estimate the cash flows of the solar PV initiative, a step-by-step analysis was carried out, with [t] representing each year evaluated, as presented in Table 4.

The process started with calculating the Capital Expenditures (CAPEX) of the Project, considering the Initial Investment data from Table 4, the number of panels simulated for both conservative and ambitious scenarios, and factoring a 6% of VAT. Afterwards, the analysis delved into the computing of O&M costs, where it was assumed that no maintenance would be required during the first year. For the second year, costs would amount to 1% of the initial investment (as indicated in Table 2), with consideration of an annual inflation rate. Furthermore, O&M costs for subsequent years were assessed based on the costs paid in the preceding year.

Next, the governmental incentive was determined by multiplying the PRR incentive by the assumed 2% allocation for this project. Following this, the annual PV production in kWh and its equivalent percentage (%) were projected, discounting the annual degradation rate of the PV system (as specified in Table 2). This degradation rate will start to be accounted for in year 2, as the panels will operate at maximum capacity in year 1. Later, a projection of the electricity price was performed, considering the annual inflation rate to calculate the savings on electricity bills that ISEG will accrue from producing renewable energy on-site. Finally, after computing the aforementioned values, the annual cash flows were calculated to proceed with the assessment of the NPV.

Table 4: Cash Flow Analysis

1. CAPEX = (Initial Investment per Panel * Number of Solar Panels) * (1+VAT)
2. O&M Costs $_{t=1}$ = 0
3. O&M Costs $_{t=2}$ = (Initial Investment * 1%) * (1 + Annual Inflation Rate)
4. O&M Costs $_{t>2}$ = (O&M Costs $_{t=t-1}$) * (1 + Annual Inflation Rate)
5. Governmental Incentive $_{t=1}$ = (PRR Incentive for ISEG) * (2%)
6. PV Production $_{t=1}$ = PV Production of each scenario in kWh
7. PV Production $_{t\geq 2}$ = (PV Production $_{t-1}$) * (1 - Annual PV Degradation Rate) in kWh
8. % PV Production $_{t=1}$ = (Average Electricity Consumption from 2019 to mid-2030 / PV Production $_{t=1}$)
9. % PV Production $_{t\geq 2}$ = (PV Production $_{t=t-1}$) – (Annual PV Degradation Rate)
10. Electricity Price $_{t}$ = (Electricity Price $_{t=t-1}$) * (1 + Annual Inflation Rate)
11. Savings $_{t}$ = (PV Production $_{t}$) * (Electricity Price $_{t}$)
12. Cash Flow $_{t=0}$ = CAPEX

13. Cash Flow $_{t=1}$ = (Savings $_{t=1}$) + (Governmental Incentive $_{t=1}$)
14. Cash Flow $_{t=t+1}$ = (Savings $_{t}$) + (O&M Costs $_{t}$)

Source: Author

4.7.2 NPV

The NPV serves as a reliable indicator for determining the worth of an investment, as it accounts for an absolute increase in capital (Olivieri et al., 2020). A positive NPV suggests that a project is viable and can be launched, whilst an NPV value equal to or below zero indicates that investing in the project is not recommended. To calculate it, the Excel 'NPV function' was employed to estimate the present value of cash flows from year 1 to year 30, applying the discount rate of 5%. Subsequently, the cash flow in year 0 was added to the result using the formula: NPV(Discount rate; Cash Flows $_{t\geq1}$) + Cash Flow $_{t=0}$.

4.7.3 ROI

The ROI ratio is a financial metric that calculates the percentage gain or loss generated during an investment in relation to its costs. It is determined by dividing the NPV, also known as Net Profit, by the initial cost of investment, and then multiplying the result by 100 to express it as a percentage. This indicator helps investors compare the potential profitability of different projects (Obeng et al., 2020).

4.7.4 Payback Period

The payback period estimates the time it takes for a project to generate enough cash flows to recover its initial cost of investment. A shorter payback period is often interpreted as a lower risk for the investor (Yard, 2000). To calculate the payback period for each scenario, it was necessary to calculate the cumulated cash flows over the 30-year life cycle, resulting in the analysis displayed in Table 5.

Table 5: Cumulated Cash Flow Analysis

1. Cumulated Cash Flow $_{t=0}$ = CAPEX
2. Cumulated Cash Flow $_{t=1}$ = (Cash Flow $_{t=1}$) + (Cumulated Cash Flow $_{t=0}$)
3. Cumulated Cash Flow $_{t=t+1}$ = (Cash Flow $_{t=1}$) + (Cumulated Cash Flow $_{t=t-1}$)
    4. If the Cumulated Cash Flow $_{t}$ $\geq$ Initial Investment
        5. t = Payback Period

6. If not
    7. Continue evaluating each year until finding the Cumulated Cash Flow $_t$ ≥ Initial Investment

Source: Author

4.7.5 LCOE

The LCOE represents the average cost per unit of electricity generated, considering the total expenses over a system's lifetime (EUR/kWh). It is usually employed as a comparative measure to assess the economic competitiveness of various energy generation technologies. This indicator is particularly valuable for investors and policymakers when making decisions about energy projects, as it helps determine which technology provides the most cost-effective energy production over time (Obeng et al., 2020; AlAjmi et al., 2016; Allouhi et al.,2016)

4.7.6 Results Discussion

The estimations of the previous indicators are summarized in Table 6.

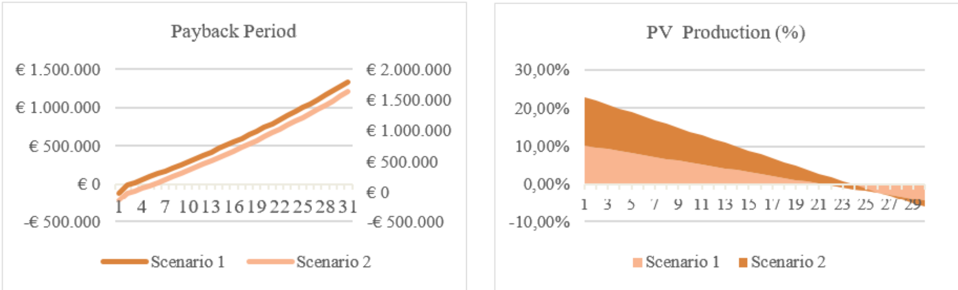
Table 6: Summary of Technical and Economic Results

	Scenario 1	Scenario 2
CAPEX (EUR)	119,497 EUR	147,409 EUR
# of Panels & Power to Install (Wp)	411 panels (148 Wp)	507 panels (183 Wp)
Total O&M Costs (EUR)	48,512 EUR	59,843 EUR
PV Production by 2030 (kWh)	184,996 kWh	228,313 kWh
PV Production by 2030 (%)	8.25%	10.66%
Total Savings (EUR)	1,433,669 EUR	1,405,731 EUR
NPV (EUR)	538,606 EUR	650,053 EUR
ROI (%)	451%	441%
Payback Period (year)	5	6
LCOE (EUR/kWh)	0.09 EUR	0.09 EUR

Source: Author

In general, the results obtained suggest that, on average, the cost of generating one kWh of electricity using the PV system implemented at ISEG is estimated to be 0.09 EUR over the project's lifespan. This cost will serve as a measure to compare the cost of electricity generated by this PV system with future renewable energy projects. Furthermore, the first scenario presented a lower initial investment (CAPEX) which led to lower O&M costs but higher total savings, primarily due to the smaller number of panels and power capacity installation, compared to the second scenario. Moreover, the two approaches generated a positive NPV and ROI that exceeded 400%, indicating that the project is theoretically viable, with a payback period of 5 years and 6 years for the first and second scenarios, respectively. This implies that both scenarios will have a faster return on initial investment and increased financial feasibility. However, if the solar PV technology has an initiation date in January 2025, the first scenario will not be able to meet the ECO.AP 2030 target, given that, over time, the PV degradation rate will significantly impact the amount of electricity produced as shown in Figure 6. In this case, by 2030, the PV production for the first scenario is projected to reach 184,966 kWh, constituting only 8.25% of the total consumption, whereas the second scenario is expected to meet this objective with a production of 228,313 kWh, meaning 10.66% of the total consumption.

Figure 6: Payback Period vs PV Production



Source: Author

Since the main aim of this project is to produce a minimum of 10% renewable energy, it is crucial to assess the long-term consequences of each approach. According to the forecasts, the second scenario is not only expected to have higher energy production and greater power capacity by 2030 but also a stronger financial viability over the project's life cycle due to its larger NPV. Thus, when comparing both options, the second scenario emerges as the preferred choice for ISEG, because it aligns with the ECO.AP 2030 target and the strategic objective of increasing renewable energy production within ISEG's infrastructure.

5. CONCLUSIONS

5.1 Main Conclusions

This project presented a proposal to begin a transition process to solar energy within ISEG's framework, due to the multiple benefits it offers in terms of cost-effectiveness and flexible implementation. The main objective was to align with the ECO.AP 2030 target and achieve a minimum production rate of 10% renewable energy by simulating a rooftop PV grid-tied system, based on a conservative and ambitious approach, where some of the buildings were selected, to meet or even surpass the annual production target using HelioScope software. The process involved a review of the solar PV market to identify the most suitable panels for maximizing energy production, finding that monocrystalline panels offer the best performance, despite their higher initial investment compared to other options such as polycrystalline and thin-film cells. Moreover, a benchmark with various educational institutions also revealed that monocrystalline technology tends to last longer, and is more energy-efficient, resulting in higher energy production over its lifespan.

To determine the financial viability of the project and reach the 10% renewable energy goal, an in-depth analysis of historical energy consumption patterns at ISEG was conducted. The results indicated that the university has sufficient area and capacity to produce more than 10% renewable energy and generate net profit either through the conservative or the ambitious scenario if a governmental subsidy is considered. It is noteworthy to mention that opting for the ambitious approach could potentially leverage a higher NPV than the conservative one and deliver an average payback period of 6 years. Additionally, the forecasts suggested that by 2030, the university could achieve a renewable energy production rate of 10.66% with the ambitious scenario, thereby demonstrating superior performance and meeting the ECO.AP 2030 target if the project is launched in January 2025. In addition, considering that solar panels typically have a lifespan of around 30 years, it is imperative to implement appropriate lifecycle management. This includes recycling usable parts and establishing effective waste disposal methods to ensure a continued contribution to sustainable practices (Papamichael et al., 2022).

Furthermore, the project underscores the viability of transitioning to renewable energy sources at ISEG, particularly through the implementation of solar PV panels, due to the university's strategic location and the abundant solar irradiance levels experienced in Lisbon throughout the year, especially during the summer months. By integrating this technology, ISEG could benefit from potential cost savings, given that, by producing more than 10% of its energy on-site, the university could potentially save 1.4 million EUR in electricity bills, assuming an annual inflation rate of 2.4%.

In general, this proactive approach could ensure the university's compliance with national targets, yield a higher profit, and establish a resilient renewable energy infrastructure for the future. Solar PV offers a sustainable and clean alternative to traditional fossil fuel-based energy sources. Therefore, contributing to environmental conservation and reducing CO2 emissions (Olivieri et al., 2020).

5.2 Limitations and Future Research

Although the project delivered a positive feasibility for integrating solar PV systems into the university infrastructure, some limitations were encountered. Firstly, due to the restricted access to data, certain assumptions were made to forecast the economic indicators of the project and the design of the solar PV layout. Moreover, due to the inevitable degradation of solar PV panels over time, regular O&M expenses will be required to sustain optimal efficiency and achieve the ECO.AP 2030 target.

Moreover, it is recommended to compare the LCOE of this project with other renewable energy sources, such as bioenergy and wind turbines, to analyze the viability of integrating multiple clean technologies into ISEG's electricity framework to enhance overall energy production and contribute to its sustainability objectives. Additionally, it is suggested to examine installing complementary panels across the campus and consider the integration of a battery storage system, to evaluate other scenarios where the 10% threshold is exceeded. For instance, focusing on 20% or 30% as main production goals. Besides, it is advised to explore the possibility of selling energy surpluses to the grid during months of excess electricity production between June, July, and August to estimate how this revenue will influence the NPV and payback period of the project. For future works, the analysis of implementing solar tracking techniques and Artificial Intelligence (AI) robotic arms for optimal cleaning could be considered (Vodapally & Ali, 2022), to increase energy efficiency over time. Lastly, it is advised to contemplate the procurement of energy from companies that predominantly rely on renewable sources, since during 2023 the electricity coming from the provider Luzboa constituted only 31% renewable energy.

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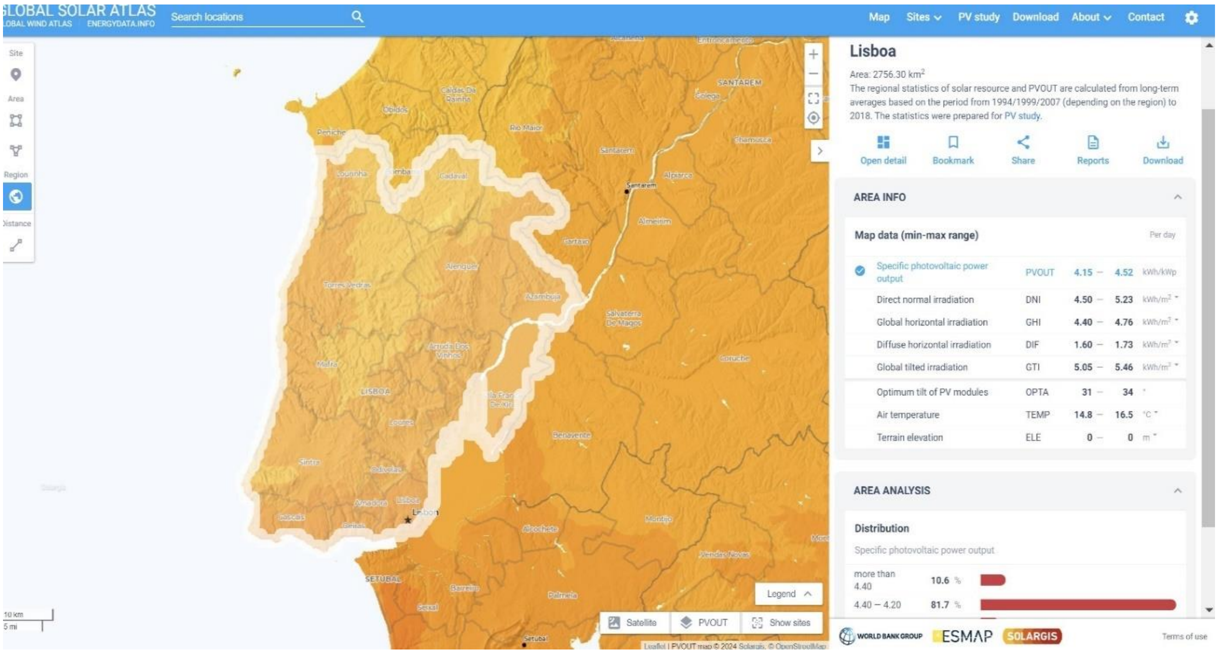
ANNEXES

In this section, the annexes that support the main body of the project description can be found. These complementary materials include figures, reports, and data obtained for the development of this thesis. These include:

- Annex 1: Lisbon PVOUT Range
- Annex 2: Simulation Scenario 1 – HelioScope Report
- Annex 3: Simulation Scenario 2 – HelioScope Report
- Annex 4: Galp Simulation Quote

Annex 1: Lisbon PVOUT Range



Annex 2: Simulation Scenario 1 – HelioScope Report

HelioScope — Annual Production Report produced by Silvia Castro

Design 1 - Conservative Approach MFW - Solar PV Initiative, Rua do Quelhas 6

Report

Project Name	MFW - Solar PV Initiative
Project Address	Rua do Quelhas 6
Prepared By	Silvia Castro silviac241@hotmail.com

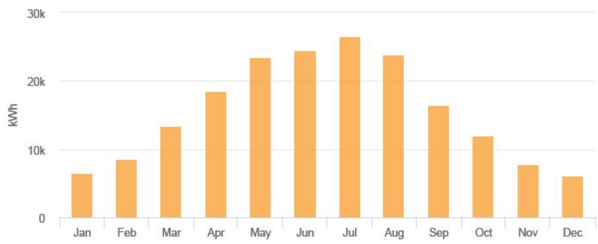
ISEG Lisbon School of Economics & Management Universidade de Lisboa

System Metrics

Design	Design 1 - Conservative Approach
Module DC Nameplate	148.0 kW
Inverter AC Nameplate	140.0 kW Load Ratio: 1.06
Annual Production	188.7 MWh
Performance Ratio	84.4%
kWh/kWp	1,275.4
Weather Dataset	TMY, Lisboa, INETI (epw)
Simulator Version	06edf7d6ab-42ed6b842a-2e07d81e3d-92fa4d4602

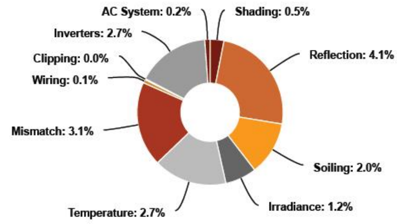
Project Location

Monthly Production



Month	GHI (kWh/m²)	POA (kWh/m²)	Shaded (kWh/m²)	Nameplate (kWh)	Grid (kWh)
January	63.3	53.3	53.0	7,118.0	6,546.0
February	80.7	69.1	68.7	9,392.1	8,693.0
March	118.5	106.1	105.5	14,597.4	13,448.3
April	155.8	145.3	144.6	20,209.3	18,551.0
May	197.4	186.5	185.6	26,030.3	23,559.1
June	206.8	196.3	195.3	27,465.6	24,593.6
July	227.8	214.3	213.3	29,979.2	26,629.5
August	209.9	194.0	193.1	27,057.1	24,055.6
September	147.7	134.6	133.9	18,609.1	16,593.4
October	107.4	96.9	96.3	13,254.6	12,012.9
November	72.7	63.6	63.2	8,545.4	7,814.7
December	60.3	51.2	50.8	6,789.2	6,214.7

Sources of System Loss



HelioScope

Annual Production Report produced by Silvia Castro

Annual Production

	Description	Output	% Delta
Irradiance (kWh/m²)	Annual Global Horizontal Irradiance	1,648.3	
	POA Irradiance	1,511.1	-8.3%
	Shaded Irradiance	1,503.4	-0.5%
	Irradiance after Reflection	1,441.7	-4.1%
	Irradiance after Soiling	1,412.9	-2.0%
	Total Collector Irradiance	**1,412.9**	**0.0%**
Energy (kWh)	Nameplate	209,047.4	
	Output at Irradiance Levels	206,617.7	-1.2%
	Output at Cell Temperature Derate	200,989.5	-2.7%
	Output After Mismatch	194,660.2	-3.1%
	Optimal DC Output	194,403.5	-0.1%
	Constrained DC Output	194,343.1	0.0%
	Inverter Output	189,076.9	-2.7%
	Energy to Grid	**188,711.9**	**-0.2%**
Temperature Metrics			
	Avg. Operating Ambient Temp		18.6 °C
	Avg. Operating Cell Temp		25.3 °C
Simulation Metrics			
		Operating Hours	4577
		Solved Hours	4577

Condition Set

Description	Condition Set 1
Weather Dataset	TMY, Lisboa, INETI (epw)
Solar Angle Location	Meteo Lat/Lng
Transposition Model	Perez Model
Temperature Model	Sandia Model
Irradiation Variance	5%
Cell Temperature Spread	4° C
Module Binning Range	-2.5% to 2.5%
AC System Derate	0.50%

Temperature Model Parameters

Rack Type	a	b	Temperature Delta
Fixed Tilt	-3.56	-0.075	3°C
Flush Mount	-2.81	-0.0455	0°C
East-West	-3.56	-0.075	3°C
Carport	-3.56	-0.075	3°C

Soiling (%)

J	F	M	A	M	J	J	A	S	O	N	D
2	2	2	2	2	2	2	2	2	2	2	2

Module Characterizations

Module	Uploaded By	Characterization
SPR-X22-360-COM (SunPower)	HelioScope	Sunpower_SPR_X22_360_COM.PAN, PAN

Component Characterizations

Device	Uploaded By	Characterization
SYMO 10.0-3-M (Jan 2016) (Fronius)	HelioScope	CEC

Components

Component	Name	Count
Inverters	SYMO 10.0-3-M (Jan 2016) (Fronius)	14 (140.0 kW)
AC Home Runs	1/0 AWG (Aluminum)	14 (7,450.4 m)
Strings	10 AWG (Copper)	38 (1,149.5 m)
Module	SunPower, SPR-X22-360-COM (360W)	411 (148.0 kW)

Wiring Zones

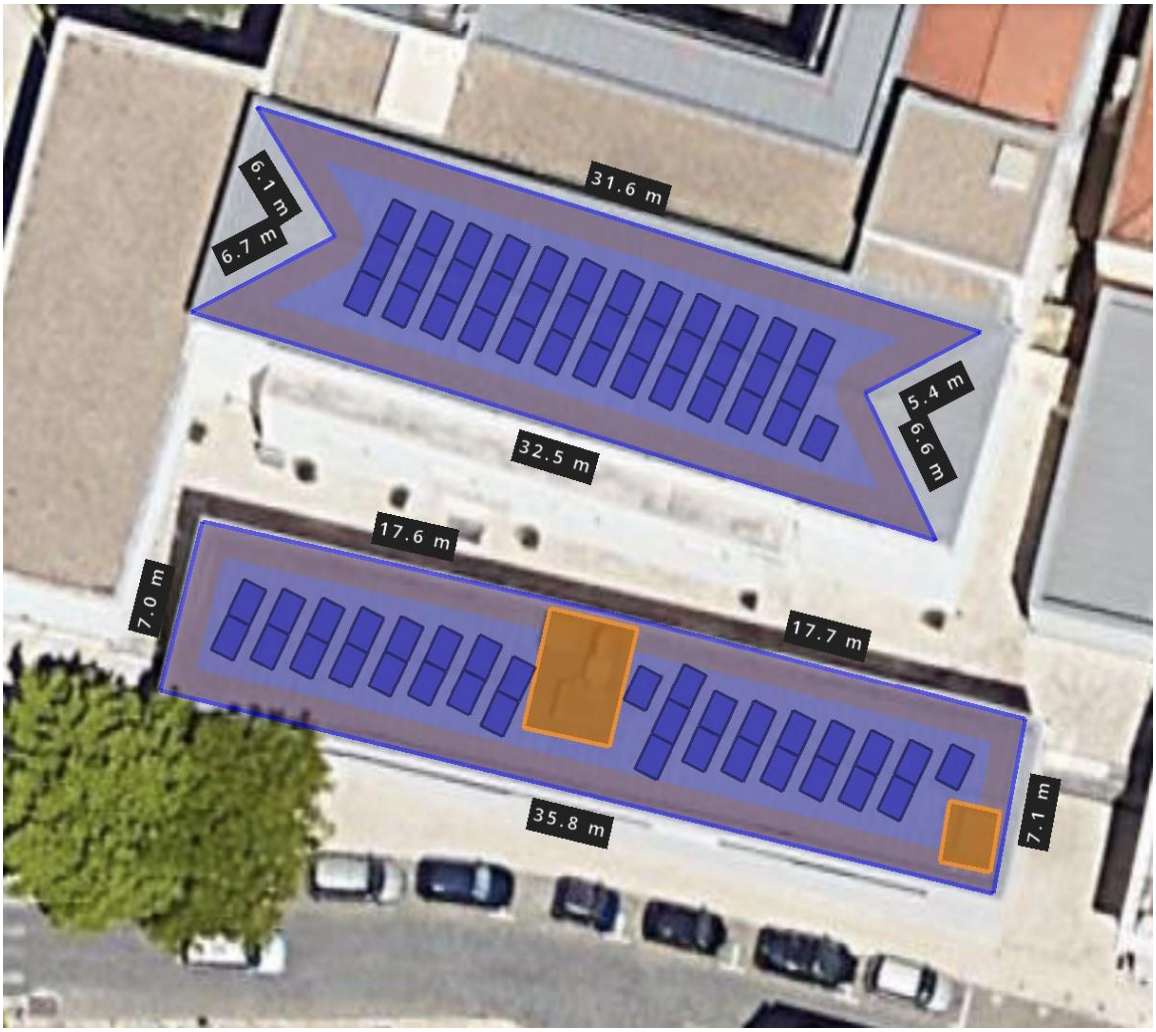
Description	Combiner Poles	String Size	Stringing Strategy
Wiring Zone 1	-	5-13	Along Racking
Wiring Zone 2	-	5-13	Along Racking
Wiring Zone 3	-	-	Along Racking
Wiring Zone 4	-	-	Along Racking
Wiring Zone 5	-	5-13	Along Racking
Wiring Zone 6	-	5-13	Along Racking

Field Segments

Description	Racking	Orientation	Tilt	Azimuth	Intrarow Spacing	Frame Size	Frames	Modules	Power
Francesinhas 2	Fixed Tilt	Landscape (Horizontal)	10°	296.00336°	0.6 m	1x1	208	208	74.9 kW
Francesinhas 1	Fixed Tilt	Landscape (Horizontal)	10°	296.00336°	0.6 m	1x1	133	133	47.9 kW
Quelhas 6.1	Fixed Tilt	Landscape (Horizontal)	10°	296.00336°	0.6 m	1x1	37	37	13.3 kW
Quelhas 4	Fixed Tilt	Landscape (Horizontal)	10°	296.00336°	0.6 m	1x1	33	33	11.9 kW


HelioScope
Annual Production Report produced by Silvia Castro
Detailed Layout
HelioScope


16.8 m
18.1 m
72.2 m
18.3 m
17.9 m
18.1 m
16.8 m
35.3 m
36.8 m
17.3 m
22.1 m
22.7 m
2.1 m
0.4 m
14.7 m
17.6 m


6.1 m
6.7 m
31.6 m
5.4 m
6.6 m
32.5 m
17.6 m
7.0 m
17.7 m
35.8 m
7.1 m

Annex 3: Simulation Scenario 2 – HelioScope Report

HelioScope — Annual Production Report produced by Silvia Castro

Design 2 - Ambitious Approach MFW - Solar PV Initiative, Rua do Quelhas 6

Report

Project Name	MFW - Solar PV Initiative
Project Address	Rua do Quelhas 6
Prepared By	Silvia Castro silviac241@hotmail.com

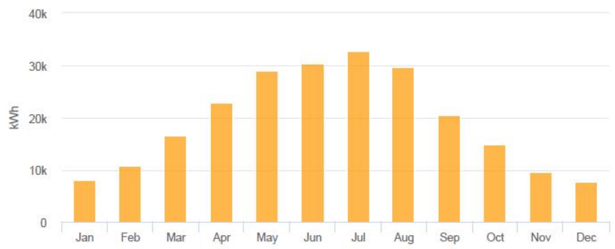
ISEG Lisbon School of Economics & Management Universidade de Lisboa

System Metrics

Design	Design 2 - Ambitious Approach
Module DC Nameplate	182.5 kW
Inverter AC Nameplate	200.0 kW Load Ratio: 0.91
Annual Production	232.9 MWh
Performance Ratio	84.5%
kWh/kWp	1,276.2
Weather Dataset	TMY, Lisboa, INETI (epw)
Simulator Version	06edf7d6ab-42ed6b842a-2e07d81e3d-92fa4d4602

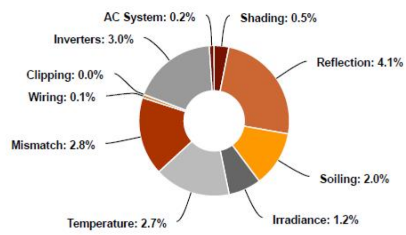
Project Location

Monthly Production



Month	GHI (kWh/m²)	POA (kWh/m²)	Shaded (kWh/m²)	Nameplate (kWh)	Grid (kWh)
January	63.3	53.3	53.0	8,778.8	8,072.8
February	80.7	69.1	68.7	11,583.5	10,727.7
March	118.5	106.1	105.5	18,003.6	16,593.5
April	155.8	145.3	144.5	24,925.0	22,897.9
May	197.4	186.5	185.5	32,104.2	29,087.6
June	206.8	196.3	195.3	33,875.1	30,395.8
July	227.8	214.3	213.3	36,975.2	32,878.0
August	209.9	194.0	193.1	33,371.5	29,688.1
September	147.7	134.6	133.9	22,951.3	20,470.8
October	107.4	96.9	96.3	16,347.1	14,816.8
November	72.7	63.6	63.2	10,538.9	9,636.8
December	60.3	51.2	50.8	8,372.9	7,671.0

Sources of System Loss



HelioScope

Annual Production Report produced by Silvia Castro

Annual Production

	Description	Output	% Delta
Irradiance (kWh/m²)	Annual Global Horizontal Irradiance	1,648.3	
	POA Irradiance	1,511.1	-8.3%
	Shaded Irradiance	1,503.2	-0.5%
	Irradiance after Reflection	1,441.6	-4.1%
	Irradiance after Soiling	1,412.7	-2.0%
	Total Collector Irradiance	**1,412.7**	**0.0%**
Energy (kWh)	Nameplate	257,827.1	
	Output at Irradiance Levels	254,829.9	-1.2%
	Output at Cell Temperature Derate	247,889.2	-2.7%
	Output After Mismatch	240,934.6	-2.8%
	Optimal DC Output	240,646.9	-0.1%
	Constrained DC Output	240,633.7	0.0%
	Inverter Output	233,336.5	-3.0%
	Energy to Grid	**232,936.7**	**-0.2%**
Temperature Metrics			
	Avg. Operating Ambient Temp		18.6 °C
	Avg. Operating Cell Temp		25.3 °C
Simulation Metrics			
		Operating Hours	4577
		Solved Hours	4577

Condition Set

Description	Condition Set 1
Weather Dataset	TMY, Lisboa, INETI (epw)
Solar Angle Location	Meteo Lat/Lng
Transposition Model	Perez Model
Temperature Model	Sandia Model

Temperature Model Parameters

Rack Type	a	b	Temperature Delta
Fixed Tilt	-3.56	-0.075	3°C
Flush Mount	-2.81	-0.0455	0°C
East-West	-3.56	-0.075	3°C
Carport	-3.56	-0.075	3°C

Soiling (%)

J	F	M	A	M	J	J	A	S	O	N	D
2	2	2	2	2	2	2	2	2	2	2	2

Irradiation Variance	5%
Cell Temperature Spread	4° C
Module Binning Range	-2.5% to 2.5%
AC System Derate	0.50%

Module Characterizations

Module	Uploaded By	Characterization
SPR-X22-360-COM (SunPower)	HelioScope	Sunpower_SPR_X22_360_COM.PAN, PAN

Component Characterizations

Device	Uploaded By	Characterization
SYMO 10.0-3-M (Jan 2016) (Fronius)	HelioScope	CEC

Components

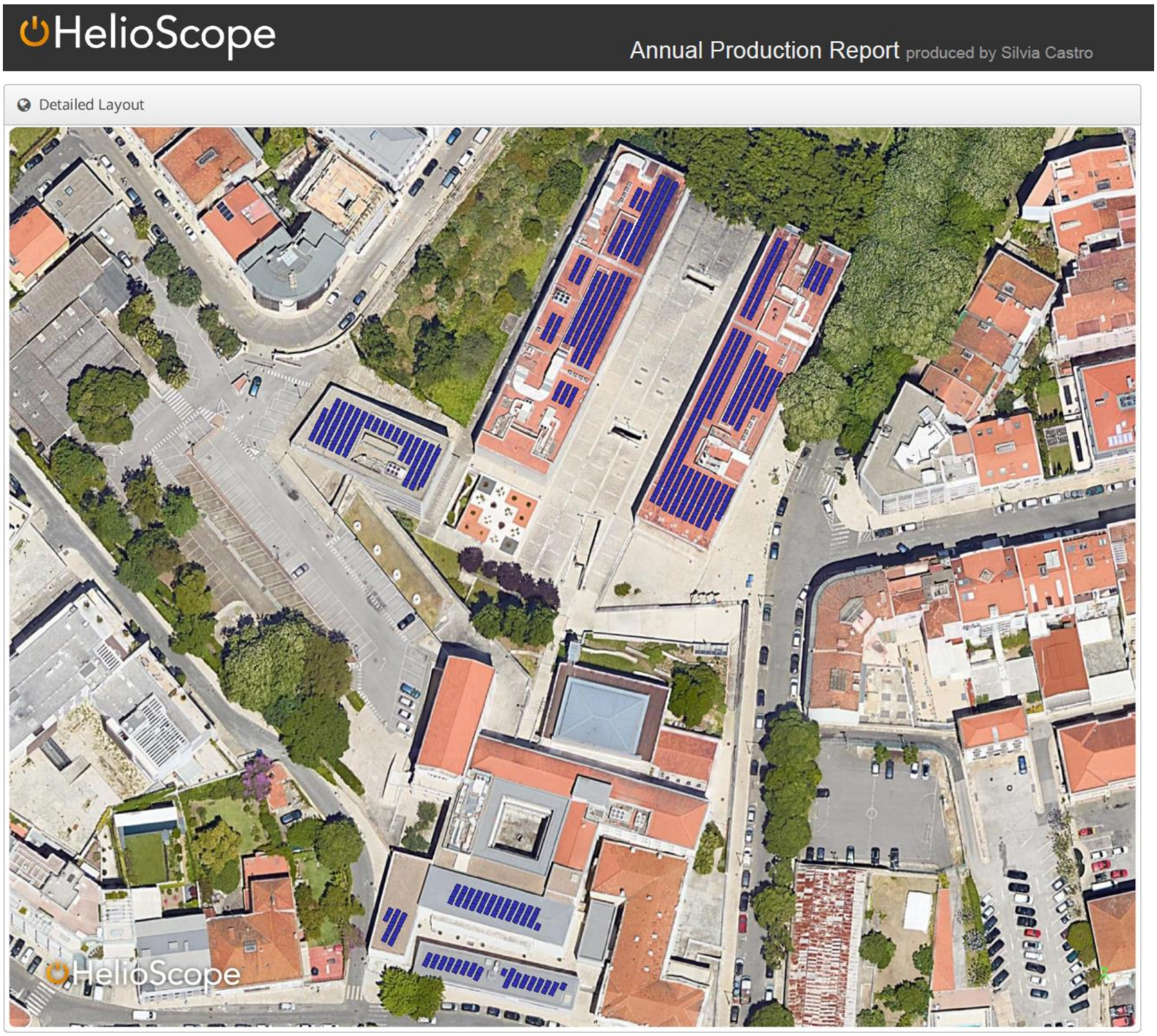
Component	Name	Count
Inverters	SYMO 10.0-3-M (Jan 2016) (Fronius)	20 (200.0 kW)
AC Home Runs	1/0 AWG (Aluminum)	20 (10,034.8 m)
Strings	10 AWG (Copper)	51 (1,248.6 m)
Module	SunPower, SPR-X22-360-COM (360W)	507 (182.5 kW)

Wiring Zones

Description	Combiner Poles	String Size	Stringing Strategy
Wiring Zone 1	-	5-13	Along Racking
Wiring Zone 2	-	5-13	Along Racking
Wiring Zone 3	-	5-13	Along Racking
Wiring Zone 4	-	5-13	Along Racking
Wiring Zone 5	-	5-13	Along Racking
Wiring Zone 6	-	5-13	Along Racking

Field Segments

Description	Racking	Orientation	Tilt	Azimuth	Intrarow Spacing	Frame Size	Frames	Modules	Power
Francesinhas 2	Fixed Tilt	Landscape (Horizontal)	10°	296.00336°	0.6 m	1x1	201	201	72.4 kW
Francesinhas 1	Fixed Tilt	Landscape (Horizontal)	10°	296.00336°	0.6 m	1x1	144	144	51.8 kW
Library	Fixed Tilt	Landscape (Horizontal)	10°	296.00336°	0.6 m	1x1	80	80	28.8 kW
Quelhas 6.1	Fixed Tilt	Landscape (Horizontal)	10°	296.00336°	0.6 m	1x1	37	37	13.3 kW
Quelhas 4	Fixed Tilt	Landscape (Horizontal)	10°	296.00336°	0.6 m	1x1	33	33	11.9 kW
Quelhas 6.2	Fixed Tilt	Landscape (Horizontal)	10°	296.00336°	0.6 m	1x1	12	12	4.32 kW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Detailed Layout
HelioScope


16.8 m
18.1 m
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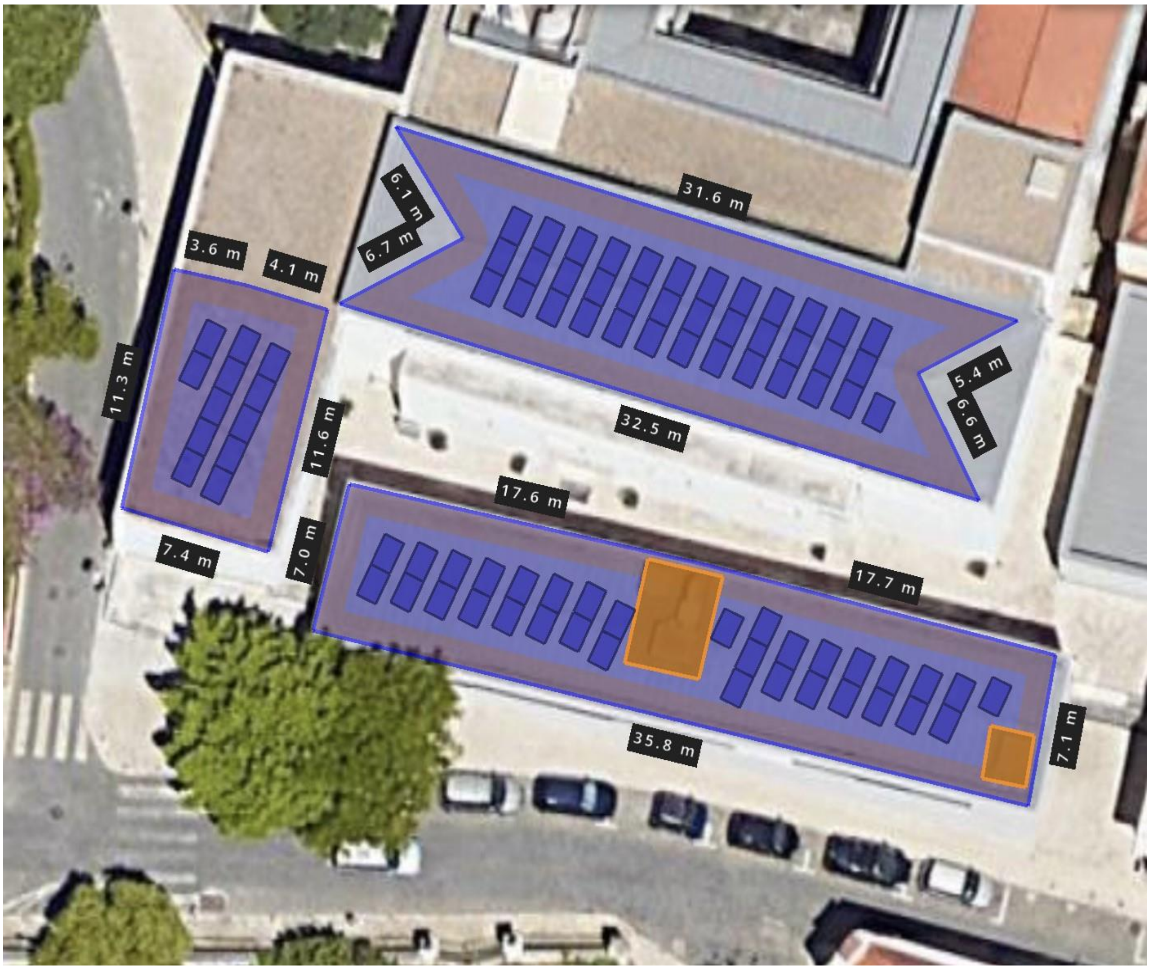
2.1 m
0.4 m
14.7 m
17.6 m


14.5 m
29.2 m
31.4 m
15.0 m


31.6 m
6.1 m
6.7 m
3.6 m
4.1 m
11.3 m
11.6 m
32.5 m
5.4 m
6.6 m
17.6 m
7.4 m
7.0 m
17.7 m
35.8 m
7.1 m

Annex 4: Galp Simulation Quote