



MASTER'S DEGREE IN INDUSTRIAL ENGINEERING

MASTER'S THESIS

MODELING AND DATA ANALYSIS FOR SELF-  
CONSUMPTION SOLAR GENERATION

Author: Jorge Carbonell de la Cámara

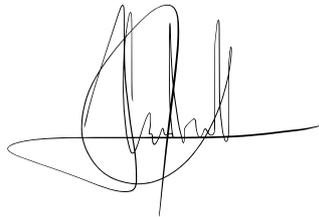
Director: José Pablo Chaves Ávila

Madrid



I declare, under my responsibility, that the Project submitted with the title  
Modeling and Data Analysis for Self-Consumption Solar Generation  
at the ETS of Engineering - ICAI of the Universidad Pontificia Comillas in the  
Academic year 2022/23 is of my authorship, original and unpublished and  
has not been submitted before for other purposes.

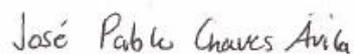
The Project is not plagiarism of another, neither totally nor partially and the information  
that has been taken from other documents it is duly referenced.



Signed: Jorge Carbonell de la Cámara Date: 15/06/2023

Authorized the delivery of the project

THE DIRECTOR



Signed: José Pablo Chaves Ávila Date: 15/06/2023





MASTER'S DEGREE IN INDUSTRIAL ENGINEERING

MASTER'S THESIS

MODELING AND DATA ANALYSIS FOR SELF-  
CONSUMPTION SOLAR GENERATION

Author: Jorge Carbonell de la Cámara

Director: José Pablo Chaves Ávila

Madrid

# Acknowledgments

I would like to express my deepest appreciation to my family, partner and friends for their unwavering encouragement and understanding throughout this journey. Their love, patience, and moral support have been instrumental in helping me overcome challenges and persevere in the pursuit of my academic goals.

I would also like to extend my thanks to the Comillas Pontifical University, particularly the Institute of Technological Research (IIT), for their continuous support and resources provided during the entire process. The opportunity to conduct this research at Comillas Pontifical University has been instrumental in shaping my understanding of the subject matter and refining my skills.

I am grateful to Siemens for their assistance in this research project by providing access to the PSS®DE software. This software played a crucial role in conducting simulations and analyzing the data, enabling a comprehensive evaluation of the photovoltaic installations.

Finally, I would like to express my sincere gratitude to my project supervisor, José Pablo Chaves Ávila, for his guidance, expertise, and unwavering support throughout the completion of this master's thesis. His invaluable insights and feedback have greatly contributed to the success of this research.

I am truly grateful for the contributions of all those mentioned above and many others who have supported me in various ways during the course of this master's thesis. Your collective support and guidance have been invaluable, and I am honored to have had the opportunity to work on this research project.



# MODELING AND DATA ANALYSIS FOR SELF-CONSUMPTION SOLAR GENERATION

**Author:** Carbonell de la Cámara, Jorge.

Director: Chaves Ávila, José Pablo.

## ABSTRACT

This project analyses the implementation of a photovoltaic self-consumption system at Comillas Pontifical University to reduce energy costs and carbon footprint. It involves regulatory analysis, scenario simulation, economic evaluation, and recommendations. Extensive research demonstrates the feasibility and benefits of photovoltaic systems, showcasing cost savings, reduced reliance on fossil fuels, and positive environmental impact. The project sets an example for other institutions and aligns with sustainable development goals.

**Keywords:** Photovoltaic, Self-Consumption, Carbon Footprint, Environment, Simulation, Sustainable, Cost Savings, Renewable, Regulation, Software, Energy

## 1. Introduction

The global transition towards a more environmentally conscious energy model is driven by the awareness of the negative impact of traditional energy resources on the environment and the problems they pose, such as depletion of reserves, energy dependence, and pollution. Renewable energies, particularly solar generation, offer a solution by saving finite resources, reducing waste and greenhouse gases, and providing a safe and inexhaustible energy source. This project at the Comillas Pontifical University focuses on modeling and analyzing self-consumption generation using photovoltaic panels, contributing to the promotion of renewable energy, and addressing the greenhouse effect.

Beyond the environmental benefits, the use of renewable energy sources like solar energy also brings economic advantages, including job creation and energy independence. By investing in renewable energy infrastructure, countries can reduce their reliance on imported fossil fuels and increase their energy self-sufficiency.

## **2. Project definition**

The project aims to analyze photovoltaic generation at Comillas Pontifical University, with a particular focus on the Institute for Technological Research (IIT) and considering different business models to improve the current situation. The project aims to identify the applicable Spanish regulations, acquire skills in using Siemens' PSS®DE tool, obtain an optimal scenario considering the current regulations, conduct a comprehensive economic analysis, and provide recommendations for improvement and the most suitable business model. These objectives align with the United Nations' Sustainable Development Goals, promoting the use of renewable energy, reducing carbon emissions, and fostering economic growth and innovation.

To achieve these objectives, the project utilizes Siemens' PSS®DE software for simulations and analysis. Additionally, offers from three external companies (A, B, and C) to renovate their photovoltaic installations will be considered, serving as a starting point and guidance for the project. The gathered information will enable an evaluation of the economic feasibility of the installation and provide concrete recommendations for implementing a cost-effective and sustainable photovoltaic system.

## **3. Description of the system**

The system design has been developed after conducting a thorough analysis of the state of the art, considering the Spanish regulatory framework, specifically focusing on the regulations in Madrid, where the installation will take place. Additionally, careful consideration has been given to the various components and elements required for an efficient and sustainable photovoltaic system.

To determine the optimal scenario for the installation, relevant input parameters have been gathered. Environmental factors, such as solar radiation and local climatic conditions, as well as the building's energy consumption and electricity prices in the area, have been taken into account. A crucial aspect of the system planning is the analysis of the available surface area for the installation. The available space at the IIT has been thoroughly evaluated, considering site-specific constraints and characteristics. Based on this evaluation, an optimal surface distribution has been selected to maximize solar energy capture and ensure system efficiency and performance.

Subsequently, simulations have been conducted using specialized software to validate and optimize the proposed design. These simulations have allowed for the evaluation of the system's energy performance under different scenarios and conditions. Technical aspects such as energy production and expected consumption, as well as CO<sup>2</sup> emission reduction, have been taken into consideration.

In addition to the technical analysis, a detailed economic assessment has been carried out to evaluate the financial viability of the installation. Initial costs for component acquisition and installation, as well as operating and maintenance expenses over the system's lifespan, have been considered. This analysis provides a comprehensive understanding of the economic and financial benefits achievable with the photovoltaic installation.

#### **4. Results**

The technical evaluation of the system demonstrated excellent energy production capabilities, with high levels of solar energy capture and a substantial reduction in greenhouse gas emissions.

Furthermore, the economic analysis confirmed the financial feasibility of the photovoltaic installation. The initial investment costs for component acquisition and installation were balanced by significant cost savings in energy consumption. The project exhibited favorable financial metrics, including a short payback period, high return on investment, positive net present value, and an attractive internal rate of return. These indicators indicate the profitability and potential long-term benefits of the project.

#### **5. Conclusions**

The project's findings confirm the positive performance of photovoltaic installations in terms of energy production, cost savings, and greenhouse gas emissions reduction. The economic analysis demonstrated the financial feasibility of such installations, considering factors such as initial investment, operational costs, and available incentives. Additionally, the environmental assessment highlighted the significant contribution of photovoltaic systems in mitigating climate change and reducing dependence on fossil fuels.

Moving forward, future research should prioritize two areas closely related to the project and of significant interest for the university. The first area is collective self-consumption, which involves exploring the potential benefits and challenges of implementing this model in photovoltaic installations. The second area is the integration of additional renewable energy sources with photovoltaic systems. Focusing on these research directions will contribute to the advancement and widespread adoption of sustainable and renewable energy solutions in the field of renewable installations.

# *Memory Index*

<b>Chapter 1. Introduction.....</b>	<b>6</b>
1.1 Motivation.....	6
1.2 Justification.....	7
1.3 Objectives.....	9
<b>Chapter 2. State of the Art.....</b>	<b>11</b>
2.1 Actual Situation of Self-Consumption Solar Generation.....	11
2.2 Potential of Solar Energy in Spain.....	13
2.3 Growth Prospects for Self-Consumption Solar Generation.....	14
2.4 New Business Models and Current Constraints.....	15
<b>Chapter 3. Regulatory Framework.....</b>	<b>16</b>
3.1 Types of Installations.....	17
3.1.1 Self-Consumption Without Surplus.....	17
3.1.2 Self-Consumption With Surplus.....	17
3.2 Collective Self-Consumption.....	18
3.3 Administrative Procedures.....	19
3.4 Solar Panels Subsidies.....	21
<b>Chapter 4. Components of a Photovoltaic Installation.....</b>	<b>23</b>
4.1 Photovoltaic Solar Modules.....	23
4.2 Solar Inverter.....	25
4.3 Battery or Accumulator.....	27
4.4 Structure and Support.....	28
4.5 Other Elements.....	28
<b>Chapter 5. Methodology.....</b>	<b>30</b>
5.1 Analysis of the Current Installation.....	30
5.2 Software PSS@DE by Siemens.....	32
5.3 Comparison of Offers received by Companies for New installations.....	33
5.3.1 Photovoltaic Parameters & Electric Load.....	34
5.3.2 Simulation Results.....	36

<b>Chapter 6. Case Study.....</b>	<b>40</b>
6.1 Input Parameters.....	41
6.1.1 Electric Load.....	41
6.1.2 Electricity Prices.....	43
6.2 Surface Analysis.....	46
6.2.1 Segment I Analysis.....	50
6.2.2 Segment II Analysis.....	60
6.2.3 Optimal Surface Distribution.....	61
6.3 Installation Components.....	62
6.4 Optimal Scenario Simulation.....	67
6.5 Degradation Factor.....	71
6.6 Economic Analysis.....	74
<b>Chapter 7. Analysis of Results.....</b>	<b>82</b>
<b>Chapter 8. Conclusions and Future Work.....</b>	<b>85</b>
<b>Chapter 9. Alignment with the Sustainable Development Goals (SDGs).....</b>	<b>87</b>
9.1 SDG 7: Affordable and Clean Energy.....	88
9.2 SDG 9: Industry, Innovation and Infrastructure.....	89
9.3 SDG 13: Climate Action.....	90
<b>Chapter 10. Bibliography.....</b>	<b>91</b>
<b>ANNEX I. Photovoltaic Power Potential (PVOUT).....</b>	<b>94</b>
<b>ANNEX II. Global Horizontal Irradiation (GHI).....</b>	<b>95</b>
<b>ANNEX III. Direct Normal Irradiation (DNI).....</b>	<b>96</b>
<b>ANNEX IV. Photovoltaic Parameters for IIT by PSS®DE.....</b>	<b>97</b>
<b>ANNEX V. Dimensioned Plan of the IIT Roof.....</b>	<b>99</b>
<b>ANNEX VI. Electric Load for IIT by PSS®DE.....</b>	<b>100</b>

## *Index of Figures*

Figure 1. Map of the Area of Interest (BIC in Orange).....	8
Figure 2. Solar Self-Consumption in the EU in 2021 in MW (SolarPower Europe & UNEF) .....	11
Figure 3. Sectoral Breakdown for New Installed Capacity During 2022.....	12
Figure 4. Growth Prospects for Self-Consumption Solar Generation.....	14
Figure 5. Administrative Procedures. Source: Own elaboration.....	21
Figure 6. Components in a Photovoltaic Solar Module. Source: own elaboration.....	23
Figure 7. Difference between Central or String Inverters (left) and Microinverters (right). Source: Own elaboration.....	26
Figure 8. Diagram of an Installation with Battery and Grid Connection. Source: Own elaboration.....	27
Figure 9. Evolution of Photovoltaic Solar Generation. Source IRENA.....	31
Figure 10. Annual Photovoltaic Production for each Offer.....	34
Figure 11. IIT's Daily Consumption for 2021 (Estimation).....	35
Figure 12. IIT'2 Monthly Consumption for 2021 (Estimation).....	36
Figure 13. A's Offer Sankey Diagram.....	37
Figure 14. B's Offer Sankey Diagram.....	38
Figure 15. C's Offer Sankey Diagram.....	38
Figure 16. Electric Load (Original Data).....	42
Figure 17. Electric Load (After Data Processing).....	43
Figure 18. 2.0TD Active Energy Billing Term vs. Price of Surplus Energy from Self- Consumption (2020).....	45
Figure 19. 2.0TD Active Energy Billing Term vs. Price of Surplus Energy from Self- Consumption (2022).....	46
Figure 20. Segmented Roof Surface.....	47
Figure 21. Distance Calculation Segment I Case I.....	50
Figure 22. Surface Distribution Segment I Case I.....	52

*INDEX OF FIGURES*

Figure 23. Distance Calculation Segment I Case II.....	53
Figure 24. Surface Distribution Segment I Case II .....	54
Figure 25. Distance Calculation Segment I Case III .....	55
Figure 26. Surface Distribution Segment I Case III .....	57
Figure 27. 20°R (Case I: Left), 10°R (Case II: Center) and Sail 10° (Case III: Right) .....	58
Figure 28. Surface Distribution Segment II.....	61
Figure 29. Optimal Surface Distribution .....	62
Figure 30. Solar Paneles SunPower SPR-P3-410-COM-1500.....	63
Figure 31. Solar Inverter Huawei SUN2000-12KTL-M2-3PH.....	64
Figure 32. Structure EnnovaBloc Sail 10°. Source: Own elaboration.....	65
Figure 33. Scenario I: Without Compensation for Surplus Energy. Source: Own elaboration .....	69
Figure 34. Scenario II: With Compensation for Surplus Energy .....	70
Figure 35. Evolution of Photovoltaic Generation from 2003 to 2016 (Old Installation) ....	72
Figure 36. Degradation Factor Evolution .....	74
Figure 37. Energy Prices Evolution in €/MWh during Project Lifetime of the installation. (OMIP).....	78
Figure 38. DCF Scenario I (5 first years).....	79
Figure 39. DCF Scenario II (5 first years).....	80
Figure 40. SDG's 7, 9 and 13.....	88

## *Index of Tables*

Table 1. Comparison between Offers .....	33
Table 2. Comparison between Simulation and Offered Generation .....	39
Table 3. Weights, Loads and Security Factors in Cases I, II and III .....	59
Table 4. Peak Power, Efficiency and Annual Photovoltaic Generation in Cases I, II and III .....	59
Table 5. CapEx in Cases I, II and III .....	59
Table 6. Investment for the Installation Components.....	66
Table 7. Degradation Factor Comparison.....	72
Table 8. Financial Metrics Comparison .....	81
Table 9. Comparative Table Offers vs. Simulated Scenarios .....	83

## **Chapter 1. INTRODUCTION**

### ***1.1 MOTIVATION***

As the years go by, the whole world is following a transition towards a model much more aware of the impact that human beings have on the environment, in the short, medium, and long term. The intensive exploitation of traditional energy resources, such as coal, oil, and natural gas, poses problems such as depletion of reserves, energy dependence, supply difficulties, and pollution.

The main environmental problem we find worldwide concerning current energy consumption is the greenhouse effect. Renewable energies allow for saving finite natural resources and generating less waste and greenhouse gases, positioning itself as a safe and inexhaustible energy source. It seems clear that greater exposure to renewable energies in the energy generation matrix will also allow protection against the volatility of the price of oil and natural gas, something that is being experienced very closely due to the energy crisis produced by the rise in energy prices due to the war between Russia and Ukraine.

In this way, renewable energies are shown as an alternative source, with solar generation being one of the best-known and widespread to date. In recent years it has been gaining strength among different entities and even individuals to take advantage of the space that exists on the roofs of their buildings to place some panels and reduce the price of their electricity bill contributing positively to the environment. This project is based on modeling and analysis for self-consumption generation at the Comillas Pontifical University.

At the level of personal motivation about the project, the fact of being able to work in collaboration with the IIT is a great opportunity and, in addition, photovoltaic energy is a very contemporary and attractive subject. More and more often it is observed how not only companies but also individuals make the decision to make the necessary investment to carry out a photovoltaic installation on their homes to take advantage of the space of their roofs achieving a reduction in the electricity bill sustainably.

In addition to the environmental benefits, the use of renewable energy sources such as solar energy can also contribute to the development of local economies and job creation. The renewable energy sector has been growing rapidly, and according to the International Renewable Energy Agency (IRENA), it employed 11.5 million people globally in 2019. This growth is expected to continue as the demand for renewable energy increases.

Moreover, the use of renewable energy sources can also promote energy independence and security, especially for countries that rely heavily on imported fossil fuels. By investing in renewable energy infrastructure, these countries can reduce their dependence on foreign energy sources and increase their energy self-sufficiency.

Another important aspect to consider is the role of renewable energy sources in achieving the Sustainable Development Goals (SDGs). The SDGs were adopted by the United Nations in 2015 as a universal call to action to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity by 2030. This will be developed deeply in Chapter 9.

Finally, it is worth mentioning that the development of self-consumption generation using photovoltaic panels is not only limited to the residential sector. Commercial and industrial sectors can also benefit from the installation of photovoltaic systems, reducing their energy costs and environmental impact. In this sense, the project being developed at the Comillas Pontifical University has the potential to contribute to the expansion of self-consumption generation not only at the individual level but also at the commercial and industrial levels.

## ***1.2 JUSTIFICATION***

The importance of this project lies in two main points. On the one hand, the growing importance of a more sustainable and environmentally conscious energy generation model. On the other hand, the need to renovate the photovoltaic installation of the IIT building, the possibility of improving the ICAI installation, and even the option of proposing an installation for the ICADE building located at Alberto Aguilera 23, which currently has no installation. These second two options are somewhat different because the ICADE and ICAI

buildings are both Assets of Cultural Interest (BIC), which implies a regulatory change and special measures.

From ArcGIS Online, a cloud-base mapping and analysis solution, it has been obtained the Figure 1, which represents the location of the three buildings object of study highlighting in orange those that are Assets of Cultural Interest (ICAI & ICADE).



*Figure 1. Map of the Area of Interest (BIC in Orange)*

The renovation of the IIT's installation is not only a necessary initiative, but also a strategic one. By reducing energy consumption costs and decreasing the carbon footprint, the IIT can set an example for other institutions in the field of sustainable energy practices. The installation of a photovoltaic system aligns perfectly with the IIT's goals of sustainability and energy efficiency. Moreover, it presents an opportunity to engage the institution's students and faculty in a hands-on learning experience, which can promote awareness and understanding of the importance of renewable energy sources.

Expanding the photovoltaic installation to the ICADE and ICAI buildings could also bring significant benefits in terms of sustainability and cost savings. However, this would require a thorough analysis of the energy needs and characteristics of each building, as well as a careful consideration of the potential impact on the surrounding area. Therefore, it is important to focus on the installation of the IIT as the first step, which can serve as a pilot

project for future installations in other buildings of the Pontifical University of Comillas. This approach allows for a more strategic and informed decision-making process and ensures that the installations are tailored to the specific needs of each building.

### ***1.3 OBJECTIVES***

The objectives of the project are essential to define the scope and purpose of the study. As stated in the motivation and justification, the project aims to analyze photovoltaic generation data from the Comillas Pontifical University, particularly from the Institute for Technological Research (IIT) and consider different business models to make recommendations to improve the current situation.

To achieve this goal, the project has set several objectives, which are listed below:

- 1. Regulation:** Identify the current Spanish regulation applicable to the generation dedicated to self-consumption and the implications for the installation in the IIT, as well as for the installations in ICAI and ICADE, which may be different due to their status as Goods of Cultural Interest. This objective aims to ensure that the project complies with the relevant legislation and regulations to avoid legal or technical problems that may arise during the project implementation.
- 2. Use of the tool:** Acquire the necessary skills in the tool provided by Siemens, called PSS®DE, to consider different technological alternatives and obtain the desired results. This objective is crucial to ensure that the project team can effectively use the software tool to perform the required analysis and simulations. The project team will undergo training in the use of the tool before starting the actual work.
- 3. Obtaining a definitive scenario:** Once the first two objectives have been achieved, the project team aims to obtain the optimal scenario considering the current regulation through the tool. This objective involves conducting tests with different configurations to determine the most suitable scenario for the IIT.
- 4. Economic analysis:** Conduct a comprehensive economic analysis of the proposed scenario to determine the cost-effectiveness of the installation. This objective aims

to evaluate the economic feasibility of the project and determine the return on investment for the university.

- 5. Recommendation:** Based on the analysis and economic evaluation, make recommendations to improve the current situation and identify the most appropriate business model for the installation of a photovoltaic system in the IIT. This objective aims to provide the university with concrete and actionable recommendations for implementing a photovoltaic system in a cost-effective and sustainable manner.

Overall, the objectives of the project are aligned with the sustainable development goals of the United Nations, particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 13 (Climate Action). The project seeks to promote the use of renewable energy sources, reduce carbon emissions, and promote economic growth and innovation.

## Chapter 2. STATE OF THE ART

### 2.1 ACTUAL SITUATION OF SELF-CONSUMPTION SOLAR GENERATION

In 2021, solar energy in Europe observed an unprecedented growth, increasing installed capacity by 25.9 GW, 34% more than in 2020. These figures highlight the energy transition underway in Europe, observing a society increasingly aware of the need to implement sustainable energy consumption. The photovoltaic power (elBoletin, 2022) installed in the European Union reached 164.9 GW, placing Spain in third position with 17.9 GW, only surpassed by Germany and Italy.

One of the factors driving this increase is the growth in self-consumption solar generation. Even though Spain was one of the countries that later started to boost self-consumption generation, it ranked fourth, with 1,203 MW installed in 2021 (Figure 2).

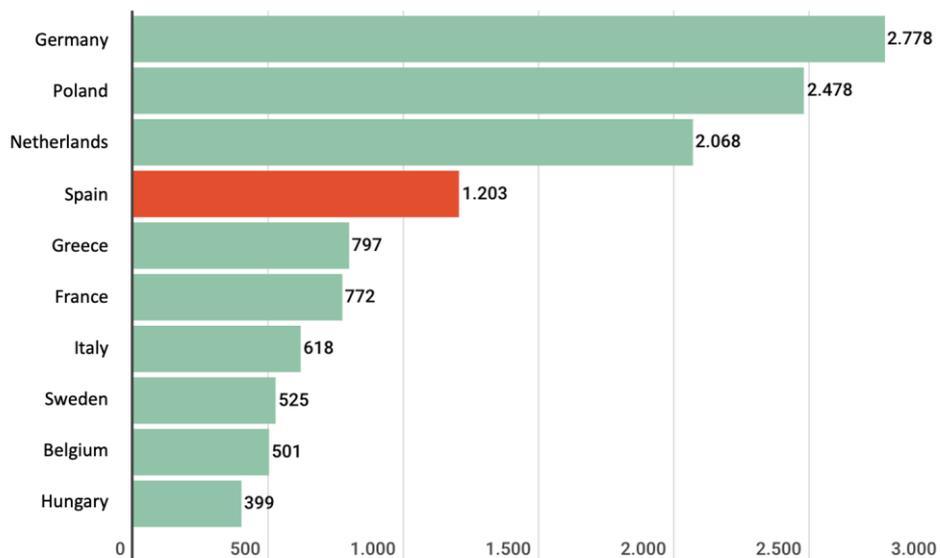
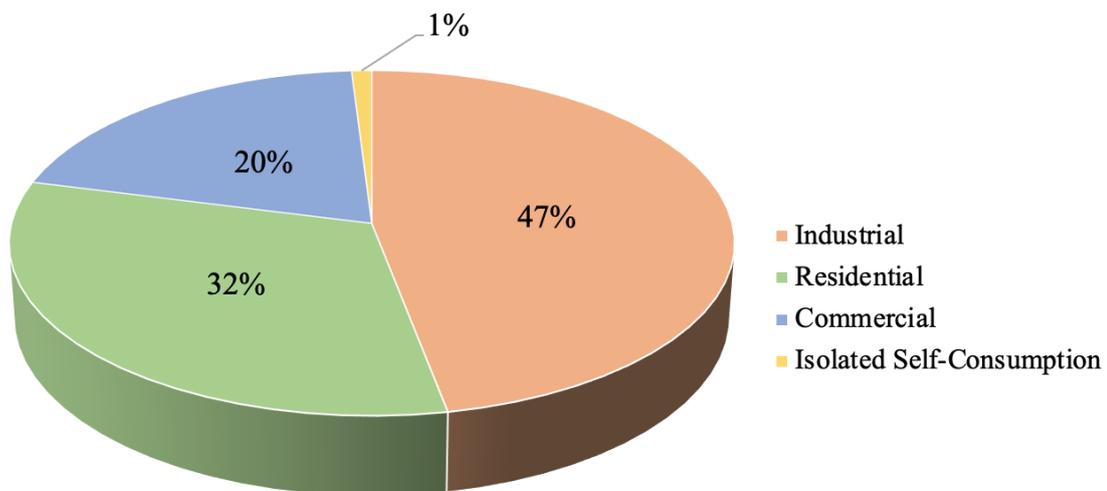


Figure 2. Solar Self-Consumption in the EU in 2021 in MW (SolarPower Europe & UNEF)

This "late boost" by Spain was due to the so-called "Sun Tax" which was repealed in 2018 unleashing the huge potential of self-consumption in Spain. As a result, Spain regained after 11 years of its position in photovoltaic energy in Europe ranking sixth worldwide (Lopez Escalante, 2021).

Even though 2021 was a historic year in terms of growth in installed photovoltaic self-consumption in Spain, 2022 has seen a 108% growth compared to the previous year. According to data recorded by the Spanish Photovoltaic Union (UNEF), the figure for new self-consumption solar power capacity installed was 2507 MW, compared to the 1203 MW installed in 2021. At the end of 2022, Spain had 5249 MW of cumulative installed capacity in terms of self-consumption. The new installed capacity during 2022 follows a sectorial distribution as shown in Figure 3. It is worth noting that the sector that has shown the greatest growth during this last year has been the industrial sector, from 42% to 47%.



*Figure 3. Sectoral Breakdown for New Installed Capacity During 2022*

The general director of UNEF, José Donoso (UNEF, 2023), stated that "The high electricity prices caused by the uncertainty following the invasion of Ukraine, as well as the boost provided by the aid included in the Government's Recovery Fund, have led to self-consumption continuing to break records in our country. In addition, the first collective self-consumption projects are starting to be put into operation, a trend that will continue to grow and boost the sector even more. The progressive elimination of administrative barriers and

local incentives have also led more and more individuals to become self-consumers, thus joining the fight against climate change. This generates a demonstration effect that will make self-consumption a very common element in our homes and businesses".

## ***2.2 POTENTIAL OF SOLAR ENERGY IN SPAIN***

The large number of daylight hours that Spain enjoys makes it one of the richest countries in solar energy (IFEMA, 2022), making it the European country with the greatest photovoltaic power potential. To analyze the solar energy potential in Spain, calculations were made using high-resolution data (Solargis) and photovoltaic modeling software:

- Photovoltaic Power Potential (PVOUT): is defined as the long-term average of the electricity production potential of a 1 kWp photovoltaic plant connected to the grid. ANNEX I. Photovoltaic Power Potential (PVOUT) shows the PVOUT values for Spain, highlighting for Madrid, daily values between 4,2 and 4,6 kWh/kWp and annual values between 1534 and 1680 kWh/kWp.
- Global Horizontal Irradiation (GHI): is defined as the radiation received by a square meter of the horizontal surface and includes direct, diffuse, and reflected radiation. It is the most important parameter for flat-plate photovoltaic technologies. ANNEX II. Global Horizontal Irradiation (GHI) shows the GHI values for Spain, highlighting for Madrid, daily values between 4,2 and 4,6 kWh/m<sup>2</sup> and annual values between 1534 and 1680 kWh/m<sup>2</sup>.
- Direct Normal Irradiation (DNI): is the most important parameter for concentrating solar power (CSP) and concentration solar photovoltaic (CPV) technologies. It is defined as the radiation measured at a given location in the direction of the incident beam. ANNEX III. Direct Normal Irradiation (DNI) shows the DNI values for Spain, the values for Madrid would be between 5.2 and 5.6 kWh/m<sup>2</sup> per day and between 1899 and 2045 kWh/m<sup>2</sup> per year.

Spain has 3000 hours of sunshine per year (Madrid has 2691 hours/per year) compared to 1600 hours in Germany, the current leader in self-consumption in the European Union. This shows that Spain has great potential to develop in this type of clean energy.

### 2.3 GROWTH PROSPECTS FOR SELF-CONSUMPTION SOLAR GENERATION

After surpassing the milestone of 5 GW of installed capacity in 2022, the prospects for the development of self-consumption solar generation in Spain are limitless. Since 2015, installed solar self-consumption capacity has been doubling year after year. This is largely due to the reduction in costs associated with solar PV and the path to follow set by the European Union and other international bodies.

According to the estimation made by APPA Renewables (observed in Figure 4), Spain will reach the target set in the 2030 Agenda in 2024, six years before the date required in the self-consumption roadmap. APPA's spokesperson considers the goal to be too simple and proposes increasing the target from 9 to 14 GW by 2030.

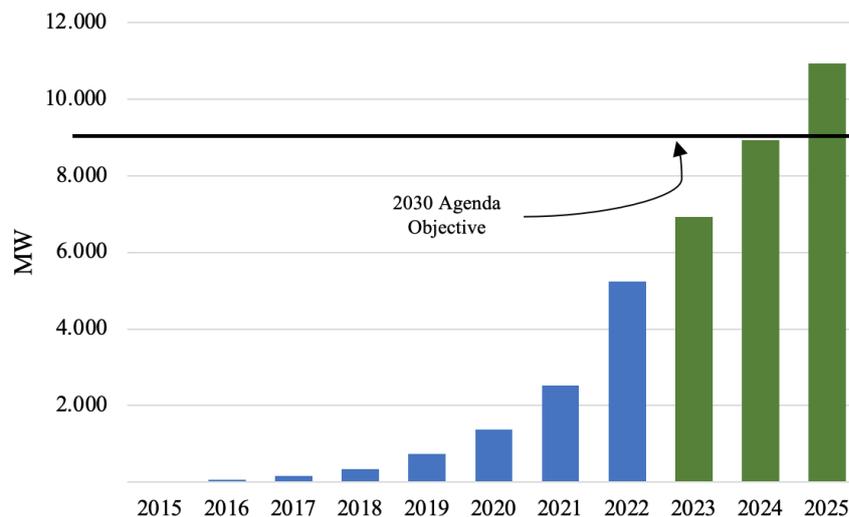


Figure 4. Growth Prospects for Self-Consumption Solar Generation

---

## ***2.4 NEW BUSINESS MODELS AND CURRENT CONSTRAINTS***

In the past, the tools necessary for the implementation of solar panels and batteries were quite expensive, however, the growth and development of this type of renewable and clean energy, and technological advances have led to a significant reduction in the costs associated with photovoltaic installations. If we add to this fact the economic aid offered by public administrations and new regulatory frameworks that greatly facilitate the process, we can observe an exponential growth of self-consumption solar generation in homes, industries, and other companies.

As a direct consequence of last year's growth, some bottlenecks have been observed, resulting in strong price increases of 10-15% for industry and 20-30% for individuals. This price increase is also driven by the current inflationary period in which we find ourselves, with an annual variation rate of the Spanish CPI in January 2023 of 5.8%. Another of these bottlenecks is defined by the tension generated in the supply chain by the shortage of inverters (mainly), batteries, and even modules. Finally, there have been staff shortages in the sector, estimated at 50,000 people (M. Velez, 2023).

The strong growth of photovoltaic energy in Spain is favoring the emergence of new business models, two of which stand out:

- Virtual batteries: a new concept offered by certain energy marketers that allows the accumulation of surpluses produced and not consumed.
- Shared self-consumption and energy communities: because more than 70% of the population lives in apartments, the Government has extended the radius of shared self-consumption to two kilometers, thus matching the rest of the European Union countries. This point is of special interest for this project as presented the following chapters.

## **Chapter 3. REGULATORY FRAMEWORK**

This chapter is key to the development of this project because the government is committed to promoting renewable self-consumption by offering an attractive regulatory framework. The administrative, technical, and economic conditions for the self-consumption of electricity are regulated by RD 244/2019 of April 5.

One of the most relevant aspects of this new regulation was the repeal of the sun tax, which consisted of a charge on self-consumed energy established in RD 900/2015 and was an impediment to the ecological transition. It is highly improbable the establishment of a solar energy toll measure in the future because it would go totally against the Sustainable Development Goals.

It is also worth mentioning the measures adopted in RDL 20/2022 of December 27, which facilitate the deployment of renewable energy facilities and self-consumption. Some of these measures are the streamlining and simplification of the environmental impact declaration procedures, the modification of the retributive regime for renewable facilities, or the increase of the distance between generating facilities or self-consumption plants to 2000 meters (previously 1000 m). This RDL involves measures to respond to the economic and social consequences of the war in Ukraine and to support the reconstruction of the island of La Palma and other situations of vulnerability (Mendoza Losana, 2023).

This chapter describes the different types of installations, the modalities and requirements for collective self-consumption, and the administrative procedures for carrying out a self-consumption photovoltaic installation.

### **3.1 TYPES OF INSTALLATIONS**

The economic regulation of self-consumption relates to the existence of energy surplus. Surplus refers to the energy produced by the solar panels that cannot be consumed by the associated load. The regulation allows the consumer to sell the surplus in exchange of economic compensation, which can be used by other consumers.

The two types of installations distinguished by the the regulation (IDAE & ENERAGEN, 2022) and the requirements to belong to each of them are defined below.

#### **3.1.1 SELF-CONSUMPTION WITHOUT SURPLUS**

Self-consumption installations without surplus are defined as those with an anti-spill system preventing surplus electricity injection into the transmission or distribution grid. In this type of installation, the consumer is the owner of the installation, the owner may be another entity and there is not a separate producer entity. It should be noted that in the case of collective self-consumption without surpluses, there is the possibility of using the compensation of surpluses among the members of the community.

This type of installation is different from the off-grid one since the latter is connected to the grid, with the only difference being that it does not share its energy surplus.

#### **3.1.2 SELF-CONSUMPTION WITH SURPLUS**

Self-consumption facilities with surpluses are defined as those that, in addition to generating electricity for self-consumption, have the capacity to inject the surpluses from their solar panels into the transmission and distribution grids. Due to the existence of a series of requirements to allow the discharge of surplus energy to the grid, the regulation distinguishes two types of self-consumption facilities with a surplus:

- **Installations with compensation:** in this case, the consumer uses the energy from the self-consumption installation when it is needed, being able to buy energy from the grid when self-generated energy is not sufficient to meet its electricity consumption. When the energy produced by the self-consumption installation is

greater than that needed (surplus), it can be injected into the grid. Compensation refers to the fact that, in each billing period, the invoice issued by the retailer compensates the cost of the energy purchased with the value of the surplus energy injected into the grid. The value of the surplus energy can be defined either by the average price of the hourly market minus the cost of deviations or by a price agreed between the consumer and the supplier. The necessary conditions to belong to this type of installation are as follows (IDAE & ENERAGEN, 2022):

- The primary energy source is of renewable origin.
  - The total potential of the associated production facilities does not exceed 100 kW.
  - If applicable, the consumer has signed a single supply contract for the associated consumption and for auxiliary consumption with the marketing company.
  - The consumer and associated producer have signed a self-consumption surplus compensation contract as defined in article 14 of RD 244/2019.
  - The production facility is not subject to the collection of an additional or specific remuneration regime.
- **Non-compensated installations:** those facilities that do not comply with the previously stipulated requirements or prefer not to voluntarily accept the compensation of surpluses. In this case, the surplus will be sold by the associated producer (the one registered in the RAIPEE) in the electricity market.

### **3.2 COLLECTIVE SELF-CONSUMPTION**

Collective self-consumption is defined in the RD 244/2019 of the BOE as follows: "Collective self-consumption: a consumer subject is said to participate in a collective self-consumption when it belongs to a group of several consumers that are fed, in an agreed manner, with electrical energy that is sourced from production facilities close to the consumption facilities and associated to the same."

In basic terms, collective self-consumption consists of the installation of solar panels by several participants, the main advantages of which are a lower initial outlay, a faster return on investment, and an increase in the available useful surface area on which the installation is carried out. Collective self-consumption can be carried out in residential buildings and/or companies, in business parks, or in residential areas. Another advantage of this modality is that each of the consumers who are part of the agreement can have their supply contracted with different marketers.

The requirements to belong to collective self-consumption are as follows:

- All participants must be connected to the same transformation center and the energy distributed must be in the low voltage.
- The production system and the participants must be registered in the same cadastral reference.
- The maximum distance between the PV plant and each of the participants must be less than two kilometers.

In addition, all participants must sign an energy-sharing agreement stating the type of self-consumption, the self-consumption code (CAU), the associated consumers with their sharing coefficients, and the associated generation facility or facilities.

### ***3.3 ADMINISTRATIVE PROCEDURES***

The following is a definition of the milestones in terms of administrative procedures when starting up a self-consumption installation. They are a set of 17 steps to be carried out with the administrations and the distribution and commercialization companies. The steps are as follows (Guijarro Ruiz, 2023):

- 1. Installation Design:** technical report for low voltage installations and power lower or equal to 10kW and technical project for installations with power higher than 10kW.

2. **Access and Connection Permits and Guarantees or Warranties:** the company that carries out the installation must request the self-consumption code (CAU) from the distributor. Exempt from requesting access and connection permits are installations without surpluses and those with a power of less than or equal to 15 KW. The rest of the installations must process these accesses through the installation company.
3. **Environmental and public health authorizations.**
4. **Preliminary administrative and construction authorization:** installations with a power of less than 100 kW in low voltage are exempted.
5. **Building permit and construction and works tax (ICIO).**
6. **Execution of the installations.**
7. **Initial inspection and periodic inspections:** low-voltage installations and those with no surplus are normally exempted.
8. **Certificates of installation and/or certificates of completion:** In low voltage the certification is carried out by the CIE while in high voltage the requirements must be consulted in the RIAT.
9. **Installation authorization:** low-voltage installations with power equal to or less than 100 kW are exempted.
10. **Access contract for the installation:** must be requested by those facilities that have a supply contract for auxiliary production services.
11. **Energy supply contract for auxiliary services:** it is the installation companies that determine the need to draw up this contract.
12. **Activity license:** only applies to installations with surpluses that are not eligible for compensation due to the sale of energy to the electricity market.
13. **Sharing agreement and surplus compensation contract:** the sharing agreement applies to collective self-consumption facilities and the compensation contract is carried out in facilities under simplified compensation.
14. **Inscription in the Autonomous Registry of consumption:** this registration must only be made by self-consumption installations with surpluses with power equal to or greater than 100 kW in LV and all self-consumption installations with surpluses in HV.

**15. Inscription in the administrative registry of self-consumption of electrical energy:** applies to installations with surplus.

**16. Registration in the administrative registry of electricity production facilities (RAIPRE):** applies to installations with surpluses with power equal to or greater than 100 kW.

**17. Representation contract in the market for the sale of energy:** only applies to installations with surpluses that are not eligible for compensation due to the sale of energy to the electricity market.

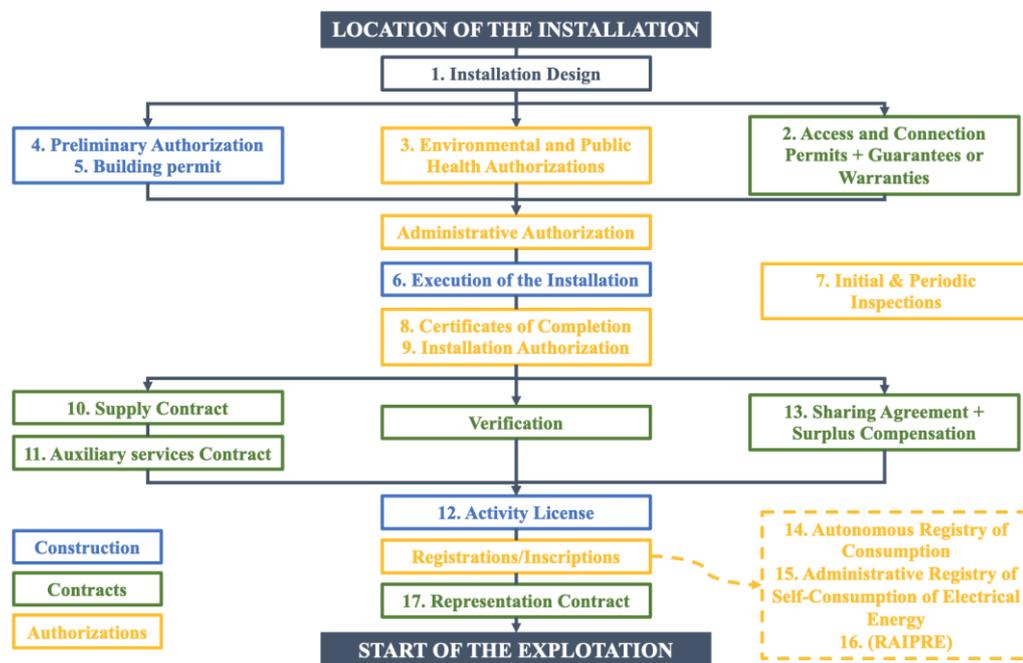


Figure 5. Administrative Procedures. Source: Own elaboration

### 3.4 SOLAR PANELS SUBSIDIES

The year 2023 is the last year to apply for subsidies for solar panels financed by the Next Generation European funds to promote self-consumption. These subsidies allow greatly

reduce the investment to be made to carry out a photovoltaic installation of self-consumption and apply to both companies and individuals.

The subsidies are divided into 6 different programs depending on the beneficiary and the type of installation to be carried out. In the case of the present project, "Program 1" for the installation of solar panels for companies in the service sector would apply and offers a subsidy of between 15% and 45%. It should be noted that the public administrations are currently collapsed, and the processes are lengthening.

The requirements for a company to be a beneficiary of the subsidy are as follows (Haro, 2023):

- To be a legal entity.
- Not to have any taxes pending payment.
- Not to have debts with the Treasury or Social Security.
- The company must not be in a crisis.
- To destine the payment of the aid to the object of the subsidy.
- To present a Responsible Declaration alleging that they meet the requirements.

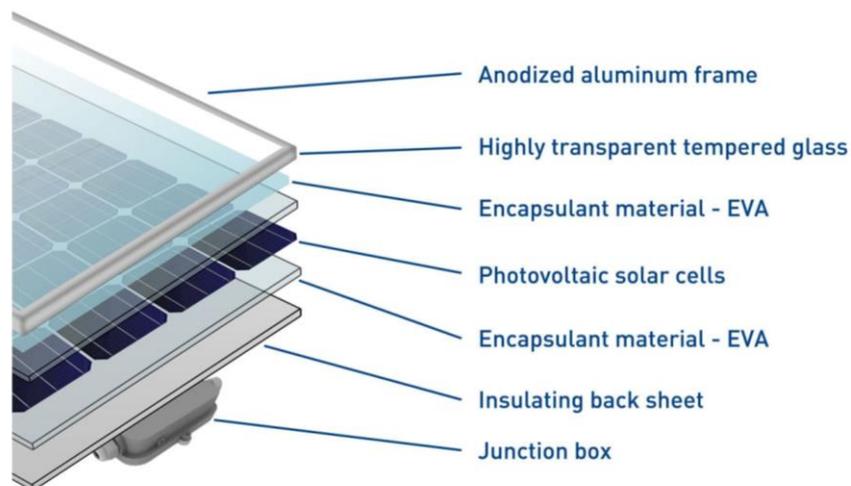
Some eligible costs would be labor, auditor's report, or management costs. However, certain costs such as VAT, promotion expenses, or environmental impact studies are considered ineligible.

## Chapter 4. COMPONENTS OF A PHOTOVOLTAIC INSTALLATION

### 4.1 PHOTOVOLTAIC SOLAR MODULES

Photovoltaic modules, more commonly known as solar panels, are the basic component of any solar installation. They are made up of photovoltaic cells whose function is to transform the incident solar radiation into direct current, which is then transformed into alternating current to be used by households.

The vast majority of solar panels on the market are composed of silicon and/or gallium arsenide, which are responsible for absorbing the sun's energy and converting it into electricity. Solar panels are composed of the following elements (Figure 6).



*Figure 6. Components in a Photovoltaic Solar Module. Source: own elaboration*

- **Anodized aluminum frame:** aluminum frame placed on the most superficial part of the panel, making it robust.

- **Highly transparent tempered glass:** glass casing whose function is to protect the panel from external meteorological conditions.
- **Encapsulant material – EVA:** normally there are two layers of encapsulation insulating the photovoltaic cells whose function is to retain and transmit solar energy.
- **Photovoltaic solar cells:** composed of semiconductor material with excess negatively charged electrons, usually silicon, and another positively charged semiconductor material with missing electrons, usually boron. This composition produces an absorption of photons when the panel is exposed to solar radiation, initiating a continuous electric current.
- **Insulating back sheet:** it is a sheet that acts as an insulator between the photovoltaic cells and the junction box.
- **Junction box:** its function is to feed the inverter with the direct current generated by capturing the flow of electrons.

Considering the type of photovoltaic cell, we can distinguish the following three categories of solar panels (Alusín Solar Structures):

- **Monocrystalline:** these are single-crystal silicon cells with a circular or octagonal shape and a uniform dark blue color. This type is manufactured by melting pure silicon and boron and offers an efficiency of between 15% and 18%.
- **Polycrystalline:** formed by a set of silicon crystals with a more rectangular shape and more intense color. The manufacturing process is like that of monocrystalline but with fewer crystallization phases, which results in a somewhat lower yield, between 12% and 14%.
- **Amorphous:** this type of cell is cheaper and therefore less efficient than the previous ones because they are composed of uncrystallized silicon. They are manufactured by depositing them in sheet form on a plastic or glass surface. The yields offered are less than 10% and are therefore the cells normally used in calculators and watches.

---

## 4.2 *SOLAR INVERTER*

The inverter is an essential element in any photovoltaic installation since it is responsible for transforming the direct current produced by the photovoltaic modules into alternating current 220V 50Hz, which is used by the electrical equipment of a business or home.

In addition, inverters collect and store information about the production, consumption, and status of the installation, thus allowing monitoring of these parameters. It is a highly efficient and safe equipment that must be adapted to the power needs, the characteristics of the roofing, and the type of consumption of the installation.

To distinguish between the different types of inverters (Rocha, 2022), it is first necessary to classify them into two groups: photovoltaic inverters for grid connection and battery photovoltaic inverters for off-grid installations.

Grid-connected inverters take electricity directly from the solar panels and transform it into a waveform identical to that of the grid, thus allowing the energy to be consumed and the surplus to be sold. There are three types of grid-connected inverters:

- **Microinverter:** small power inverters that can connect to a maximum of four solar panels. Its main advantages are the maximization of power and the ease of detecting faults in the photovoltaic modules, however, its price is higher than that of other inverters on the market.
- **String inverter:** usually used in larger installations and work by connecting the strings of the solar panels together. In this case, in the event of a failure or drop in performance in a panel, a reduction in the inverter's production would be observed. They usually have several inputs with maximum power trackers in order to make the installation more efficient.
- **Central inverter:** this type of inverter is used in installations with more than 100 kW of power, such as photovoltaic parks. The differences with the previous ones lie in their robustness, as they usually have a considerable size and weight, and in the fact that they usually have a single maximum power tracker.

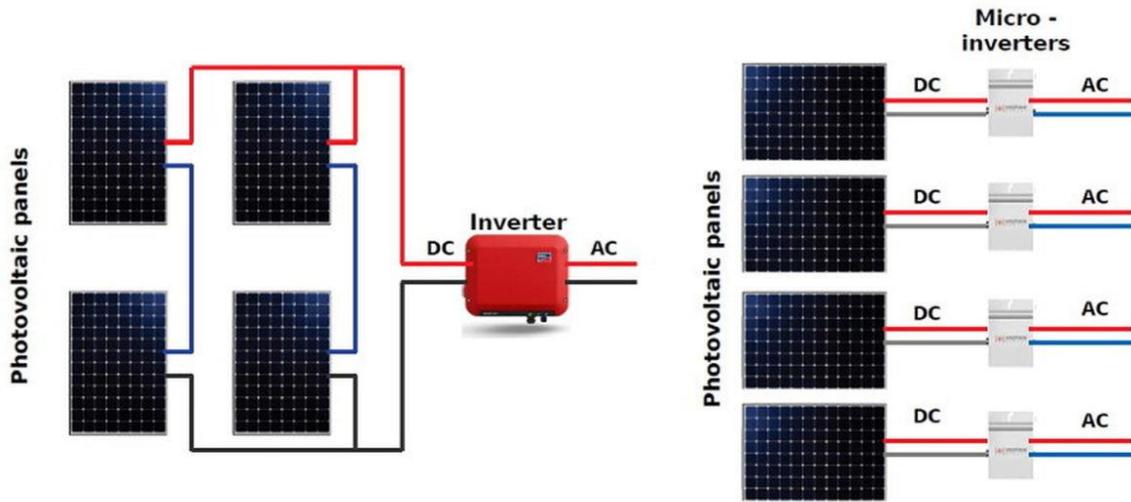


Figure 7. Difference between Central or String Inverters (left) and Microinverters (right). Source: Own elaboration

On the other hand, inverters for off-grid installations generate their grid with the desired waveform to be used directly in the electrical equipment. There are three types of inverters for off-grid installations:

- **Standard inverter:** a normal inverter whose only function is to transform the direct current stored in the batteries into alternating current.
- **Inverter-charger:** this inverter topology is capable of, in addition to transforming direct current into alternating current, converting an auxiliary input of alternating current into direct current to charge the battery. This auxiliary input is usually a generator set.
- **Hybrid inverter:** as its name suggests, this type of inverter offers a charge controller that allows direct connection of all solar panels, batteries, and consumption. In addition, it has a built-in battery charger, so it is the most versatile option and the most expensive.

### 4.3 BATTERY OR ACCUMULATOR

Solar batteries allow the storage of the electrical energy generated by the solar panels for later use. The use of smart batteries allows giving continuity to the electrical supply using the accumulated energy in the moments in which the production of the panels is reduced by the fact of a rainy day, certain shadows, or during the night.

This element is usually implemented in off-grid installations, but it is also used in grid-connected installations to improve their efficiency, as it can be seen in Figure 8. Depending on the manufacturing technology, four main types can be distinguished: lithium-ion, nickel-cadmium, lead-acid, and flow-through.

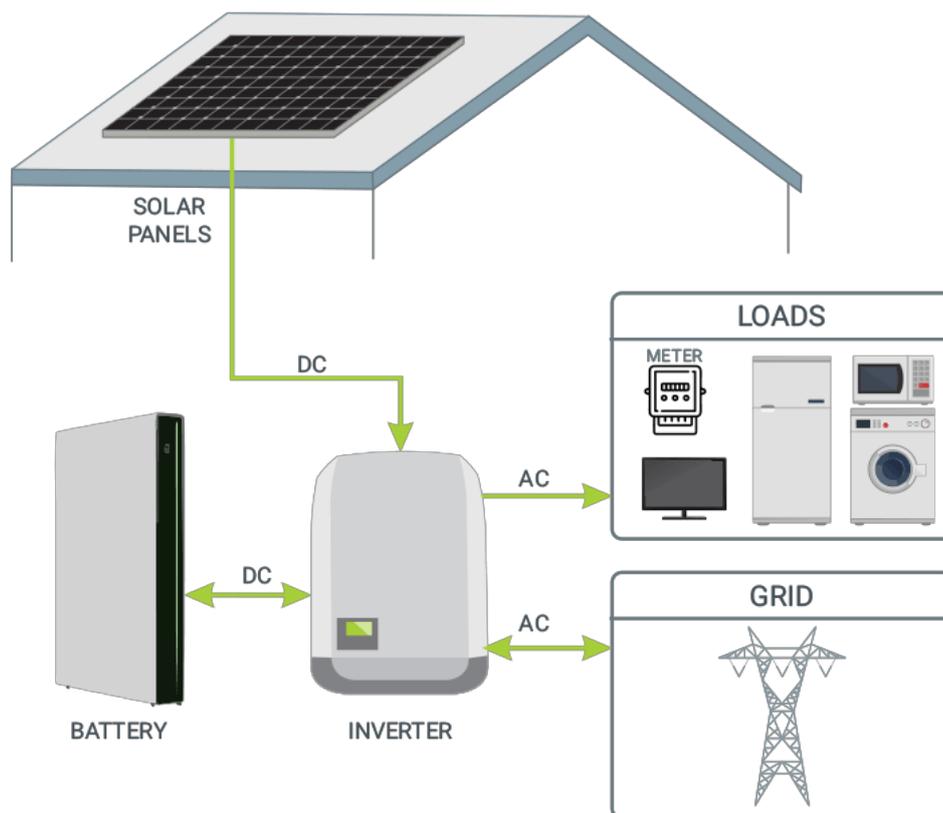


Figure 8. Diagram of an Installation with Battery and Grid Connection. Source: Own elaboration

---

## **4.4 STRUCTURE AND SUPPORT**

The structure and support are passive components that must withstand external weather conditions or agents (rain, snow, strong winds...) and facilitate the installation of the modules. The inclination of the structure will be responsible for the solar panel to receive the optimum radiation, hence its importance.

Its function is indispensable within the photovoltaic installation, guaranteeing the correct orientation and inclination of the same. When choosing the type of structure to be used, it is necessary to consider the type of surface, its material, orientation, and inclination. Ideally, the panels should be oriented to the south to capture the greatest amount of daily solar radiation, however, there is a margin of disorientation of about 45°, without the losses being very noticeable (EFC Solar). The inclination depends mainly on the place where the installation is going to be carried out and the time of the year in which you want to obtain a higher yield. For a higher performance in summer, inclinations of about 20° or 30° are observed, while to maximize performance in winter, these inclinations should be higher (between 50° and 60°).

## **4.5 OTHER ELEMENTS**

- **Power optimizers:** components located between the set of modules and the inverter whose function is to improve the performance of the operation by bringing each of the modules to work at maximum power. Mainly achieve that each of the modules operates independently of the rest, thus avoiding the loss of performance when any of the modules has a defect, shadow, or other circumstances. Another way to overcome this drawback is with the previously mentioned microinverters, a more expensive but also more flexible option.
- **Meter:** it allows the monitoring of the installation by measuring the photovoltaic production in real-time. In the case of grid-connected installations, a bi-directional meter is needed to measure the energy consumed from the grid and the surplus produced by the photovoltaic installation. If the installation is eligible for

---

compensation, these surpluses will be compensated with the amount of energy consumed.

- **Monitoring software:** this is the application or web portal that allows the owner of the installation to monitor different variables of his installation through his PC, cell phone, or tablet. These variables include instantaneous photovoltaic consumption and generation, among others, which will maximize the efficiency of the installation. Additionally, the monitoring software allows the detection of a possible reparation or maintenance.
- **Protection equipment:** this equipment is necessary to protect users and the installation itself against possible incidents such as short circuits, overloads, shunts, or surges. The most common protection equipment are the fuses, circuit breakers, differential switches, varistors, or grounding. All these devices are commonly integrated into the electrical panel next to the inverter.

## **Chapter 5. METHODOLOGY**

### ***5.1 ANALYSIS OF THE CURRENT INSTALLATION***

At present, the Comillas Pontifical University has made significant progress towards sustainable energy solutions by installing photovoltaic systems in two out of its three buildings located in the Argüelles area of Madrid. Specifically, one of the buildings, which houses the School of Engineering (ICAI) located at Calle Alberto Aguilera 25, has a photovoltaic installation. The other building that has undergone such an installation is the Institute of Technological Research (IIT), which is located at Calle de Sta. Cruz de Marcenado 26, situated just behind the ICAI building. This shows the university's commitment towards achieving sustainable energy goals while also contributing to reducing greenhouse gas emissions, reducing energy costs, and promoting renewable energy use in Madrid.

This project focuses on the renovation of the photovoltaic installation of the IIT building because these resources are quite old (about 20 years) and are currently so deteriorated that they produce practically no electricity. The Institute for Research in Technology (IIT) is a non-profit university institute whose main objective is to promote research and training of postgraduates in a wide variety of fields. To achieve this end, the IIT has a team of 164 researchers operating in 38 countries and almost 1500 collaborating companies.

The Ministry for the Ecological Transition and the Demographic Challenge issued a Roadmap in 2021 to promote self-consumption in Spain, bringing it closer to all consumers. (Ministerio para la Transición Ecológica y el Reto Demográfico, 2021) After undergoing the public hearing process, the document incorporates measures to promote collective self-consumption (neighborhood communities) and certain regulatory changes to improve the agility of the start-up of the facilities, also pursuing the improvement of industrial competitiveness by reducing costs associated with energy. It is estimated that the installed capacity of self-consumption in 2030 will be 14,000 MW compared to 2,500 MW in 2021.

To establish a correct framework for the current situation of photovoltaic solar energy, the information collected by the International Renewable Energy Agency has been used globally and nationally. Total PV capacity (IRENA, 2021) globally reached 710 GW at the end of 2020, due to a new capacity increase of 125 GW during the same year, which corresponds to the largest capacity increase of all renewable energy sources. The cost of manufacturing solar panels has fallen drastically in the last decade, specifically, by 93% between 2010 and 2020, this, added to a decrease in the cost of electricity (LCOE) for photovoltaic projects of 85%, represents an increase in the interest of this type of energy, which is accompanied by an increase in the number of photovoltaic installations. The following graphs show the evolution of photovoltaic solar generation from 2011 to 2020 in Spain (right) and globally (left).

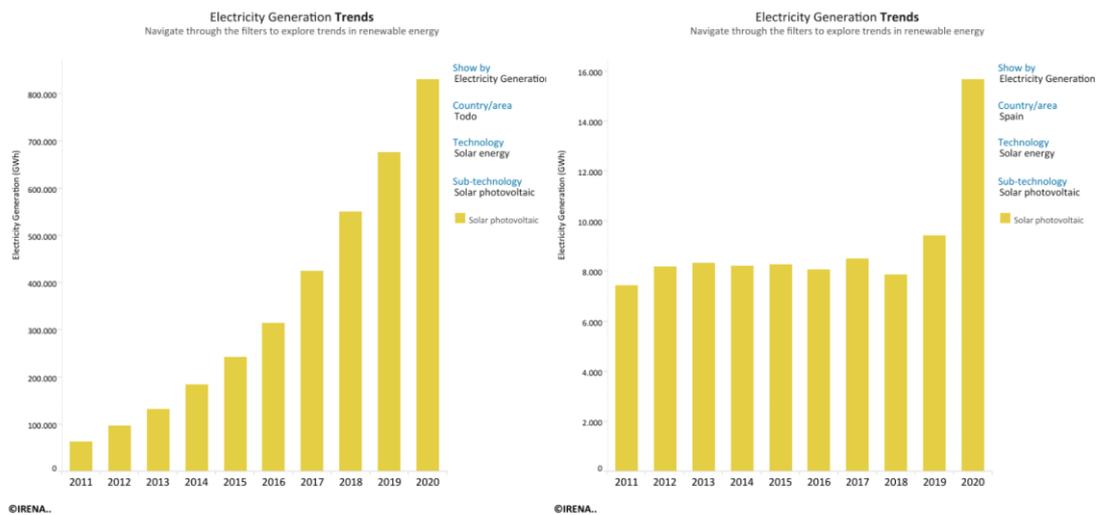


Figure 9. Evolution of Photovoltaic Solar Generation. Source IRENA

---

## 5.2 *SOFTWARE PSS®DE BY SIEMENS*

PSS®DE software, a tool provided by SIEMENS to IIT, was used to perform simulations and analyze all possible scenarios. During the project, meetings have been held with the SIEMENS employees in charge of this tool to give them feedback and receive advice on the use of the software. As a starting point, training courses were held to improve knowledge of the use of PSS®DE.

The software is positioned as a technical-economic simulation solution for distributed resources that helps users maximize the value of the investment in energy assets, reducing the levelized cost of electricity (LCoE) while optimizing CO<sub>2</sub> emissions. In this way, it is possible to accelerate investment decisions with great clarity by simulating results to quantify the techno-economic benefits of generation project decisions.

One interesting aspect of this software is the fact that it does not use computer computational resources as it offers cloud computing. By using Amazon Web Services (AWS) the software has a huge computational capacity. In addition, it has a large asset library and a powerful optimization algorithm. To set a project, it is necessary to follow the following steps:

- **Define the time series:** this refers to loads, irradiation/wind, and electricity rates...
- **Parameterize the technologies:** this consists of determining which technologies will be used and their scope, cost, and efficiency. Additionally, it is necessary to define the constraints associated with each type of technology.
- **Configure the optimization:** CO<sub>2</sub> emission limits, economic limits of the system...

Once the project is defined, an evaluation of the results offered by the software is carried out, allowing an analysis of the different stakeholders through different technical and financial KPIs as well as energy flow diagrams and time series visualizations.

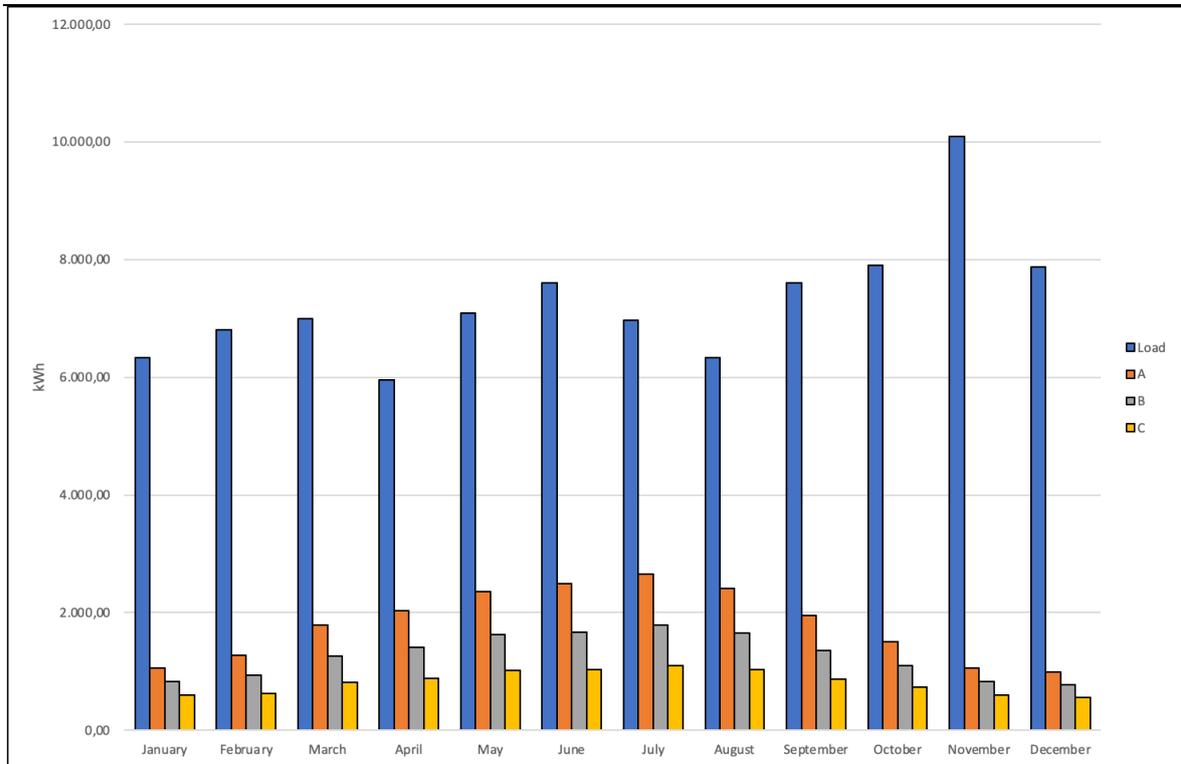
### ***5.3 COMPARISON OF OFFERS RECEIVED BY COMPANIES FOR NEW INSTALLATIONS***

As a base point for the realization of the project, there is information on offers made by 3 companies other than the IIT to renew their photovoltaic installation. The three companies that bid were A, B, and C and the three offers are very different from each other, mainly in the number of modules to be installed, ranging from 11 to 27. Table 1, a comparative table between the parameters of each of the offers: the number of modules, the unit and total peak power of the installation, the number of inverters, and the total area occupied by the installation. The differences observed are due to the final size decided by each of the bidding companies, since each one chose a very different value from the others as the optimum. This is due to the available area on the roof of the IIT and the shadows that are observed on it throughout the day, something that will be discussed later during the case study.

*Table 1. Comparisson between Offers*

	Number of Modules	Power (wp/ud)	Number of Inverter	Peak Power (kWp)	Surface (m2)
<b>A</b>	27	540	1	14,58	69,6
<b>B</b>	22	465	1	10,23	44
<b>C</b>	11	550	1	6,05	28,42

The graph shown in Figure 10 represents the electrical load consumed by the IIT during the year 2021, as it was the one used to make the offers, compared to the PV production of each one of them. The company with the highest production is A, with an aggregate annual production of 21,594.70 kWh, which represents an energy saving of 24.66%. In second place is B, with an aggregate annual production of 15,260 kWh, which represents an energy saving of 17.43%. Lastly, with an energy saving of 11.27%, we find C, which estimates an annual photovoltaic production for its installation of 9,871 kWh.



*Figure 10. Annual Photovoltaic Production for each Offer*

After carrying out the above analysis on the magnitudes offered by each of the companies, each of the offers has been modeled in the PSS®DE software to make comparisons between the results obtained in the simulation and those offered by the companies. When performing this in the software, it is necessary to determine the input parameters such as solar radiation or the load consumed by the IIT building itself.

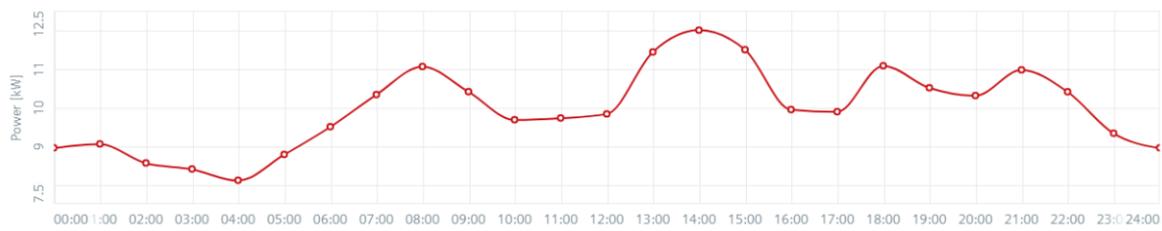
It should be noted that for the modeling of the offers, economic factors have not been taken into account, but only technical factors, therefore these simulations allow observing the energy taken from the grid, the surplus energy injected into the grid, the photovoltaic generation, and the emissions in tons of CO<sub>2</sub> saved annually.

### 5.3.1 PHOTOVOLTAIC PARAMETERS & ELECTRIC LOAD

In order to perform the simulation in the PSS®DE software it is necessary to feed it with the input data, in this case, the photovoltaic parameters and the consumption load for the IIT. As economic factors such as the cost of energy or the surplus compensation price have not

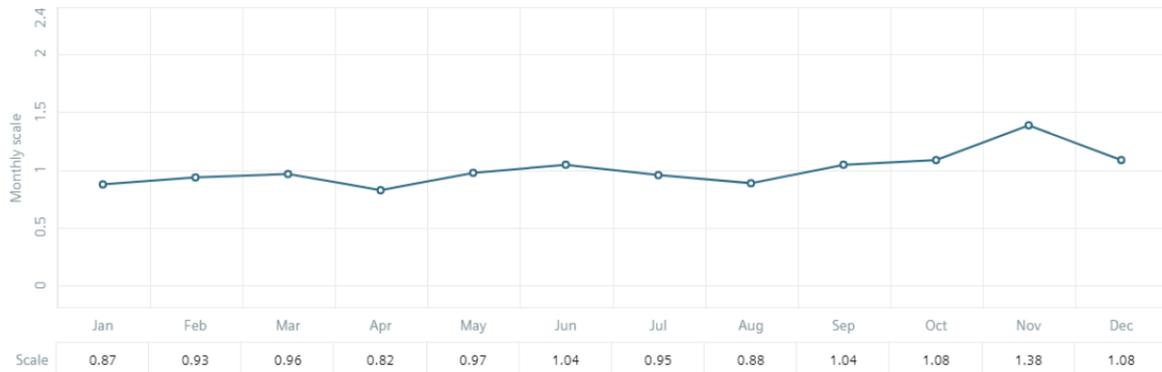
been considered, these data are not entered as inputs for the modeling of the three bids. These economic factors will be taken into account and will be key in the simulation of the optimal case study.

The obtaining of the PV parameters at the site location (C. de Sta. Cruz de Marcenado, 26, 28015 Madrid, Spain) has been done with the software itself. These parameters can be seen in ANNEX IV. Photovoltaic Parameters for IIT by PSS®DE and are diffuse radiation ( $W/m^2$ ), direct radiation ( $W/m^2$ ), ambient temperature (hr) and global horizontal radiation ( $W/m^2$ ). These parameters allow calculating the amount of photovoltaic energy that the panels will be able to generate.



*Figure 11. IIT's Daily Consumption for 2021 (Estimation)*

Once the PV parameters have been defined, it is time to define the consumption load of the IIT building. The consumption data for the building for the year 2021 provided in the A offer have been used as a basis. Since these data did not consider the daily consumption distribution, it has been estimated taking into account the university schedules. Figure 11 shows how peak periods have been estimated at the time of entering the university (8:00), at lunch time (13:00 to 16:00), at mid-afternoon break (18:00) and at the end of classes (21:00).



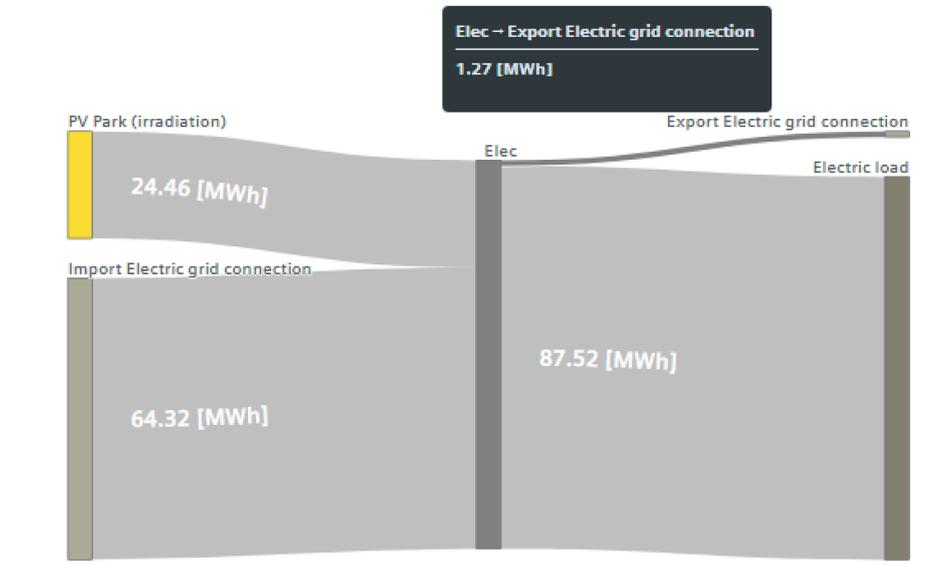
*Figure 12. IIT'2 Monthly Consumption for 2021 (Estimation)*

Figure 12 shows the monthly distribution of the aforementioned load. Finally, the estimated total annual load would be 87.52 MWh (capacity factor of 60.34%) with a daily average of 9.99 kWh. This estimate is used for a correct comparison of the offers since they were made during 2021. This estimated load will be replaced by the actual load consumed in the IIT building in 2022 with data provided by the university for the final case study.

### 5.3.2 SIMULATION RESULTS

At this point, the results obtained from the simulation with PSS®DE using the data from each of the bids will be presented and compared with each other and with the estimates made by the bidding companies.

The first of the bids (A), proposed the installation of 27 photovoltaic modules using an inverter, using 69.9 m<sup>2</sup> of surface area and reaching a peak power of 14.58 kWp. The simulation estimated an annual PV generation of 24.46 MWh and a surplus export to the grid of 1.27 MWh. With these characteristics the installation would reduce its CO<sub>2</sub> emissions by 7 tons per year, going from 26 to 19 and including 27.6% of renewable energy in the building's energy mix.



*Figure 13. A's Offer Sankey Diagram*

The second of the bids (B), proposed the installation of 22 photovoltaic modules using an inverter, using 44 m<sup>2</sup> of surface area and reaching a peak power of 10.23 kWp. The simulation estimated an annual PV generation of 17.16 MWh and a surplus export to the grid of 6.71 kWh. With these characteristics the installation would reduce its CO2 emissions by 5 tons per year, going from 26 to 21 and including 19.6% of renewable energy in the building's energy mix.

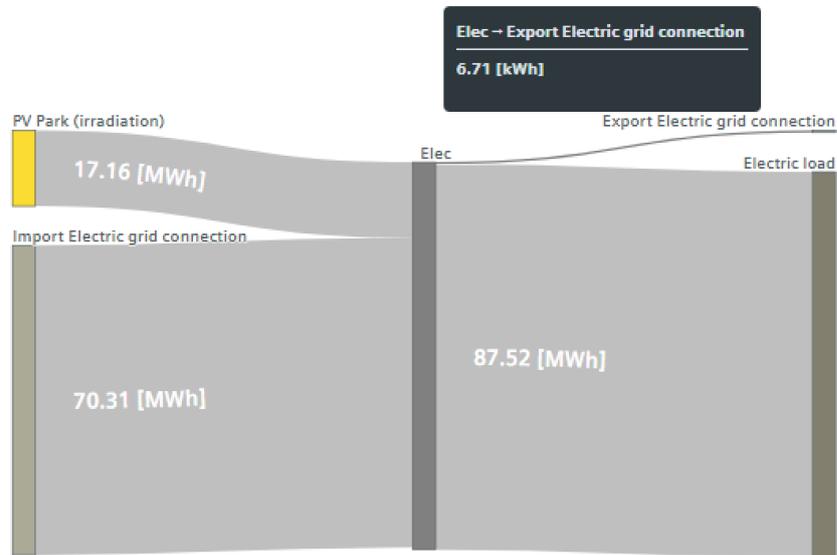


Figure 14. B's Offer Sankey Diagram

The third of the bids (C), proposed the installation of 11 photovoltaic modules using an inverter, using 28,42 m<sup>2</sup> of surface area and reaching a peak power of 6.05 kWp. The simulation estimated an annual PV generation of 10.15 MWh without surplus. With these characteristics the installation would reduce its CO<sub>2</sub> emissions by 3 tons per year, going from 26 to 23 and including 11.6% of renewable energy in the building's energy mix.

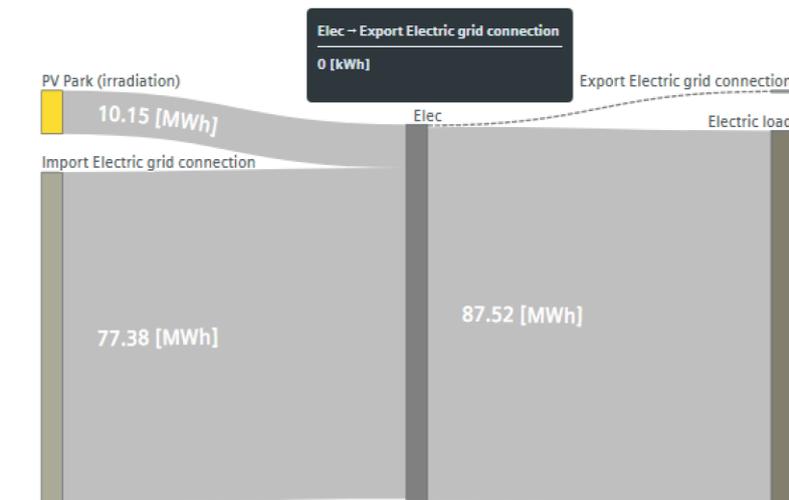


Figure 15. C's Offer Sankey Diagram

Table 2 shows a comparative table between the parameters of each of the bids, the PV generation estimated by the bidding company and the PV generation obtained in the simulation. The PV generation obtained in the simulation is somewhat higher in all cases than the power offered by each of the companies. This is due to the fact that this simulation did not take into account the performance of the inverter and therefore does not take into account the losses related to it, which are usually 2-3% approximately. For the case study in the next chapter, an inverter is considered and therefore its efficiency will be taken into account when carrying out the simulation.

*Table 2. Comparison between Simulation and Offered Generation*

	Number of Modules	Number of Inverters	Used Surface	Peak Power	Photovoltaic Generation (Company)	Photovoltaic Generation (PSS <sup>®</sup> DE)
A	27	1	69,6 m <sup>2</sup>	14,58 kWp	21,59 MWh	24,46 MWh
B	22	1	44 m <sup>2</sup>	10,23 kWp	15,26 MWh	17,16 MWh
C	11	1	28,42 m <sup>2</sup>	6,05 kWp	9,87 MWh	10,15 MWh

## **Chapter 6. CASE STUDY**

This chapter consolidates and analyzes all the information gathered in the previous chapters to achieve the best possible scenario for the photovoltaic installation on the roof of the IIT building. This endeavor involves a multi-step process that begins with defining the input parameters. These parameters include factors such as the geographical location of the building, solar radiation data, and meteorological conditions, among others. It is essential to gather and analyze all relevant data accurately to obtain the most reliable and precise results.

Furthermore, it is necessary to conduct a thorough surface analysis to determine the optimal placement and arrangement of the photovoltaic panels on the IIT building's roof. This analysis should consider factors such as the roof's dimensions, orientation, inclination, and shading. Based on this analysis, the components of the installation, such as the number and type of photovoltaic panels, inverters, and wiring, among others, should be defined.

Once all the input parameters and components of the installation have been defined, it is then possible to simulate the photovoltaic installation's performance using PSS®DE software. This software allows for the modeling and simulation of the installation's behavior, considering factors such as solar radiation, temperature, shading, and electrical performance. Through the simulation, it is possible to estimate the installation's electricity generation potential and evaluate its economic viability, which includes analyzing economic parameters such as the initial investment, payback period, and internal rate of return.

The successful completion of this chapter and the optimization of the photovoltaic installation on the roof of the IIT building will contribute to achieving the overall objective of this thesis, which is to propose a photovoltaic installation design for the IIT building that maximizes its electricity generation potential while ensuring its economic viability. This proposal will serve as a model for future photovoltaic installations in similar buildings, contributing to the widespread adoption of renewable energy sources and the reduction of greenhouse gas emissions.

---

## **6.1 INPUT PARAMETERS**

Input parameters refer to the values used as input in the simulation, essential to provide the necessary information for the software to perform the simulation properly. It is important to define them carefully to ensure accurate and meaningful results.

The electrical load consumed by the IIT and the electricity prices for different study periods are defined in this section (ANNEX IV. Photovoltaic Parameters for IIT by PSS®DE includes the photovoltaic parameters required to carry out the simulation).

### **6.1.1 ELECTRIC LOAD**

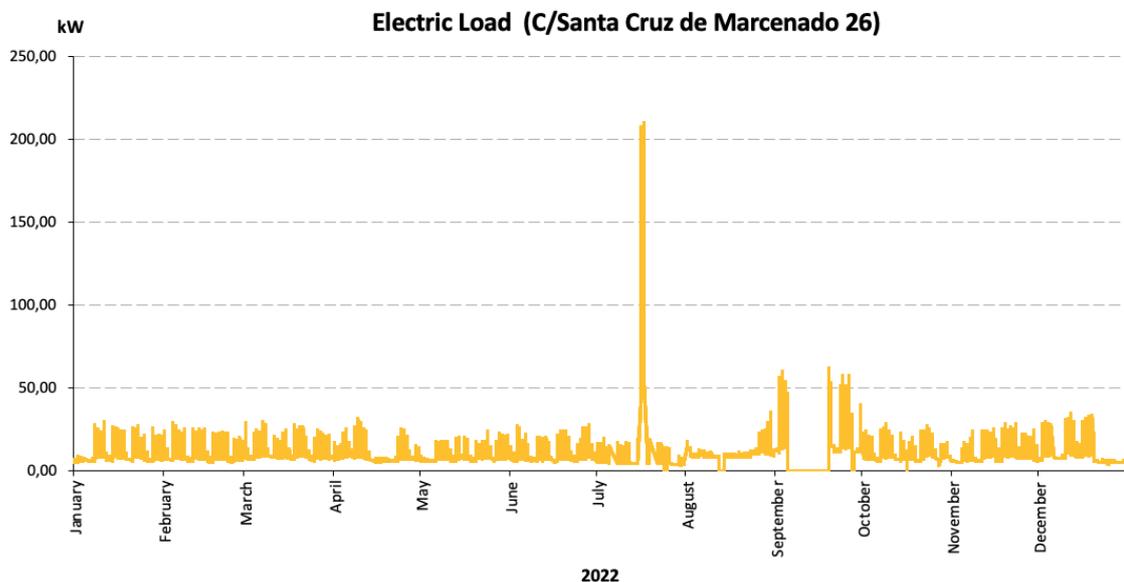
In order to accurately simulate the photovoltaic installation on the roof of the IIT building, it is crucial to define the input parameters, starting with the electricity load profile. The IIT, like many university buildings, experiences variable electricity consumption influenced by factors such as the time of year, the academic calendar, and building occupancy. Therefore, a comprehensive analysis of the electricity load profile is necessary to ensure the proper sizing and optimization of the self-consumption installation.

For the purpose of this study, the analysis will focus on the year 2022, considering the specific electricity consumption patterns of the IIT during that period. By examining the historical data and patterns, it is possible to gain insights into the building's electricity consumption behavior throughout the year. It is important to note that the electricity consumption of the IIT may exhibit similar seasonal variations as the university as a whole.

The analysis of the electricity load profile involves collecting data on the building's energy consumption, including both peak and off-peak periods, as well as variations during weekdays and weekends. Additionally, other factors such as special events or holidays that may impact electricity consumption will be taken into account. The data will be obtained from the university's energy monitoring systems or through direct measurements if available.

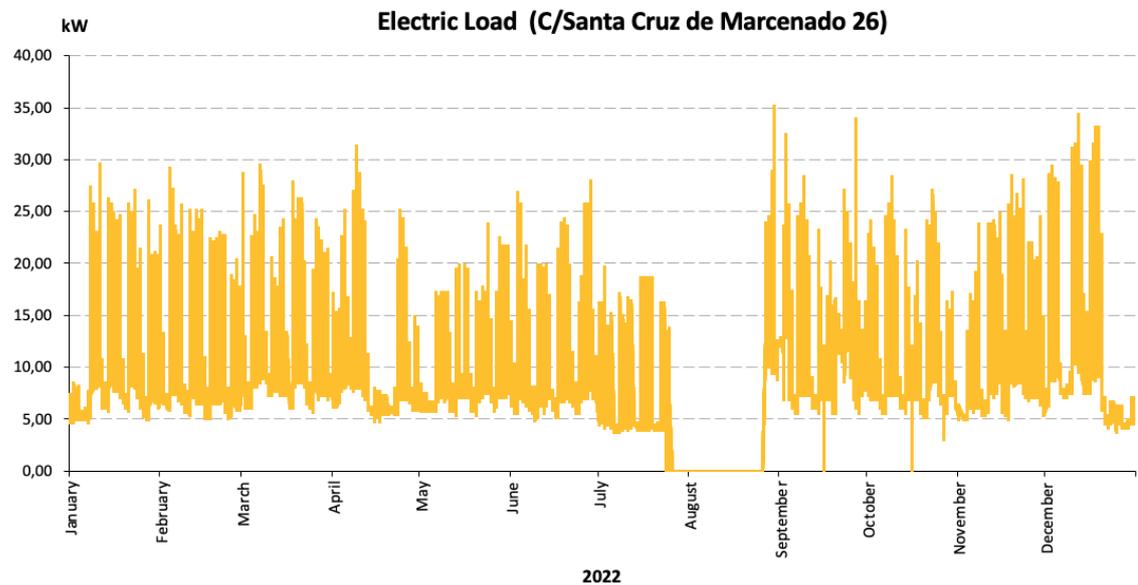
The data obtained from the university's energy monitoring system, as shown in Figure 16, reveals the need for data processing due to certain values that are nonsensical, such as the

outliers observed in mid-July or the period with null measurements in September. These inconsistent data points need to be treated before proceeding with the simulation and analysis. It is necessary to employ data cleaning and filtering techniques, such as outlier removal, interpolation of missing values, and correction of erroneous measurements. A clean and reliable dataset will serve as the foundation for accurate simulation and appropriate analysis of the building's electrical load.



*Figure 16. Electric Load (Original Data)*

The presence of outliers in the electricity consumption data observed in July was identified as a result of measurement errors in the monitoring system. To ensure the accuracy of the data, these outliers were substituted with the average values recorded for that specific month. This data refinement process aimed to provide a more reliable representation of the actual electricity load profile. The period with null measurements has been shifted to align with the university's vacation period, which spans from July 26th to August 26th. Additionally, values for September have been calculated by interpolating data from October and utilizing a portion of the July data since they are the closest months with similar consumption patterns. The Figure 17 illustrates the final electricity load profile resulting from these data adjustments. The heat map and the graph in PSS®DE format can be found in ANNEX VI. Electric Load for IIT by PSS®DE.



*Figure 17. Electric Load (After Data Processing)*

## 6.1.2 ELECTRICITY PRICES

Electricity prices in Spain refer to the value assigned to the KWh of electricity consumed in the Spanish electricity market. These prices may vary depending on several factors, such as supply and demand of electricity, seasonality, availability of energy resources, and production and transportation costs, among others.

The Spanish market is composed of different auctions and markets, where electricity producers and distributors offer and purchase electricity at the best possible price. Electricity prices in Spain are also influenced by government policies, such as taxes and regulated tariffs, affecting both producers and consumers of electricity.

In general, electricity prices in Spain have been the subject of intense debate and controversy in recent years, due to their volatility and their impact on Spanish households and businesses. As a result of this volatility, even more, accentuated in recent times due to the large increases in electricity prices caused by the war between Russia and Ukraine and the current global inflationary period, two separate simulations have been carried out: one with electricity prices in 2020 and the other with prices in 2022.

The electricity price values for 2020 and 2022 have been obtained from ESIOS, a website of the Spanish TSO, Red Eléctrica de España. Its main function is to guarantee the supply of electricity throughout the country and to this end, it is responsible for integrating all electricity market agents and providing real-time information on electricity generation and consumption. In addition, it is responsible for monitoring the Spanish electricity system to ensure its stability and security, which makes it a key entity in the Spanish electricity market. For both years, the following are analyzed:

- **PVPC 2.0TD Active Energy Billing Term** (called Grid Price from now on): is the new regulated electricity tariff in Spain, which is based on the Voluntary Price for the Small Consumer (PVPC for its acronym in Spanish) and which came into force in June 2021 (for 2020 the previously applied tariff has been used) This tariff includes a real-time active energy billing modality, which allows electricity consumption to be measured and billed according to the time of day it is produced, enabling consumers to control their consumption and adjust it to their needs and budget, generating savings on electricity bills and greater energy efficiency.
- **PVPC Price of Surplus Energy from Self-Consumption** (will be called Surplus Price from now on): it is the price paid for electricity generated from renewable sources, such as solar photovoltaic energy, which is not consumed by the owner or user of the system and is fed into the electricity grid. This price varies throughout the day depending on the time of day and is set according to the supply and demand of electricity. When a renewable energy user discharges its surplus energy to the electricity grid, it can receive financial compensation for it, which is calculated based on the PVPC for the surplus energy at that time. This simplified compensation mechanism aims to encourage the self-consumption of renewable energy and distributed generation of electricity in Spain.

Figure 18 shows the values of these two indicators for 2020. It should be noted that the Surplus Price followed a distribution practically identical to that of the Grid Price multiplied by a factor of approximately 0.5. This means that the price of energy used from the grid is

twice as expensive as the price at which surplus energy from renewable self-consumption is sold.

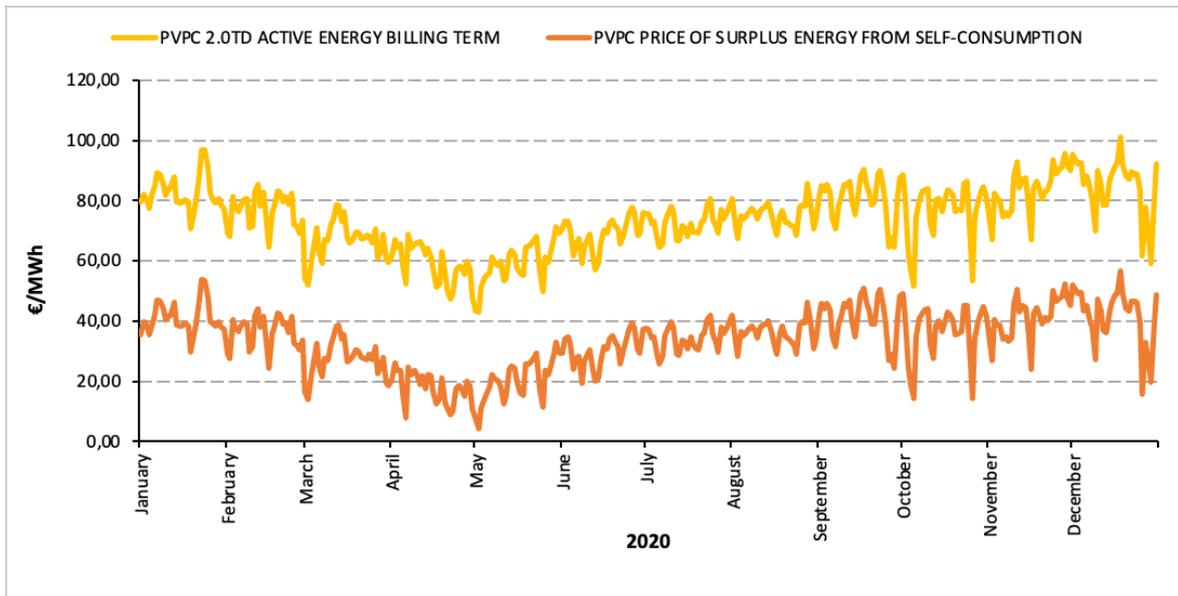


Figure 18. 2.0TD Active Energy Billing Term vs. Price of Surplus Energy from Self-Consumption (2020)

Figure 19 shows a similar comparison, but this time for the year 2022. At first glance, it can be seen that the values presented for the price of electricity in 2022 are substantially higher than the prices in 2020. Similar values would only be reached by the end of December 2022. Additionally, it is observed that the relationship between Grid Price and Surplus Price values is not so similar to the one observed in 2020.

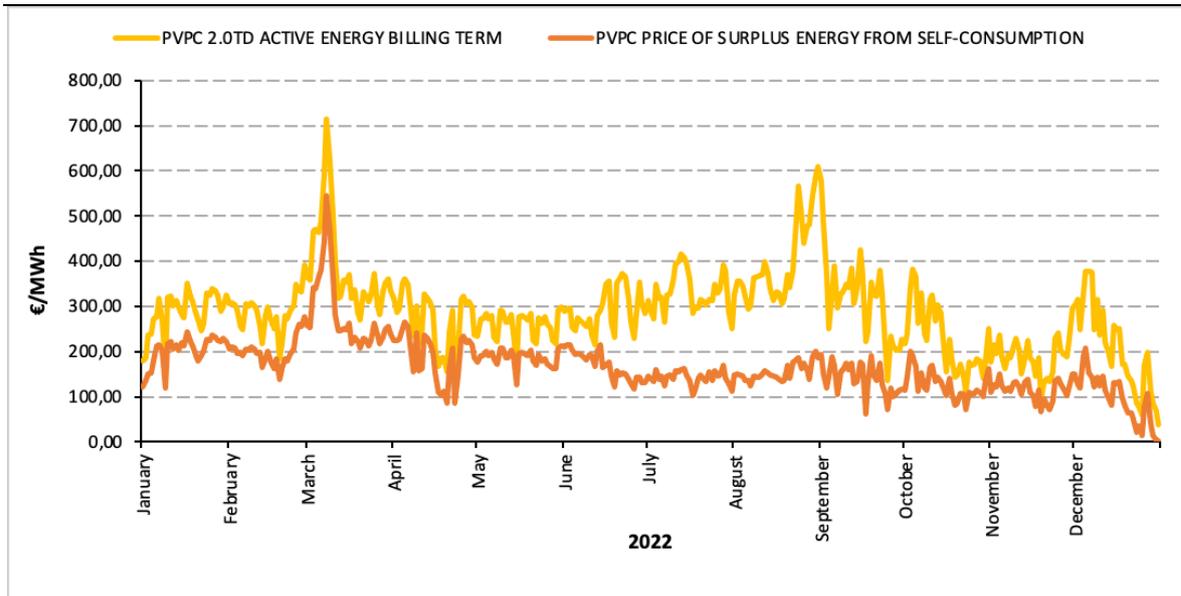


Figure 19. 2.0TD Active Energy Billing Term vs. Price of Surplus Energy from Self-Consumption (2022)

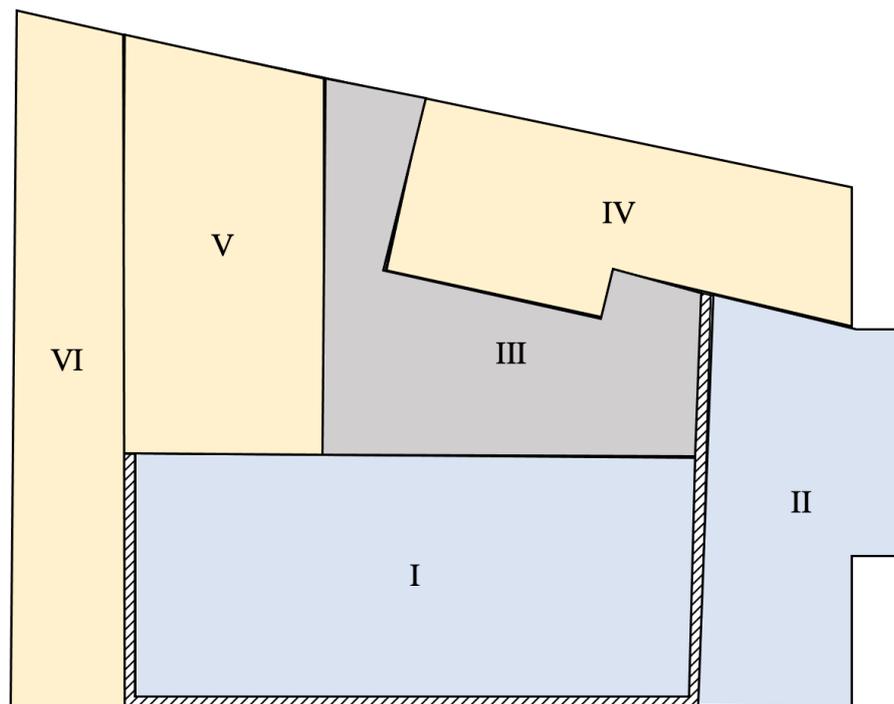
After running the simulations with 2020 prices (standard prices) and 2022 prices (unusually high prices) using the PSS®DE software offered by Siemens, we came to the conclusion that regardless of the price input we introduce, the optimal point is reached for the maximum possible power to be installed. This is because even if we were to install more power than our building consumes, being able to inject this power into the grid (and receive a payment for it) the optimum will always be reached with the maximum number of panels that can be installed on the roof. Therefore, the following section (6.2) will determine the size of the photovoltaic installation to be carried out, being therefore of great importance for this project.

## 6.2 SURFACE ANALYSIS

Considering that the optimal scenario is obtained for the maximum photovoltaic power to be installed, this section is of vital importance, since it determines the maximum number of panels that can be installed on the roof of the IIT building. ANNEX V. Dimensioned Plan of the IIT Roof shows the IIT roof plan obtained from the Catastro website and dimensioned using AutoCAD. Due to the fact that certain measurements are not defined in the original Catastro plan, it is necessary to make the following considerations:

- The roof wall is 20x60 cm (width x height) all around the roof (shown as grated in Figure 20).
- The angle of the inclined slope of the building, the one facing the front of the building, is 30°.
- The height of the stairwell (the hexagon at the top right) is 3 m.
- The structure at the rear (water tank with solar panels on the upper left) is also 3 m high.

Once the dimensions and the necessary considerations or assumptions have been established to fully define the roof surface of the building, it has been divided into six sections as shown in Figure 20.



*Figure 20. Segmented Roof Surface*

Each of the sections has certain characteristics that differentiate it from the others. With respect to the color code, it should be noted that the surfaces marked in blue are those on

which solar panels are to be installed, the gray surface is a surface highly affected by shadows (so it is not interesting to install panels) and the yellow surfaces are surfaces with certain elements or characteristics that prevent a photovoltaic installation from being carried out on them. The characteristics and peculiarities of each of these sections are explained below:

- **Segment I:** Useful surface with dimensions of approximately 10.15 x 4.29 m. The approximate is because the surface does not form a perfect rectangle offering inclination at its lower end (the one that makes contact with segment II). This segment will be analyzed in detail in section 6.2.1.
- **Segment II:** Useful surface with a heptagonal shape and with the peculiarity of being arranged with an inclination of 30°, which is used to place the panels with this inclination. This segment will be analyzed in detail in section 6.2.2.
- **Segment III:** Surface with no physical impediment to place panels, but highly affected by shadows and therefore uninteresting to be part of the photovoltaic installation. This is due to the fact that it is located next to Segment IV and Segment V, and both offer elements with a height of 3 meters that generate a large number of shadows on Segment III.
- **Segment IV:** Heptagonal surface on which panels cannot be installed because of the stairs that allow access to the roof.
- **Segment V:** Trapezoidal surface on which panels cannot be installed because it is occupied by a tank and offers space to place other elements of the photovoltaic installation.
- **Segment VI:** Trapezoidal surface whose dimensions prevent the photovoltaic installations.

It should be noted that SunPower SPR-P3-410-COM-1500 monocrystalline solar panels, model SPR-P3-410-COM-1500, with a power of 410W and a size of 2066 x 998 x 35 mm, are used for the segment analysis in the following sections. The characteristics of these panels are explained in more detail in section 6.3.

In order to dimension the photovoltaic installation, it is necessary to take into account the restrictions and requirements established by the Technical Building Code regarding structural safety. In the Basic Document on Structural Safety of Actions for Building (DB-SE-AE for its acronym in Spanish), the conditions for the design and calculation of building structures are detailed, including structures to support photovoltaic solar energy systems on roofs. The most relevant requirements to be considered are the following:

- **Allowable roof load:** the maximum weight that can be placed on the roof of the building must be determined by a structural calculation specific to the building in question. This depends on factors such as the strength of the materials, the angle of inclination of the roof, and the type of solar panel to be installed, among others. The calculation must ensure that the load of the photovoltaic installation does not exceed the admissible load on the roof. In general, it is recommended that the maximum weight should not exceed 10% of the allowable roof load. For photovoltaic installations in flat roofs, it is estimated that the maximum weight that can be installed must be less than 60 kg/m<sup>2</sup> while, for inclined roofs, this value less than 20 kg/m<sup>2</sup>.
- **Anchoring:** the solar panel anchoring system must be designed to withstand the loads and stresses generated during use, such as wind, snow, or vibrations. The system must be compatible with the type of roof and materials of the building and must not compromise the water tightness and safety of the roof.
- **Maximum height:** the maximum height of a rooftop solar panel installation may depend on several factors, such as local regulations, roof slope, and building height, among others. In general, it is recommended that the maximum height of the photovoltaic installation on a roof should not exceed 3 meters in height. This height is considered to provide an adequate balance between safety and accessibility for maintenance and cleaning of the panels, trying to minimize the effect of wind.

All these requirements will be analyzed and taken into account when dimensioning the installation (sections 6.2.1 and 6.2.2) and when choosing the elements that are part of the photovoltaic installation (section 6.3), ensuring their due compliance.

## 6.2.1 SEGMENT I ANALYSIS

In this section, we will analyze three possible distributions for the installation of panels in Segment I and then compare them with each other.

### 6.2.1.1 Case I: 35° Inclination (PVGIS Optimum)

In this case, maximizing the number of panels to be installed in Segment I is proposed using the optimum angle of inclination indicated by the PVGIS software, an angle of 35°. The following data is used as starting point (Figure 21):

- $h_1 = 0,6 \text{ m} \rightarrow$  roof wall height.
- $lat = 40,43 \text{ m} \rightarrow$  latitude at IIT building location.
- $p = 2,07 \text{ m} \rightarrow$  length of SPR-P3-410-COM-1500 panels.
- $\alpha = 35^\circ \rightarrow$  optimum PVGIS® angle of inclination.
- $n = ? \rightarrow$  number of rows that can be placed.

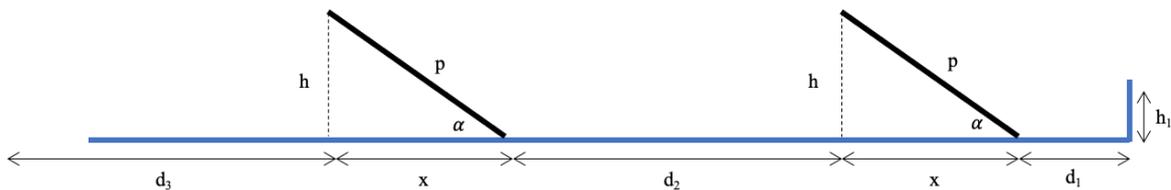


Figure 21. Distance Calculation Segment I Case I

Taking these data into account, the following equation has been prepared in order to determine the maximum number of rows of panels that could be placed without the panels casting a shadow on each other, thus avoiding the loss of production due to this effect. The possibility of shading in summer is much lower since the path of the sun is much higher, and therefore the shadow cast by the obstacle or panel in front of it is smaller. The calculated distances guarantee a minimum of four hours of sunshine around noon on the winter solstice.

Being this inequation:

$$(x + d) \cdot (n - 1) + x + d_1 \leq 10,15$$

And where  $d_1$ ,  $d$ ,  $x$  and  $h$  are defined as:

$$d_1 = \frac{h_1}{\tan(61 - lat)} = \frac{0,6}{\tan(61 - 40,43)} = 1,60 \text{ m}$$

$$h = \sin \alpha \cdot p = \sin 35^\circ \cdot 2,07 = 1,19 \text{ m}$$

$$d = d_2 = d_3 = \frac{h}{\tan(61 - lat)} = \frac{1,19}{\tan(61 - 40,43)} = 3,17 \text{ m}$$

$$x = \cos \alpha \cdot p = \cos 35^\circ \cdot 2,07 = 1,70 \text{ m}$$

Substituting in the inequation we obtain that:

$$(1,70 + 3,17) \cdot (n - 1) + 1,70 + 1,60 \leq 10,15 \quad \rightarrow \quad \mathbf{n \leq 2,41}$$

Therefore, using the optimum angle of  $35^\circ$ , two rows of panels could be placed. Determining the number of panels that make up each of the rows is simply a matter of calculating how many panels fit, taking into account the width of Segment I. Since the width of Segment I is 4.29 m and the width of each of the panels is 0.998 m, we obtain that:

$$n^* = \frac{4,29}{0,998} = 4,3$$

Therefore, two rows of four panels can be installed, which would result in an installation of 3.28 kWp (8 panels of 410 Wp) as shown in Figure 22.

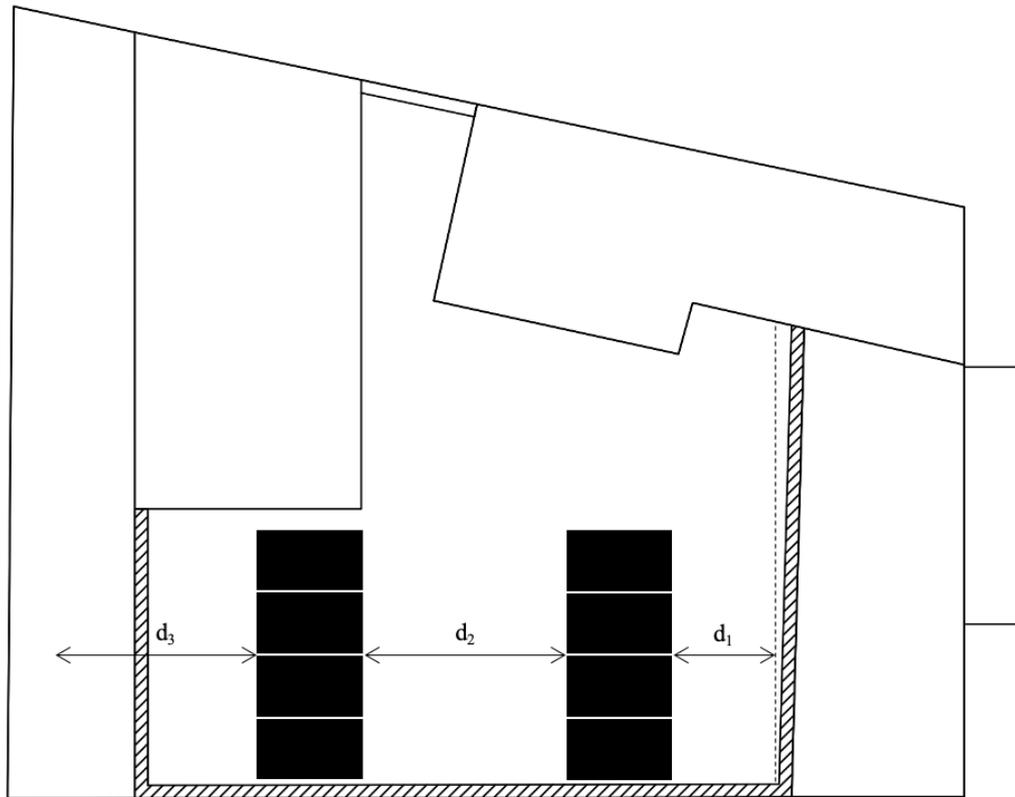


Figure 22. Surface Distribution Segment I Case I

### 6.2.1.2 Case II: Closest to Optimum Inclination to Fit 3 Rows

In this case, the aim is to obtain the inclination closest to the optimum in order to place three rows of panels on the surface, since, as was observed in the previous case, the optimum inclination only allowed placing two rows of panels. It should be noted that, by choosing an inclination different from the optimum, there will be slight losses in the photovoltaic generation of the panels, which will be defined in section 6.2.1.4. The following data is used as starting point (Figure 23):

- $h_1 = 0,6 \text{ m} \rightarrow$  roof wall height.
- $lat = 40,43 \text{ m} \rightarrow$  latitude at IIT building location.
- $p = 2,07 \text{ m} \rightarrow$  length of SPR-P3-410-COM-1500 panels.
- $\alpha = ?^\circ \rightarrow$  angle of inclination.
- $n = 3 \rightarrow$  number of rows.

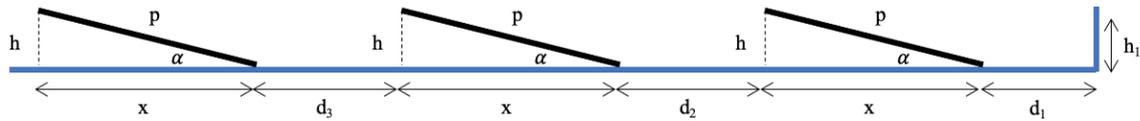


Figure 23. Distance Calculation Segment I Case II

Using the same inequation as in the previous section:

$$(x + d) \cdot (n - 1) + x + d_1 \leq 10,15$$

And where  $d_1$ ,  $d$ ,  $x$  and  $h$  are defined as:

$$d_1 = \frac{h_1}{\tan(61 - lat)} = \frac{0,6}{\tan(61 - 40,43)} = 1,60 \text{ m}$$

$$h = \sin \alpha \cdot p = \sin \alpha \cdot 2,07$$

$$d = d_2 = d_3 = \frac{\sin \alpha \cdot 2,07}{\tan(61 - 40,43)}$$

$$x = \cos \alpha \cdot p = \cos \alpha \cdot 2,07$$

Substituting in the inequation we obtain that:

$$\left( \cos \alpha \cdot 2,07 + \frac{\sin \alpha \cdot 2,07}{\tan(61 - 40,43)} \right) \cdot (3 - 1) + \cos \alpha \cdot 2,07 + 1,60 \leq 10,15$$

Simplifying:

$$(2,07 \cdot \cos \alpha + 5,51 \cdot \sin \alpha) \cdot 2 + 2,07 \cdot \cos \alpha - 8,55 \leq 0$$

$$6,20 \cdot \cos \alpha + 11,01 \cdot \sin \alpha - 8,55 \leq 0$$

And iterating we obtain that:

$$\alpha \leq 13,19^\circ$$

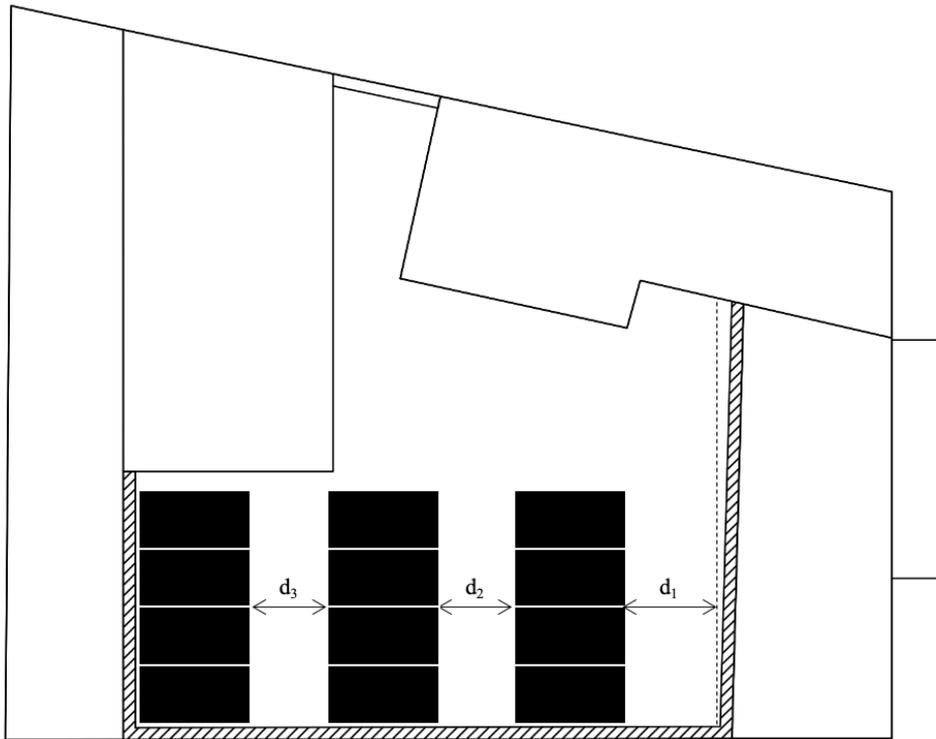
Therefore, the angle closest to the optimum is the maximum angle that meets the constraints, 13, 19°. For the maximum angle we have that:

$$x = \cos \alpha \cdot p = 2,02 \text{ m}$$

$$d_2 = d_3 = d = 1,26 \text{ m}$$

$$h = \sin \alpha \cdot p = 0,47 \text{ m}$$

With these magnitudes, three rows of four panels could be placed on Segment I, resulting in an installation of 4.92 kWp (12 panels of 410 Wp) as shown in Figure 24.



*Figure 24. Surface Distribution Segment I Case II*

### **6.2.1.3 Case III: Combined Structure for Placing 4 Rows**

In this case, it is intended to place sail supports of different heights in such a way as to generate a combined support that offers the possibility of placing 4 rows of plates. As for

the previous case it should be noted that, by choosing an inclination different from the optimum, there will be slight losses in the photovoltaic generation of the panels, which were defined in section 6.2.1.4. The following data is used as starting point (Figure 25):

- $h_1 = 0,6 \text{ m} \rightarrow$  roof wall height.
- $lat = 40,43 \text{ m} \rightarrow$  latitude at IIT building location.
- $p = 2,07 \text{ m} \rightarrow$  length of SPR-P3-410-COM-1500 panels.
- $\alpha = ?^\circ \rightarrow$  angle of inclination.
- $n = 4 \rightarrow$  number of rows.

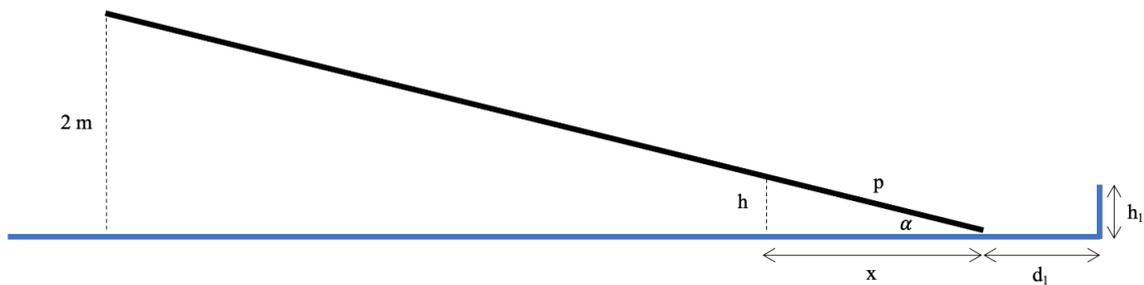


Figure 25. Distance Calculation Segment I Case III

For this third case, the following two inequations have been prepared, the first of which defines the space restriction in Segment I and the second of which limits the maximum height of the facility to 2 m, offering some leeway compared to the 3 m maximum established by the building code.

$$x \cdot n + d_1 \leq 10,15$$

$$h \cdot n \leq 2$$

And where  $d_1$ ,  $x$  and  $h$  are defined as:

$$d_1 = \frac{h_1}{\tan(61 - lat)} = \frac{0,6}{\tan(61 - 40,43)} = 1,60 \text{ m}$$

$$x = \cos \alpha \cdot p = 2,07 \cdot \cos \alpha$$

---

$$h = \sin \alpha \cdot p = 2,07 \cdot \sin \alpha$$

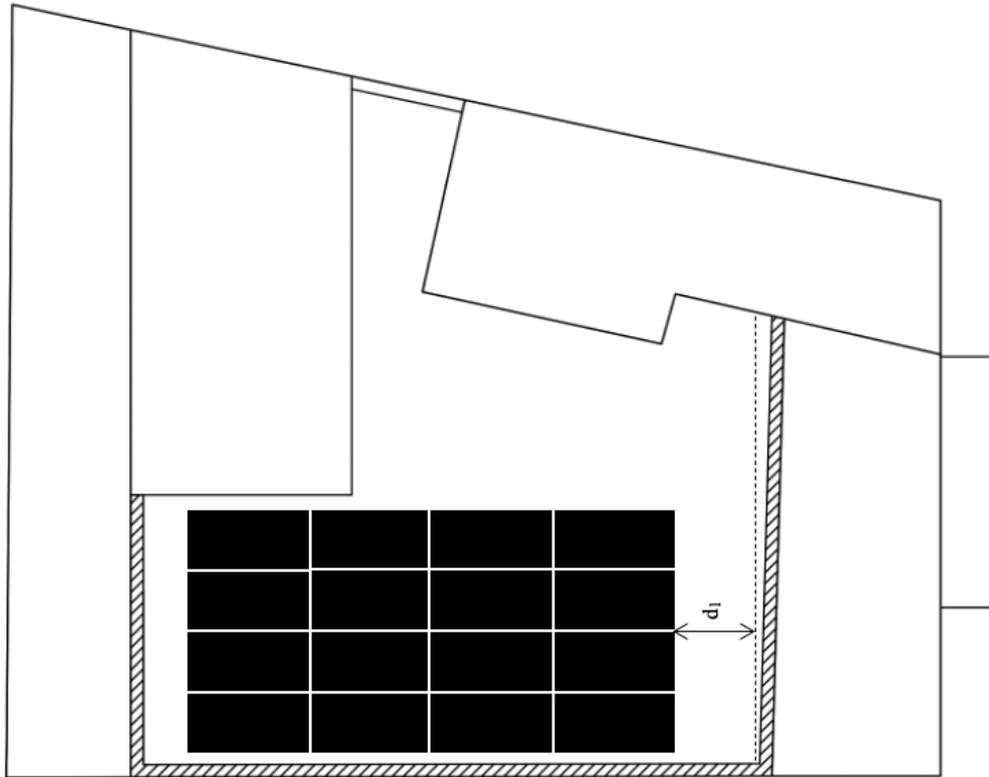
Substituting it is found that the most restrictive condition is the second one and therefore it is solved to see what is the maximum angle at which the panels can be placed so that the height of the structure is not too great (a maximum of 2 meters above the level of the roof at the highest point). Obtaining that:

$$8,28 \cdot \sin \alpha - 2 \leq 0$$

And iterating we obtain that:

$$\alpha \leq 13,97^\circ$$

With these magnitudes, four rows of four panels could be placed on Segment I, resulting in an installation of 6.56 kWp (16 panels of 410 Wp) as shown in Figure 26.



*Figure 26. Surface Distribution Segment I Case III*

#### **6.2.1.4 Comparison Between Cases**

After having analyzed the different possibilities of dimensioning the installation, it is necessary to compare them to decide which is the best option among the three. To make this comparison it is necessary to take into account that the angles of the structures on which they will be placed have standard inclinations.

The Ennova concrete flat roof structures (to be explained in more detail in section 6.3) have been chosen as they offer angles of inclination of 20°, 15°, 10°, 5°, and 0° for vertical panel placement. Therefore, for each of the three cases analyzed above, the structure with the slope closest to the maximum possible slope at the bottom will be chosen. For example, for a slope of 27°, the 20° structure would be chosen, for a slope of 19° the 15° structure would be chosen, and so on. Therefore, the concrete structures to be used for each of the cases would be as follows:

- Case I ( $\alpha = 35^\circ$ ): In this case as in case II, 5 supports are required for each row of 4 panels. For this case, the inclination closest to the optimum is achieved by using 10 EnnovaBloc 20°R with a weight of 84 kg each.
- Case II ( $\alpha \leq 13.19^\circ$ ): For this case, the inclination closest to the optimum is achieved by using 15 EnnovaBloc 10°R with a weight of 63 kg each.
- Case III ( $\alpha \leq 13.97^\circ$ ): In this last case, as the panels are placed in a sail, it is necessary to use 5 rows of 5 supports each to place the 4 rows of panels. Each of these rows of supports will be different from the other, as they will progressively increase in size to be able to offer the sail layout, the supports required are as follows:
  - 5 EnnovaBloc 10° with a weight of 28 kg each.
  - 5 EnnovaBloc 10°B with a weight of 36.5 kg each.
  - 5 EnnovaBloc 10°C with a weight of 47.5 kg each.
  - 5 EnnovaBloc 10°D with a weight of 62.5 kg each.
  - 5 EnnovaBloc 10°E, each weighing 73.4 kg.



Figure 27. 20°R (Case I: Left), 10°R (Case II: Center) and Sail 10° (Case III: Right)

The total weight of the installation (structure + panels) is then calculated to check if any of the cases do not comply with the maximum weight established in the technical building code. Any case that does not comply with this aspect will be directly discarded. These maximum loads are 60 kg/m<sup>2</sup> for flat roofs and 20 kg/m<sup>2</sup> for pitched roofs. Taking into account that the weight of each of the panels chosen is 22 kg, the weights mentioned above for the structures in each of the cases, and that the area of Segment I is 43.54 m<sup>2</sup>:

*Table 3. Weights, Loads and Security Factors in Cases I, II and III*

	Solar Panels Weight	Concrete Structure Weight	Total Weight	Total Load	Security Factor
Case I	176 kg	840 kg	1016 kg	23,33 kg/m <sup>2</sup>	2,57
Case II	264 kg	945 kg	1209 kg	27,77 kg/m <sup>2</sup>	2,16
Case III	352 kg	1239,5 kg	1591,5 kg	36,55 kg/m <sup>2</sup>	1,64

As shown in Table 3, none of the three cases exceeds the maximum allowable load on the roof and, therefore, none of the cases are discarded on this basis.

*Table 4. Peak Power, Efficiency and Annual Photovoltaic Generation in Cases I, II and III*

	Inclination	Peak Power	Efficiency	Photovoltaic Generation
Case I	20°	3,18 kWp	97,40 %	5,62 MWh
Case II	10°	4,92 kWp	92,39 %	8,25 MWh
Case III	10°	6,56 kWp	92,39 %	11,00 MWh

When calculating the annual photovoltaic production, it is important to take into account that the panels offer 100% efficiency when the angle of inclination is optimal (approximately 35° for the location analyzed) and decreases in efficiency and therefore in production are observed as the angle of inclination moves away from the optimum. The PSS®DE software and the PVGIS online tool were used to calculate these yields, obtaining the results shown in Table 4.

*Table 5. CapEx in Cases I, II and III*

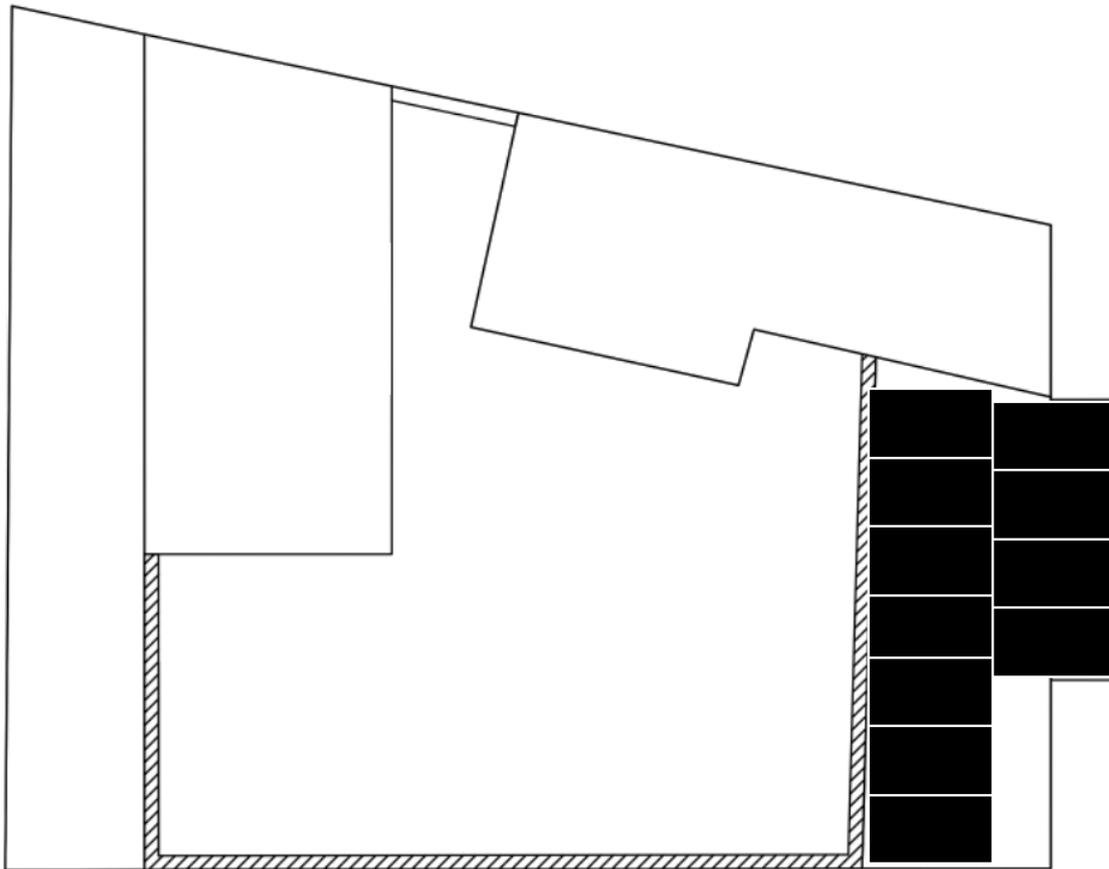
	Solar Panels CapEx	Concrete Structure CapEx	Total CapEx	Unitary CapEx
Case I	2.624,00 €	442,00 €	3.066,00 €	545,55 €/MWh
Case II	3.936,00 €	630,30 €	4.566,30 €	553,491 €/MWh
Case III	5.248,00 €	1039,80 €	6.287,80 €	571,62 €/MWh

Finally, the initial investment in panels and concrete structure has been calculated for each of the cases and, in addition, the cost in euros per MWh of annual photovoltaic production

has been calculated (Table 5). This unit calculation has been made on the annual production to also consider the installation's efficiency when making a decision. Taking into account all the calculations made above, it can be seen that the most suitable solution for segment I is case III, since, despite a slight reduction in efficiency, the total load on the roof offers a more than sufficient safety factor and the difference in unit CapEx is not too significant. This reduction in efficiency and increase in investment is offset by the reduction effect of the PV system on the electricity bill.

### **6.2.2 SEGMENT II ANALYSIS**

For the case of Segment II, the analysis is much simpler because there are not several options as in the case of Segment I. In this case, it is desired to place as many plates as possible on the inclined surface since they will not shade each other. Taking into account the projected size of the panels on the 30° inclined surface, it is concluded that 11 panels of 410 Wp each (similar to those used in Segment I) could be placed, resulting in a photovoltaic installation of 4.51 kWp. It is intended to reuse the anchorage used in the old photovoltaic installation, which consists of rails coplanar with the roof, thus leaving the panels with the same 30° inclination.

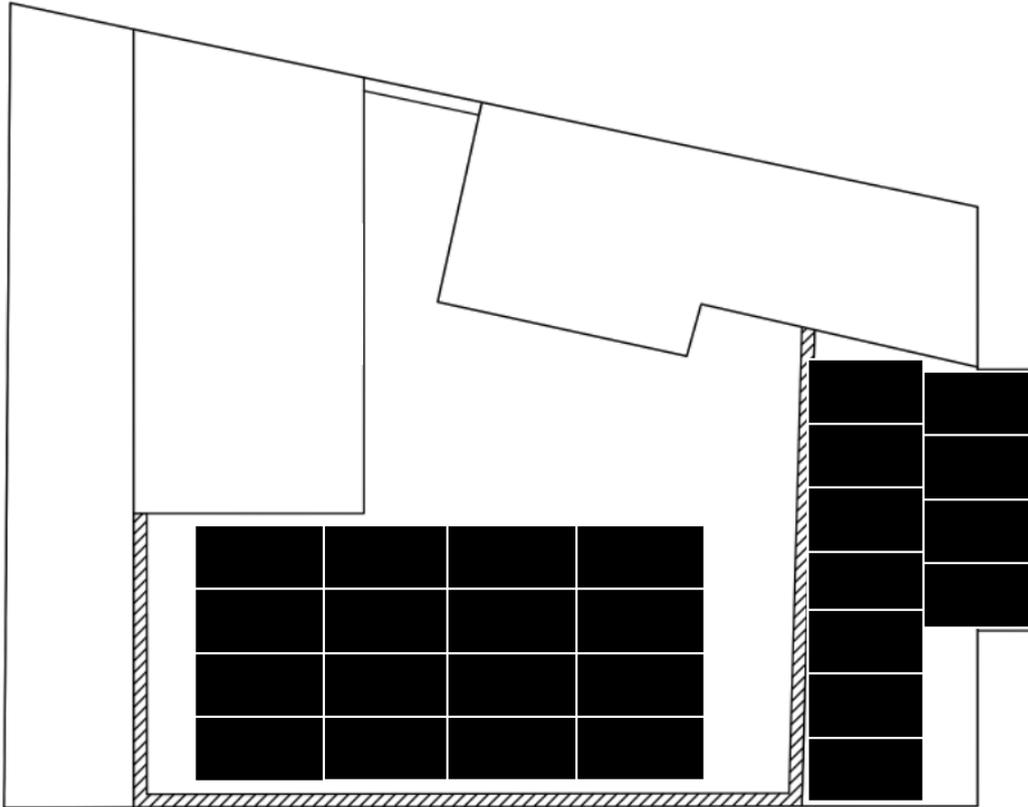


*Figure 28. Surface Distribution Segment II*

### **6.2.3 OPTIMAL SURFACE DISTRIBUTION**

Figure 29 displays the optimal distribution of 27 SunPower SPR-P3-410-COM-1500 solar modules, carefully selected after a detailed analysis to ensure maximum performance and energy efficiency. With a peak power of 11.07 kWp, this distribution has been designed to adapt to the available surface, composed of two different segments. On Segment I, a horizontal surface, 16 modules have been installed that require concrete supports, while the rest of the panels have been placed on Segment II, a surface with a 30° inclination. This optimal distribution ensures maximum performance and optimal energy efficiency for the self-consumption photovoltaic installation. The difference in inclination translates into

better performance for the modules located on Segment II, which will be taken into account in the technical-economic simulation with Siemens' PSS@DE software.



*Figure 29. Optimal Surface Distribution*

### **6.3 INSTALLATION COMPONENTS**

The choice of components in a PV system is essential to ensure optimum performance, long service life, and maximum energy efficiency. Each component of a PV system plays an important role in the operation of the system as a whole, and choosing the right components is crucial to achieving the desired results. In addition to the efficiency and quality of the components, it is important to consider the compatibility between them.

By investing in high-quality and compatible components, a functional and efficient PV system can be achieved that meets the user's energy needs sustainably and cost-effectively.

The 27 SunPower SPR-P3-410-COM-1500 panels were chosen because of their high efficiency of 19.90%, robust construction, and industry-leading performance guarantee, ensuring consistent and reliable energy production over the long term. In addition, its ease of installation and universal compatibility with existing mounting systems make it an efficient and cost-effective choice for any PV installation seeking to maximize energy production and reduce maintenance and installation costs. It is a monocrystalline solar panel with a power output of 410 W and a size of 2066x998x35 mm using an exclusive technology without bus bars or metal welds.



*Figure 30. Solar Paneles SunPower SPR-P3-410-COM-1500*

The Huawei SUN2000-12KTL-M2-3PH 3-phase inverter has been selected for this PV installation due to its ability to handle the electrical load generated by the 27 SunPower 410 W solar panels, offering high power conversion efficiency and a wide range of input voltages, ensuring constant and reliable power production. In addition, its maximum power tracking technology (MPPT) and remote monitoring capability via mobile app allow for real-time system monitoring and performance optimization. All this together with Huawei's quality assurance and customer service, make the Huawei SUN2000-12KTL-M2-3PH Three Phase a safe and reliable choice for any PV installation looking to maximize its energy efficiency and reduce long-term costs.



*Figure 31. Solar Inverter Huawei SUN2000-12KTL-M2-3PH*

For the support structure of the 16 panels of the Segment I, a combination of the 5 types of EnnovaBloc Sail 10° supports (type 10, 10B, 10C, 10D, and 10E) was chosen to create a joint structure that maximizes the stability and efficiency of the photovoltaic installation. This combination of supports allows the structure to adapt to the topography of the terrain, minimizing the amount of earthwork required and reducing installation costs.

In addition, each type of support is designed to withstand specific loads and winds, so the combination of the different types of supports allows the load to be properly distributed and guarantees the stability of the structure in any climatic condition. This combination of supports also allows for easy installation of the solar panels on the structure, as each type of support has a specific design that is perfectly adapted to the SunPower SPR-P3-410-COM-1500 model panels. In addition, the use of EnnovaBloc concrete supports ensures a long service life of the structure and reduces long-term maintenance costs.



*Figure 32. Structure EnnovaBloc Sail 10°. Source: Own elaboration*

It has been decided not to use batteries in this photovoltaic installation because it is planned to inject the surplus energy generated into the grid and to compensate for the energy production at times of lower generation. This is achieved through a grid access contract that allows the injection of energy into the grid and the receipt of energy at times when solar production is not sufficient.

In addition, the use of batteries would significantly increase the cost of installation and complexity of the system, which may not be cost-effective in terms of cost-benefit. By not using batteries, the cost of the installation is reduced, and high energy efficiency is maintained since the energy generated is used directly in the consumption of the installation and the surplus production is compensated through the electrical grid.

The initial investment cost for the photovoltaic installation has been calculated as shown in Table 6, taking into account the elements of the installation, such as the panels, inverter, and concrete structures. The total investment required for the 11.07 kWp installation is 12.515,80 €, and the cost per installed kWp is 1.130,61 €. This cost per kWp is below the market average, which is around 1.500 €/kWp. However, it is important to note that reliable and long-lasting components with proven performance have been selected for the installation.

*Table 6. Investment for the Installation Components*

Component	Product Name	Quantity	Unitary Price	CapEx
Solar Panels	SunPower SPR-P3-410-COM-1500	27	328,00 €	8.856,00 €
Inverter	Huawei SUN2000-12KTL-M2-3PH	1	2.620,00 €	2.620,00 €
Concrete Structure	EnnovaBloc 10° (ref. Enb010)	5	36,34 €	181,70 €
Concrete Structure	EnnovaBloc 10°B (ref. Enb010B)	5	43,58 €	217,90 €
Concrete Structure	EnnovaBloc 10°C (ref. Enb010C)	5	43,80 €	219,00 €
Concrete Structure	EnnovaBloc 10°D (ref. Enb010D)	5	42,02 €	210,10 €
Concrete Structure	EnnovaBloc 10°E (ref. Enb010E)	5	42,22 €	211,10 €
<b>Total</b>				<b>12.515,80 €</b>
				<b>1.130,61 €/kWp</b>

Even though the installation cost is below the market average, the selection of high-quality components ensures long-term reliability and optimal performance. The fact that the cost per kWp is lower than the market average can be attributed to careful planning and cost management. By using the right combination of components, the overall cost of the installation has been reduced without sacrificing quality or performance. Therefore, the photovoltaic installation offers an affordable and reliable solution for self-consumption, contributing positively to the environment and reducing electricity bills.

---

## **6.4 OPTIMAL SCENARIO SIMULATION**

The following section focuses on conducting a simulation of the optimal scenario for the selected photovoltaic installation (11.07 kWp) on the roof of the IIT building. This simulation aims to evaluate the performance and potential benefits of the installation under different conditions. The input parameters for the simulation and technical specifications of the components have been previously determined.

Two scenarios will be analyzed in the simulation: one with surplus energy being fed back into the grid, utilizing the compensation mechanism, and another scenario without compensation for surplus energy. Both scenarios will provide insights into the energy production, consumption, and emissions reduction potential of the photovoltaic system. The simulation results will be instrumental in assessing the feasibility and efficiency of the installation, as well as its environmental impact. These findings will contribute to the decision-making process regarding system design and optimization, aiming to achieve maximum energy efficiency and sustainability.

It is important to clarify that this section will focus solely on technical aspects, such as annual production of the installation, energy consumption, and emission reduction. Visual tools will be utilized to effectively illustrate and present the results obtained. In the next section, a detailed economic analysis will be conducted, complementing the technical and production analysis presented in this section.

Due to the 25-year warranty on the solar panels and the 10-year warranty on the concrete structures, the project's lifetime has been set at 20 years for the calculations, although it is widely known that the typical lifespan of a photovoltaic system ranges between 25 and 30 years.

When determining the lifespan of a photovoltaic installation, it is crucial to consider the warranties provided by the panel manufacturers and the support structures. The conservative decision to establish a 20-year project lifetime is based on the understanding that the warranties offered by the manufacturers serve as a significant indicator of the expected

durability of the components. A 25-year warranty on the solar panels suggests that they are expected to maintain at least 80% of their power-generating capacity during that period. Similarly, a 10-year warranty on the concrete structures indicates an expectation of maintaining their structural and functional integrity during that timeframe.

By setting a 20-year lifetime for the calculations, a conservative period is considered, taking into account the manufacturer's warranties and providing an additional margin of safety. However, it is worth noting that many photovoltaic systems continue to effectively generate electricity even after the warranty period expires. Proper and regular maintenance can contribute to extending the system's lifespan beyond the 20 years established for the project.

In Figure 33, a diagram illustrates the annual production of Scenario I, which does not involve excess energy compensation. In this scenario, when the photovoltaic installation generates electricity beyond the immediate consumption, the surplus energy goes unused. The total renewable energy share in this scenario, considering both segments, is 18.57%. As mentioned earlier, it is worth noting that the installation in Segment II performs better due to its closer alignment with the optimal tilt angle. Additionally, there is an average annual reduction of 5 tons of CO<sup>2</sup> emissions. The total photovoltaic energy generated over the 20-year project lifetime is 328.527,97 kWh. It is important to consider that the actual lifespan of the installation is likely to exceed the conservative estimate of 20 years.

The main advantage of Scenario I is the focus on direct consumption, where the generated photovoltaic energy is immediately utilized on-site. This reduces reliance on the grid and eliminates the need for excess power injection systems. However, a notable drawback of Scenario I is the unutilized excess energy generated by the photovoltaic installation. When the generated energy exceeds the immediate demand, it cannot be effectively harnessed or monetized. This limitation can restrict the potential economic benefits associated with the installation, as the excess energy is essentially wasted.

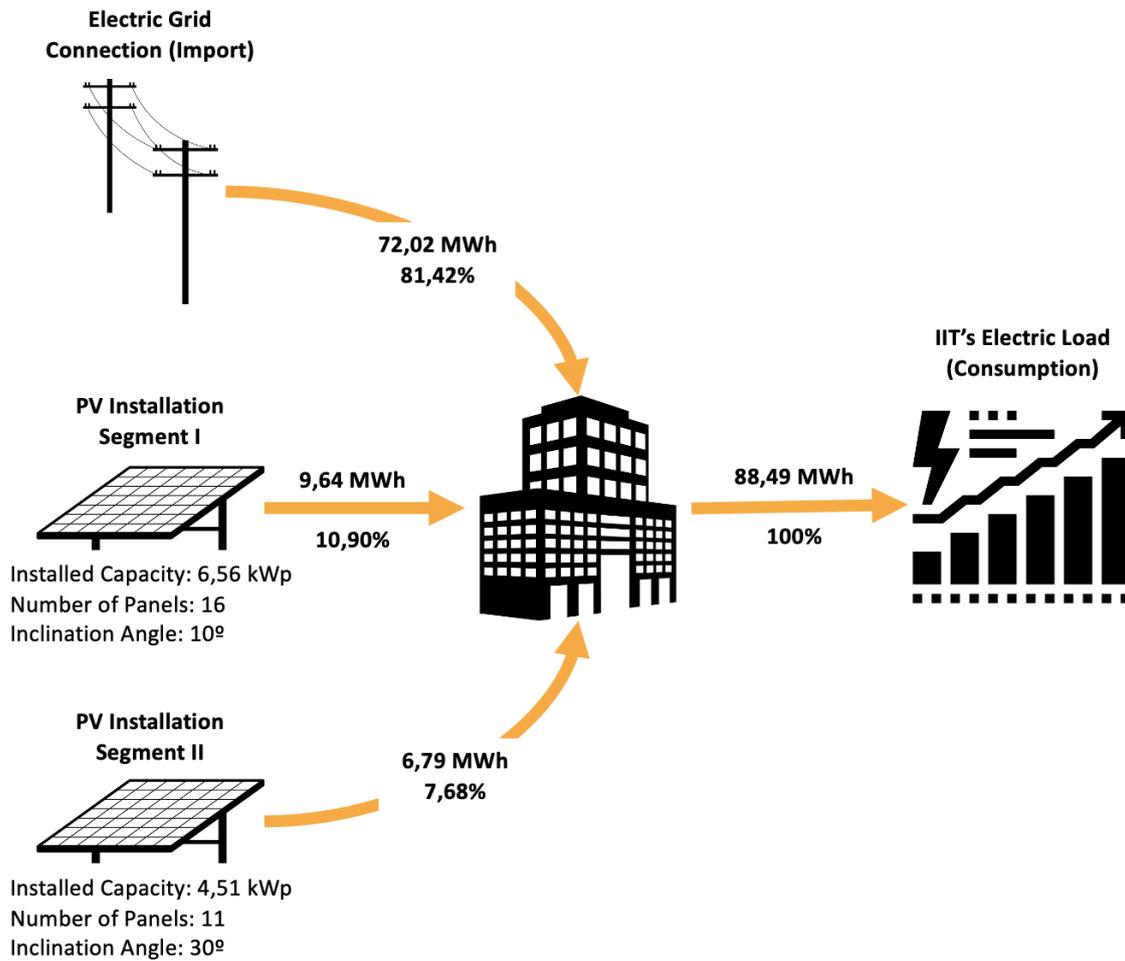


Figure 33. Scenario I: Without Compensation for Surplus Energy. Source: Own elaboration

In Figure 34, a diagram is presented showing the annual production of Scenario II, which incorporates the compensation of excess energy generated by the photovoltaic installation. In this scenario, when energy production exceeds demand at a given moment, the excess is injected into the grid and sold, allowing for a deduction in the corresponding electricity bill. The total percentage of renewable energy in this scenario is 21.02%, considering the installations in both segments. Additionally, an average annual reduction of 5 tons of CO<sup>2</sup> emissions is observed. The total photovoltaic energy generated during the estimated 20-year project lifetime amounts to 383.394,59 kWh.

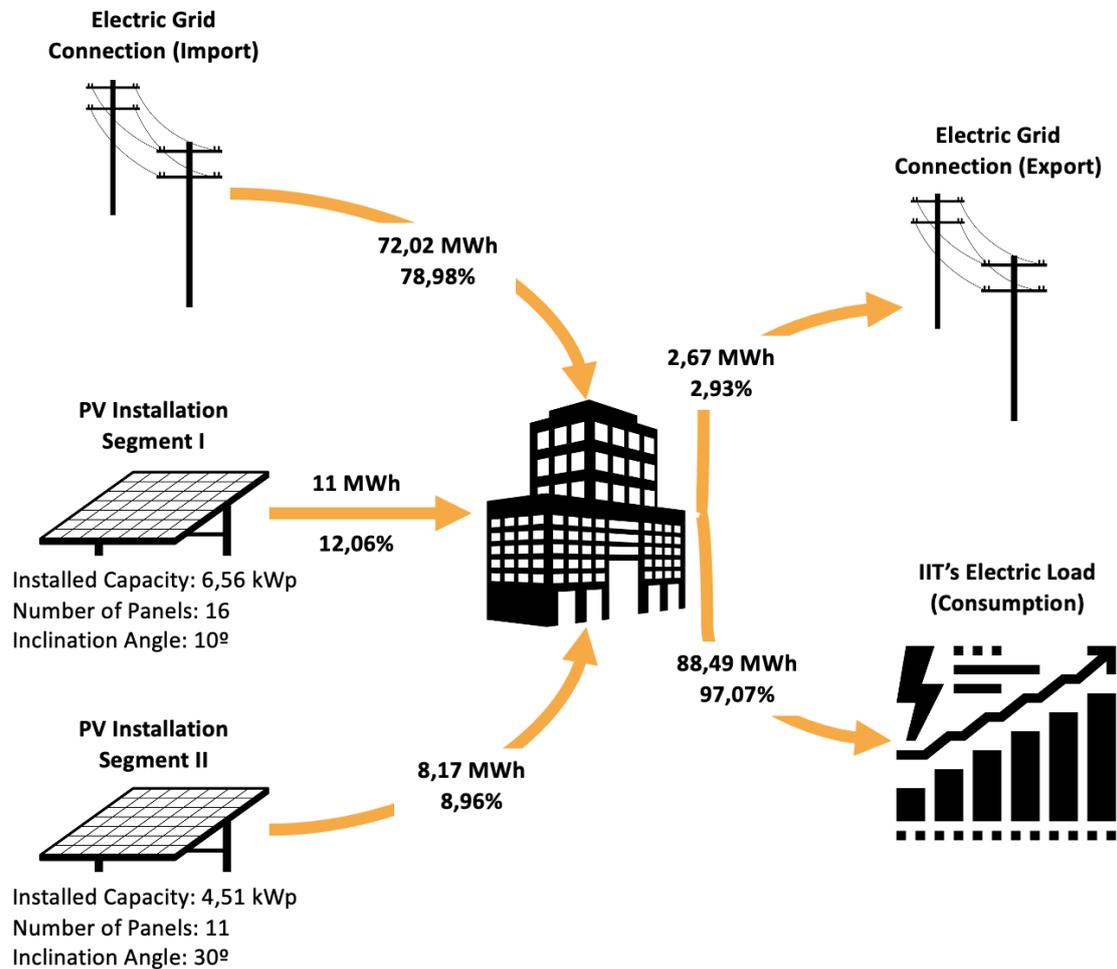


Figure 34. Scenario II: With Compensation for Surplus Energy

Scenario II allows for the compensation of excess energy generated by the photovoltaic installation, leading to economic advantages. By injecting the excess energy into the grid, it can be sold and deducted from the electricity bill, resulting in potential cost savings. Moreover, this compensation mechanism promotes the efficient utilization of renewable energy resources, maximizing the overall renewable energy share. It's important to note that, while there is a potential drawback of increased dependence on the grid, the benefits of compensating excess energy and optimizing renewable energy utilization outweigh this concern. The reliance on a reliable grid can be mitigated by ensuring a robust and well-maintained grid infrastructure.

---

## **6.5 DEGRADATION FACTOR**

This section aims to analyze the degradation factor of solar panels and its impact on the evolution of the installation in terms of production and consequently, in revenue. The degradation factor refers to the gradual decrease in the efficiency of solar panels over time due to various factors such as material aging and environmental conditions.

During the simulations conducted in the previous section, standard degradation factors provided by Siemens software were used. However, in this section, we compare the photovoltaic production of Scenario II, considered optimal, using the standard degradation factors provided by the software, with the production using degradation factors obtained through the analysis of photovoltaic production data from the old IIT building installation conducted in 2002.

It is important to note that the annual variations in photovoltaic production obtained from the data of the old installation cannot be solely attributed to the degradation of the solar panels, as many other environmental factors, such as sunlight hours and temperature, influence them. However, this data will provide relevant information about the actual degradation experienced in the old installation and allow for a comparison with the standard factors used in the simulations.

By analyzing the photovoltaic production using the degradation factors obtained from the analysis of the old installation, a more accurate assessment of the expected production evolution over time can be made. This enables more realistic projections of the revenue generated by the installation and an evaluation of the long-term profitability of the project. Additionally, it provides valuable information for maintenance and future planning of the installation, as the actual levels of solar panel degradation can be taken into account.

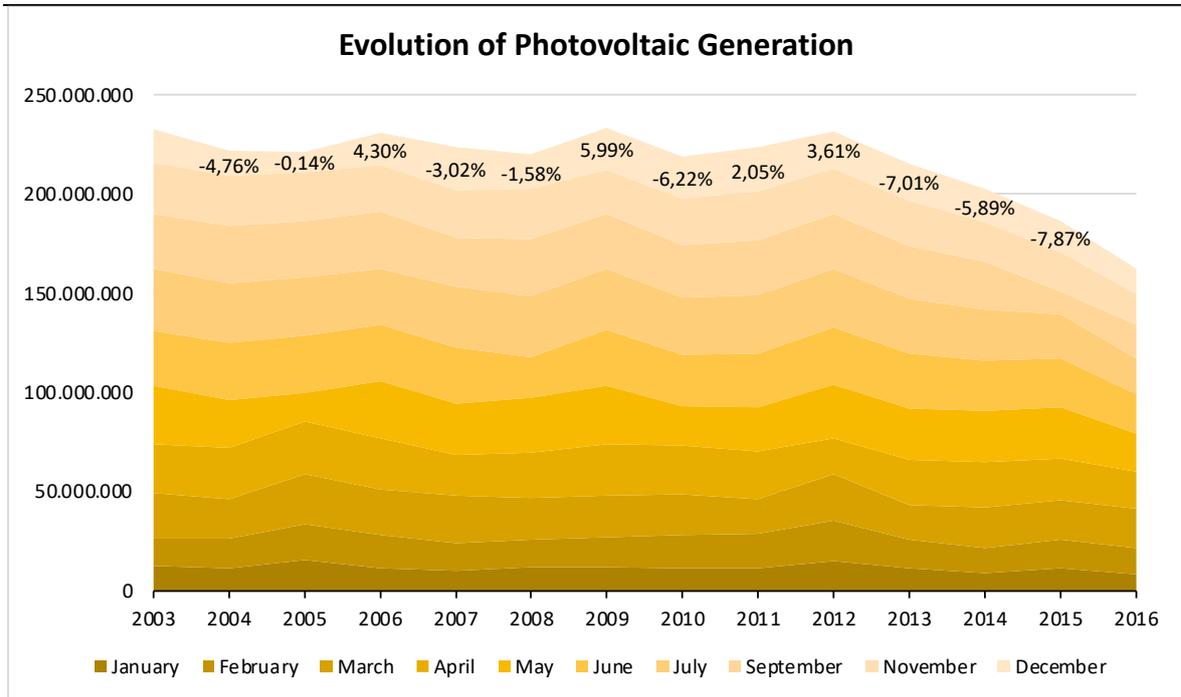


Figure 35. Evolution of Photovoltaic Generation from 2003 to 2016 (Old Installation)

Figure 35 presents the photovoltaic production data of the old IIT building installation from 2003 to 2016, allowing for an observation of its evolution over time. By analyzing this data, annual degradation factors can be calculated and compared with the standard factors used in the software simulations. This comparison will provide insights into the real-world degradation of the solar panels and contribute to a more accurate estimation of their future performance. The color code associated with each month further aids in visualizing the observed production during different periods.

Table 7. Degradation Factor Comparison

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13
Old Installation	0,95	0,95	1,04	1,01	0,95	1,04	1,00	0,96	1,06	0,97	0,87	0,86	0,79
Software	0,99	0,99	0,98	0,97	0,97	0,96	0,95	0,95	0,94	0,93	0,93	0,92	0,91

Table 7 presents the annual degradation factors of an old installation and the values provided by the simulation software over a 13-year period. By analyzing the data, the following conclusions can be drawn. Firstly, it can be observed that both the old installation and the software simulation show a general trend of degradation over time. Both data sets indicate a gradual decrease in the performance of the photovoltaic installation.

---

Secondly, it is evident that the degradation factors are quite consistent in both cases over the years. Although there are slight differences in the degradation rates between the old installation and the software simulation, overall, the values are close. This suggests that the degradation model used by the software provides a reasonable estimate of the degradation experienced in the new installation.

It is worth noting that more notable differences are observed towards the last years in the degradation factor (from 0.79 to 0.91), indicating that the old IIT installation, which utilized a less advanced technology, exhibits a poorer performance over time compared to the estimates provided by the software. Additionally, in the case of the old installation, values greater than 1 are observed. This does not imply an improvement in panel performance over time, but rather reflects the influence of weather conditions on the data. Years with values exceeding 1 may be attributed to higher solar radiation during those periods. Therefore, considering the different technologies employed in the present project compared to the old installation, we rely on the software parameters.

For the sake of accuracy and consistency, we consider the software parameters as the solar PV panel technologies used in the present project differ from those used in the old installation. By doing so, we account for the variations caused by different technologies and environmental factors. It allows us to maintain a reliable framework for analysis and decision-making throughout the project.

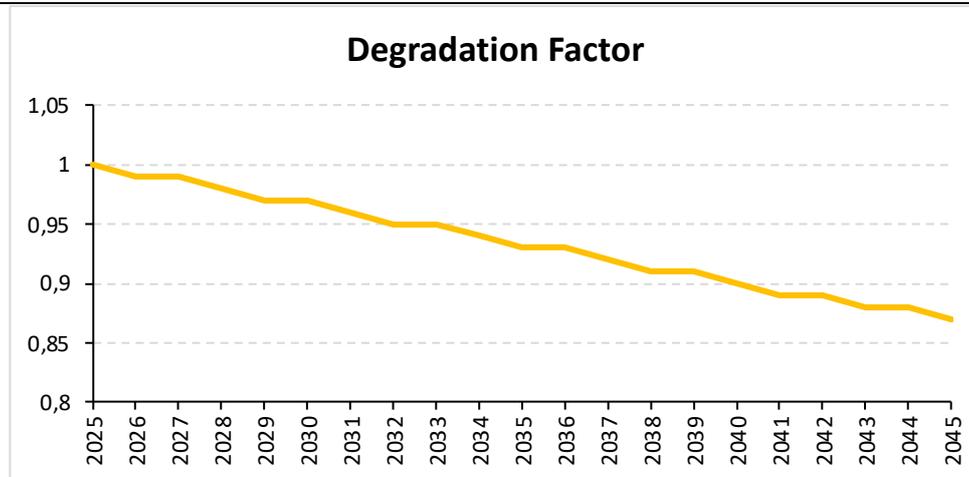


Figure 36. Degradation Factor Evolution

Figure 36 displays the evolution of the degradation factor used for the simulations conducted with the software, which is subsequently employed to obtain the optimal scenario for the current project.

## 6.6 ECONOMIC ANALYSIS

In this section, a detailed economic analysis of the two previously analyzed scenarios will be conducted. The main objective is to evaluate the financial viability of the photovoltaic installations and determine their profitability over their lifetime. Performing an economic analysis of the installation is crucial for several reasons.

Firstly, it allows for the assessment of the financial feasibility of the project and determines whether it is a profitable investment. Furthermore, the economic analysis provides a clear understanding of profitability over time.

The important aspect is that the economic analysis allows for the comparison of different scenarios and informed decision-making. It can help identify which scenario offers greater profitability and what critical factors influence the economic outcomes. This enables the optimization of the photovoltaic installation, considering both technical and financial aspects.

There are several key factors that need to be considered while conducting an economic analysis of a photovoltaic installation:

- **Initial Investment (CapEx):** In the previous sections, the initial investment of the photovoltaic installation has been carefully assessed, considering the cost of solar panels and concrete supports. The total calculated value for the initial investment is 12,515.80 € (1,120.61 €/kWp). This includes the expenses associated with procuring and installing the solar panels, as well as the necessary concrete supports to ensure the stability and durability of the system. The accurate estimation of the initial investment is crucial in determining the overall financial feasibility of the project. By considering the cost of the solar panels and concrete supports, stakeholders can make informed decisions and allocate the necessary resources for the successful implementation of the photovoltaic installation.
- **Operation and Maintenance Costs (OpEx):** The operational expenditure (OPEX) of the photovoltaic installation includes the ongoing costs associated with its maintenance, monitoring, and administration throughout its lifespan. These expenses encompass routine inspections, cleaning, repairs, insurance, and any necessary administrative fees. It is important to consider the average market value of OPEX for similar photovoltaic installations to ensure accurate financial planning. The average market value for OPEX in the photovoltaic sector ranges between 1% and 2% of the initial investment per year. Therefore, for our installation with an initial investment of 12,515,80€, the average annual OPEX is estimated to be between 125,16€ and 250,32€. Properly accounting for OPEX is crucial for assessing the overall financial performance and long-term viability of the photovoltaic system, so the highest value (250,32€) has been chosen for the economic analysis, being more conservative.
- **Energy Production and Consumption:** In the previous sections, detailed calculations were performed for the energy production and consumption in both scenarios. Various factors were taken into account, including solar radiation, technical characteristics of the installation, and electricity consumption patterns. The results revealed the amount of photovoltaic energy generated by the installation throughout the year, as well as the corresponding electricity consumption. These data

are essential for assessing the performance and efficiency of the photovoltaic systems, as well as understanding the level of energy self-sufficiency and the potential for emissions reduction in each scenario.

- **Incentives:** It is crucial to consider the impact of incentives on the overall economic returns. In this study, the analysis takes a conservative approach by assuming a 0% subsidy for the initial investment. By adopting this conservative estimate, the financial analysis provides a more cautious evaluation of the economic viability and potential returns of the photovoltaic system. Further details and information regarding incentives can be found in section 3.4.
- **Discount Rate:** The discount rate is an important factor in the economic analysis of a photovoltaic installation. This rate is used to calculate the present value of the project's future cash flows. The choice of the discount rate should consider the opportunity cost of funds, the project's cost of capital, and market conditions. In this case, the use of an 8% discount rate is justified based on the expected return of comparable risky alternative investments and current market interest rates.

Using all the factors defined above, it is necessary to establish the financial metrics to be used in assessing the profitability and financial feasibility of the project. It is important to consider the project's specific characteristics and employ the metrics collectively to gain a comprehensive understanding and compare the different scenarios defined in previous chapters. The following financial metrics have been chosen for this project:

- **Payback Period:** The payback period is a key financial metric used to assess the time it takes for an investment to recoup its initial cost. In the context of this project, the payback period is calculated to determine the timeframe required for the photovoltaic installation to generate enough savings or revenue to cover its initial investment. A shorter payback period indicates a faster return on investment and greater financial efficiency. By analyzing the payback period, decision-makers can evaluate the project's financial viability and assess its attractiveness compared to alternative investment options.

- **Return on Investment (ROI):** Return on Investment (ROI) is a fundamental financial metric used to evaluate the profitability of an investment. It measures the return generated from an investment relative to its cost. In the case of this project, the ROI is calculated to determine the percentage return on the initial investment made in the photovoltaic installation. A higher ROI indicates a more profitable investment, as it signifies greater returns compared to the initial cost. By analyzing the ROI, stakeholders can assess the financial performance of the project and make informed decisions regarding its feasibility and potential for generating positive returns.

$$ROI (\%) = \frac{\text{Net Cash Flows} - \text{Initial Investment}}{\text{Initial Investment}} \cdot 100$$

- **Net Present Value (NPV):** Net Present Value (NPV) is a financial metric used to assess the profitability of an investment by considering the time value of money. It calculates the present value of all future cash flows associated with the investment, discounted at a specific rate of return. A positive NPV indicates that the project is expected to generate more value than the initial investment, while a negative NPV suggests that the project may not be financially viable. By calculating the NPV of the photovoltaic installation, we can determine its net value in today's terms and assess whether it is a worthwhile investment. This metric takes into account the timing and magnitude of cash flows, providing a comprehensive measure of the project's financial attractiveness.
- **Internal Rate of Return (IRR):** The Internal Rate of Return (IRR) is a financial metric that measures the profitability and potential return of an investment. It represents the discount rate at which the net present value (NPV) of the cash flows from the investment becomes zero. In other words, it is the rate at which the project breaks even. A higher IRR indicates a more attractive investment, as it implies a higher return on the initial investment. By calculating the IRR of the photovoltaic installation, we can assess its financial viability and compare it with other investment opportunities. The IRR provides valuable insights into the project's potential to generate positive returns and helps stakeholders make informed decisions regarding resource allocation and project prioritization.

Therefore, a Discounted Cash Flow (DCF) analysis is conducted for each of the two scenarios defined in section 6.4 to carry out the economic analysis and make a comparison for decision-making. Additionally, the previously defined financial metrics have been calculated for both scenarios.

It is important to highlight that the DCF analysis has incorporated future prices established by the OMIP (Iberian Energy Market Operator). The OMIP is responsible for running the long-term electricity Iberian markets. The resulted future prices are essential for estimating future cash flows and determining their present value. By utilizing the prices obtained from OMIP, a precise and reliable evaluation of the financial performance of the considered scenarios is ensured.

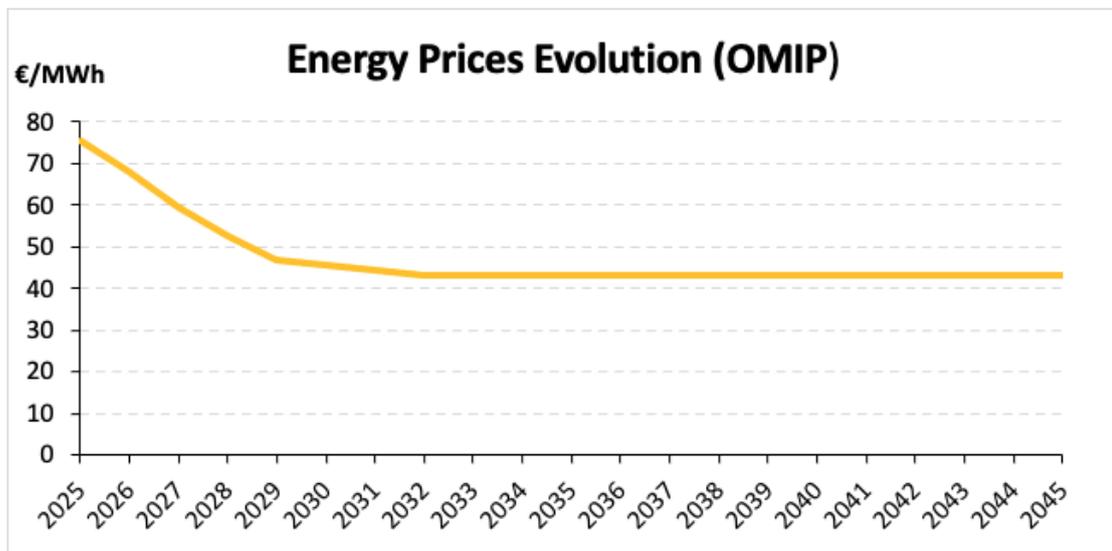


Figure 37. Energy Prices Evolution in €/MWh during Project Lifetime of the installation. (OMIP)

The analysis depicted in Figure 37 reveals a noticeable downward trend in electricity future prices. This trend is particularly significant considering the context of the current project, where unusually high prices are observed. The existence of such high prices underscores the need for a thorough examination of the energy market dynamics.

These findings have important implications for the economic evaluation of the project. The anticipated stabilization of energy prices beyond 2033 provides a more reliable basis for

assessing the financial viability and long-term profitability of the photovoltaic installation. It suggests that the investment in renewable energy infrastructure can yield increasingly favorable returns over its operational lifespan. It is crucial to take into account the evolving energy market conditions when conducting a comprehensive economic analysis.

The figure below presents the first five years of the DCF analysis for Scenario I, as depicted in Figure 38. The highlighted cells in yellow indicate the cash outflows associated with not implementing any photovoltaic installation and relying solely on grid electricity. Conversely, the cash inflows associated with the photovoltaic installation and grid connection are displayed below. The cash flow (CF) is calculated by subtracting the cash outflows with the installation from the cash inflows without the installation (highlighted in yellow). This CF value represents the actual savings achieved by implementing the installation, taking into account the initial investment or CapEx. Furthermore, the cash flows are discounted to the present time using a predetermined discount rate of 8%, as indicated in the present value (PV) row.

Period	2025	2026	2027	2028	2029	2030	
<b>Electric Grid Connection</b>	<b>Total</b>	<b>25.108,35 €</b>	<b>22.624,08 €</b>	<b>19.808,57 €</b>	<b>17.526,35 €</b>	<b>15.628,36 €</b>	<b>15.148,07 €</b>
	CapEx	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €
	OpEx	100,00 €	100,00 €	100,00 €	100,00 €	100,00 €	100,00 €
	Imported	25.008,35 €	22.524,08 €	19.708,57 €	17.426,35 €	15.528,36 €	15.048,07 €
	Exported	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €
<b>PV (Segment I &amp; Segment II)</b>	<b>Total</b>	<b>12.766,12 €</b>	<b>250,32 €</b>	<b>250,32 €</b>	<b>250,32 €</b>	<b>250,32 €</b>	<b>250,32 €</b>
	CapEx	12.515,80 €	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €
	OpEx	250,32 €	250,32 €	250,32 €	250,32 €	250,32 €	250,32 €
	Incentives	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €
<b>Electric Grid Connection</b>	<b>Total</b>	<b>20.318,91 €</b>	<b>18.310,41 €</b>	<b>16.034,11 €</b>	<b>14.188,96 €</b>	<b>12.654,47 €</b>	<b>12.266,16 €</b>
	CapEx	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €
	OpEx	100,00 €	100,00 €	100,00 €	100,00 €	100,00 €	100,00 €
	Imported	20.218,91 €	18.210,41 €	15.934,11 €	14.088,96 €	12.554,47 €	12.166,16 €
	Exported	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €
	<b>CF</b>	<b>-7.976,68 €</b>	<b>4.063,35 €</b>	<b>3.524,14 €</b>	<b>3.087,06 €</b>	<b>2.723,57 €</b>	<b>2.631,59 €</b>
8%	<b>PV</b>	<b>-7.976,68 €</b>	<b>3.762,36 €</b>	<b>3.021,38 €</b>	<b>2.450,61 €</b>	<b>2.001,91 €</b>	<b>1.791,02 €</b>

Figure 38. DCF Scenario I (5 first years)

Similar to what was explained for Figure 38, the analysis for Scenario II is illustrated in Figure 39. The main difference to highlight between the two scenarios is the contribution of the annual cash flow from exported electricity. In Scenario I, this contribution is zero, while in Scenario II, positively impacts the cash flow, making the investment significantly more profitable. It is worth noting that both scenarios yield highly satisfactory results, making them attractive options for implementing the installation.

	Period	2025	2026	2027	2028	2029	2030
<b>Electric Grid Connection</b>	<b>Total</b>	<b>25.108,35 €</b>	<b>22.624,08 €</b>	<b>19.808,57 €</b>	<b>17.526,35 €</b>	<b>15.628,36 €</b>	<b>15.148,07 €</b>
	CapEx	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €
	OpEx	100,00 €	100,00 €	100,00 €	100,00 €	100,00 €	100,00 €
	Imported	25.008,35 €	22.524,08 €	19.708,57 €	17.426,35 €	15.528,36 €	15.048,07 €
	Exported	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €
<b>PV (Segment I &amp; Segment II)</b>	<b>Total</b>	<b>12.766,12 €</b>	<b>250,32 €</b>	<b>250,32 €</b>	<b>250,32 €</b>	<b>250,32 €</b>	<b>250,32 €</b>
	CapEx	12.515,80 €	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €
	OpEx	250,32 €	250,32 €	250,32 €	250,32 €	250,32 €	250,32 €
	Incentives	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €
<b>Electric Grid Connection</b>	<b>Total</b>	<b>19.920,80 €</b>	<b>17.951,85 €</b>	<b>15.720,37 €</b>	<b>13.911,55 €</b>	<b>12.407,27 €</b>	<b>12.026,61 €</b>
	CapEx	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €
	OpEx	100,00 €	100,00 €	100,00 €	100,00 €	100,00 €	100,00 €
	Imported	20.218,91 €	18.210,41 €	15.934,11 €	14.088,96 €	12.554,47 €	12.166,16 €
	Exported	-398,11 €	-358,56 €	-313,74 €	-277,41 €	-247,20 €	-239,55 €
	<b>CF</b>	<b>-7.578,57 €</b>	<b>4.421,91 €</b>	<b>3.837,88 €</b>	<b>3.364,47 €</b>	<b>2.970,77 €</b>	<b>2.871,14 €</b>
8%	<b>PV</b>	<b>-7.578,57 €</b>	<b>4.094,36 €</b>	<b>3.290,36 €</b>	<b>2.670,83 €</b>	<b>2.183,61 €</b>	<b>1.954,05 €</b>

Figure 39. DCF Scenario II (5 first years)

Table 8 presents a comparison of the previously defined financial metrics. As anticipated based on the differences between the two installations, Scenario II demonstrates slightly superior financial metrics compared to Scenario I, although the metrics for the latter are also highly favorable. It is worth noting that the economic analysis followed a highly conservative approach, meaning that the actual results would be even more appealing if the installation were to be implemented. The significantly high IRR and ROI values, coupled with a short payback period, establish the rooftop solar panel installation at the IIT as a highly profitable investment, while simultaneously contributing to environmental preservation. Possible risks come from a high increase in solar generation installations which significantly reduce the wholesale prices where the PV generates, making the installation less attractive.

*Table 8. Financial Metrics Comparison*

	<b>Scenario I</b>	<b>Scenario II</b>
<b>NPV</b>	19.515,40 €	22.403,01 €
<b>ROI</b>	254%	295%
<b>Payback</b>	3 years	2 years
<b>TIR</b>	41%	48%

## **Chapter 7. ANALYSIS OF RESULTS**

In this chapter, we present a comprehensive analysis of the results obtained from the master's thesis project. The aim is to evaluate the technical and economic aspects of the photovoltaic installations and determine the most favorable scenario. After conducting a detailed examination of the data and applying the defined financial metrics, we can draw conclusions that will inform decision-making regarding the implementation of the project. In this regard, we will highlight the advantages of Scenario II, which allows for the compensation of surplus energy with the grid.

The technical performance evaluation focused on various factors, including energy production, efficiency, and reliability. Through detailed calculations and simulations, we determined the expected energy generation for each scenario. The results showed that both Scenario I and Scenario II have commendable energy production capacities. However, Scenario II demonstrated an additional advantage with its ability to export excess energy to the grid, enhancing its overall performance and self-sufficiency. This feature ensures a more reliable energy supply and increases dependence on the grid.

To assess the economic viability of the project, we conducted a thorough economic analysis using established financial metrics. The metrics considered included Payback Period, Return on Investment (ROI), Net Present Value (NPV), and Internal Rate of Return (IRR). The analysis involved evaluating the initial investment, operational costs, energy savings, and potential revenues. The results showed that both scenarios exhibited favorable financial metrics, indicating the potential for a profitable investment. However, Scenario II stood out with its superior metrics, primarily due to the additional revenue generated by exporting surplus energy to the grid. This can be seen in the significant increase in NPV, which is almost 3,000€ higher than Scenario I. Additionally, Scenario II showed a 7% better IRR, and the investment was recouped one year earlier compared to Scenario I.

Based on the technical and economic evaluations, it is evident that Scenario II, which allows for surplus energy compensation with the grid, is more compelling. This scenario not only

ensures a higher level of energy self-sufficiency but also provides an additional revenue stream through energy export. The ability to monetize excess energy significantly enhances the financial feasibility and profitability of the project. Moreover, Scenario II aligns with the current trends in renewable energy, as it contributes to the overall grid stability and fosters a more sustainable energy ecosystem.

In addition to the technical and economic considerations, we must also emphasize the environmental impact of the project. Both scenarios contribute to reducing greenhouse gas emissions and mitigating climate change by relying on clean, renewable energy sources. The installation of photovoltaic systems not only reduces reliance on fossil fuels but also promotes sustainable energy practices. By choosing Scenario II, we maximize the environmental benefits by optimizing energy production and minimizing the electricity curtailed.

In conclusion, the analysis of the project's results indicates that Scenario II, which allows for the compensation of surplus energy with the grid, offers a more favorable outcome. The combination of technical performance, economic viability, and environmental impact makes Scenario II the preferred choice. The superior financial metrics, including a shorter payback period, higher ROI, and favorable NPV and IRR values, demonstrate the project's profitability and potential for long-term returns. Implementing this scenario will not only contribute to the sustainability goals of the institution but also pave the way for a greener and more resilient energy future.

*Table 9. Comparative Table Offers vs. Simulated Scenarios*

	Number of Modules	Peak Power	Surplus Compensation	Photovoltaic Generation
Offer A	27	14,58 kWp	Yes	21,59 MWh
Offer B	22	10,23 kWp	Yes	15,26 MWh
Offer C	11	6,05 kWp	No	9,87 MWh
Scenario I	27	11,07 kWp	No	16,43 MWh
Scenario II	27	11,07 kWp	Yes	19,17 MWh

In Table 9, the results of installed capacity in peak power, number of photovoltaic modules, and photovoltaic generation are compared, distinguishing between cases with surplus compensation and those without. The Scenario II, considered as the optimal one, stands out with an installed capacity of 11.07 kWp using 27 photovoltaic modules, and surplus compensation is applied. This translates to a photovoltaic generation of 19.17 MWh.

Comparing the different cases, it is noteworthy that Scenario II differs from Scenario I in the presence of surplus compensation, resulting in a higher generation of useful energy. Furthermore, offer A is the most similar in terms of the number of modules, but the peak power of Scenario II is significantly lower due to the selection of modules with lower unit power.

On the other hand, offer B is the closest in terms of peak power, but there is a much greater difference in photovoltaic generation compared to Scenario II. This indicates that the components, orientations, and distribution chosen in Scenario II are superior and more optimal than in offer B.

In summary, Scenario II stands out for its higher installed capacity, number of modules, and photovoltaic generation, driven by surplus compensation and the appropriate selection of components, making it the most favorable option among the compared cases.

## Chapter 8. CONCLUSIONS AND FUTURE WORK

In this chapter, the conclusions and outline future research directions based on the analysis and findings of this master's thesis are presented. Throughout this study, we have extensively examined various aspects of photovoltaic installations, ranging from technical performance to economic viability and environmental impact. The conclusions drawn from this research provide valuable insights into the potential of photovoltaic systems as a sustainable and renewable energy solution.

The findings of this study affirm the positive performance of photovoltaic installations in terms of energy production, cost savings, and greenhouse gas emissions reduction. The economic analysis conducted has demonstrated the financial feasibility of such installations, considering factors such as initial investment, operational costs, and available incentives. Furthermore, the environmental assessment underscores the significant contribution of photovoltaic systems towards mitigating climate change and decreasing dependence on fossil fuels.

However, this study also identifies several areas that warrant further investigation. The two areas most closely related to the project and also more and of greatest interest for the university are:

- **Collective Self Consumption:** The implementation of collective self-consumption with neighboring buildings at the Universidad Pontificia de Comillas, such as ICAI and ICADE, offers exciting opportunities for creating an energy community. By leveraging the proximity of these buildings, a collaborative environment can be established to share renewable energy generation and consumption. This approach optimizes energy utilization, reduces reliance on the grid, and maximizes the efficiency of renewable energy systems. It also encourages collaboration, knowledge sharing, and the development of innovative energy management strategies. Additionally, collective self-consumption provides economic benefits by reducing energy costs and leveraging incentives and support programs. By embracing this

---

concept, the university aligns with government initiatives promoting sustainable energy practices, contributes to national energy goals, and serves as a role model for other institutions and organizations.

- **Additional Renewable Energy Sources:** The inclusion of solar thermal systems can harness the power of the sun to provide hot water or space heating for the buildings, reducing the need for traditional energy sources and enhancing energy efficiency. Additionally, technologies such as geothermal systems, or heat pumps can be explored to leverage renewable energy sources for heating and cooling requirements. Implementing these additional renewable energy technologies aligns with the sustainability goals of the Universidad Pontificia Comillas and the broader government initiatives promoting clean energy adoption. It presents an opportunity to create a more resilient and sustainable energy infrastructure that reduces reliance on fossil fuels and contributes to the global transition towards a low-carbon future. By embracing these technologies and integrating them into the energy systems, the university showcases its commitment to innovative and sustainable practices. Moreover, it sets an example for other institutions and organizations, inspiring them to explore diverse renewable energy solutions and create a more sustainable built environment.

Additionally, future research endeavors can focus on optimizing system design and component selection to maximize energy generation and improve overall system efficiency. Exploring advanced energy storage technologies and their integration with photovoltaic systems could enhance the reliability and flexibility of renewable energy supply.

By addressing these future research directions, we can advance the understanding and development of photovoltaic installations, facilitating the transition towards a sustainable and clean energy future. The findings presented in this master's thesis lay the groundwork for further exploration in these areas, with the ultimate goal of promoting the widespread adoption of photovoltaic systems and accelerating the shift towards a low-carbon society.

## **Chapter 9. ALIGNMENT WITH THE SUSTAINABLE DEVELOPMENT GOALS (SDGs)**

The SDGs are a global initiative that aims to guide countries' efforts towards a sustainable future. The Agenda 2030 sets out a set of specific and ambitious goals that cover economic, social, and environmental aspects.

Achieving these objectives involves coordinated work among different actors, from governments and the private sector to civil society and individual citizens. Everyone must work together to move in the same direction and thus contribute to achieving a fairer, more equitable, and sustainable world.

The project in question, which aims to improve energy efficiency through renewable energy, specifically photovoltaic, is aligned with several of the goals of the Agenda 2030. Through the adoption of clean and sustainable technologies, the aim is to reduce environmental impact and move towards a more sustainable and responsible energy model.

In summary, a self-consumption photovoltaic installation can significantly contribute to achieving the SDGs, as it promotes access to clean and sustainable energy, combats climate change and its negative consequences, and improves the resilience and sustainability of cities and human settlements. In addition, the installation of solar panels can also provide economic benefits, such as reducing energy costs and creating green jobs in the renewable energy industry.

In this sense, three objectives are highlighted that are particularly aligned with the project and its contribution to the Agenda 2030:



*Figure 40. SDG's 7, 9 and 13*

### ***9.1 SDG 7: AFFORDABLE AND CLEAN ENERGY***

The Goal 7 of the SDGs aims to ensure access to affordable, reliable, sustainable, and modern energy for all and to transition towards cleaner and renewable energy sources. Photovoltaic solar energy is a form of renewable energy that can help achieve this goal. The installation of solar panels on buildings, as proposed in this project, can provide a source of clean and renewable energy that can be used to power both the internal needs of the building and the electric grid. Additionally, solar energy can be used in remote locations or areas lacking energy infrastructure, contributing to the elimination of energy poverty.

A self-consumption photovoltaic installation on the roof of a building is not only a source of clean and renewable energy, but it can also help reduce dependence on fossil fuel sources and, therefore, reduce greenhouse gas emissions. In this way, photovoltaic solar energy can significantly contribute to mitigating climate change and protecting the environment. Additionally, the installation of solar panels on buildings can help reduce energy costs, which can be especially beneficial for low-income households and businesses. In summary, the use of photovoltaic solar energy can help achieve the goal of affordable and clean energy and can have a positive impact on the economy, environment, and society as a whole.

---

## ***9.2 SDG 9: INDUSTRY, INNOVATION AND INFRASTRUCTURE***

Goal 9 of the United Nations Sustainable Development Goals focuses on the need to develop resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation. The installation of a self-consumption photovoltaic system in a building can significantly contribute to achieving this goal by promoting the use of clean and sustainable technologies. Photovoltaic solar energy is one of the most innovative and constantly evolving technologies in the renewable energy industry. The installation of solar panels in a building not only contributes to reducing greenhouse gas emissions but can also promote innovation and the development of new business opportunities in the renewable energy sector.

The adoption of clean and sustainable technologies in the industry can also be key to the development of new industries and job creation. The self-consumption photovoltaic installation in a building can be a source of employment and business opportunities in the renewable energy sector, as well as in the construction industry. In addition, the use of renewable energy can reduce energy costs and improve the long-term competitiveness of companies, which can boost sustainable economic growth and job creation in local communities.

In summary, UN Goal 9 focuses on promoting innovation, sustainable infrastructure, and inclusive and sustainable industrialization. The adoption of clean and sustainable technologies, such as the installation of a self-consumption photovoltaic system in a building, can significantly contribute to achieving this goal by promoting innovation and the development of new business opportunities in the renewable energy sector, as well as fostering sustainable economic growth and job creation in local communities.

---

### **9.3 SDG 13: CLIMATE ACTION**

Objective 13 of the United Nations Sustainable Development Goals, "Climate Action," aims to mitigate climate change by reducing greenhouse gas emissions and promoting sustainable practices. The use of renewable energies, such as photovoltaic solar energy, is an effective way to reduce greenhouse gas emissions and contribute to this goal.

Photovoltaic solar energy is a renewable and clean energy source that does not produce greenhouse gas emissions during operation. By using photovoltaic solar energy instead of fossil fuels, dependence on fossil fuels is reduced, and greenhouse gas emissions are decreased. Additionally, the adoption of clean and sustainable technologies such as photovoltaic solar energy can also drive innovation and sustainable economic growth.

The installation of a self-consumption photovoltaic system on the roof of a building not only contributes to mitigating climate change but can also generate economic and social benefits. On the one hand, by reducing energy consumption from the electricity grid, energy costs are decreased, and dependence on non-renewable energy sources is reduced. On the other hand, the installation of photovoltaic systems can also create jobs in the renewable energy sector and contribute to the creation of a more sustainable and equitable economy.

## Chapter 10. BIBLIOGRAPHY

Alonso Pascual, C. (January de 2023). *Newtral*. Obtenido de Self-consumption in Spain:  
<https://www.newtral.es/autoconsumo-espana-agenda-2030/20230110/>

*Alusín Solar Structures*. (s.f.). Obtenido de Instalaciones fotovoltaicas:  
<https://alusinsolar.com/instalaciones-fotovoltaicas/#placas>

Casero Lozano, V. (2021). Diseño de instalación fotovoltaica para autoconsumo de una nave industrial en Seseña (Toledo). Madrid.

EALDE Business School. (s.f.). *All the advantages of specialization in renewable energies*. Obtenido de <https://www.ealde.es/especializacion-energias-renovables/>

*EFC Solar*. (s.f.). Obtenido de Estructuras para paneles solares:  
<https://www.efcsolar.com/energia-solar-fotovoltaica/estructuras-para-paneles-solares-tipos/>

elBoletín. (2022). *Europe's leaders in self-consumption of electricity in homes*. Obtenido de <https://www.elboletin.com/los-lideres-en-autoconsumo-electrico-en-los-hogares-de-europa/#:~:text=Alemania%20se%20mantiene%20en%20primer,un%20referente%20en%20esta%20materia.>

European Comission. (2022). *Photovoltaic Geographical Information System* . Obtenido de [https://re.jrc.ec.europa.eu/pvg\\_tools/en/](https://re.jrc.ec.europa.eu/pvg_tools/en/)

Guijarro Ruiz, C. (2023). *Selectra*. Obtenido de Normativa para la instalación de placas solares en 2023: <https://selectra.es/autoconsumo/info/normativa>

Haro, I. (2023). *Selectra*. Obtenido de Subvenciones de placas solares:  
<https://selectra.es/autoconsumo/info/normativa/subvenciones#requisitos-subvenciones-placas-solares>

- 
- IBERDROLA. (2022). *Autoconsumo fotovoltaico*. Obtenido de <https://www.iberdrola.com/innovacion/autoconsumo-fotovoltaico>
- IDAE, & ENERAGEN. (2022). *Guía Profesional de Tramitación del Autoconsumo v.4.1*. Madrid: Instituto para la Diversificación y Ahorro de la Energía (IDAE) y Asociación de Agencias Españolas de Gestión de la Energía (ENERAGEN).
- IFEMA. (2022). *Global Mobility Call*. Obtenido de The potential of solar energy in Spain: <https://www.ifema.es/global-mobility-call/noticias-sector/el-potencial-de-la-energia-solar-en-espana>
- IRENA. (2021). *Solar Energy*. Obtenido de International Renewable Energy Agency: <https://www.irena.org/Energy-Transition/Technology/Solar-energy>
- Lopez Escalante, G. (2021). *CincoDías*. Obtenido de 2021 The year of the pending revolution in photovoltaic self-consumption: [https://cincodias.elpais.com/cincodias/2021/07/26/companias/1627288213\\_104665.html](https://cincodias.elpais.com/cincodias/2021/07/26/companias/1627288213_104665.html)
- M. Velez, A. (2023). *elDiario.es*. Obtenido de El autoconsumo desborda las expectativas y la potencia instalada se duplica en solo un año: [https://www.eldiario.es/economia/autoconsumo-desborda-expectativas-potencia-instalada-duplica-ano\\_1\\_9797727.html](https://www.eldiario.es/economia/autoconsumo-desborda-expectativas-potencia-instalada-duplica-ano_1_9797727.html)
- Mendoza Losana, A. (January de 2023). *Gómez-Acebo & Pombo*. Obtenido de Real Decreto Ley 20/2022: <https://www.ga-p.com/publicaciones/real-decreto-ley-20-2022-medidas-de-impulso-sostenible-a-las-instalaciones-de-energias-renovables-y-de-autoconsumo/>
- Ministerio para la Transición Ecológica y el Reto Demográfico. (2021). *Hoja de Ruta del Autoconsumo*. Madrid.
- Murcia Hernandez, A. (2019). Instalación fotovoltaica para autoconsumo de una vivienda familiar. Valencia.

---

Nations, U. (s.f.). *Sustainable Development Goals*. Obtenido de <https://sdgs.un.org/es/goals>

Perez Garcia, J. (2019). Análisis de una instalación fotovoltaica para autoconsumo en una PIME. Valladolid.

Rocha, A. (2022). *MPV Solar Reference*. Obtenido de ¿Qué tipos de inversor fotovoltaico existen? : <https://www.mpvsolarreference.com/post/qué-tipos-de-inversor-fotovoltaico-existen>

Solargis. (s.f.). Obtenido de <https://solargis.com/es/maps-and-gis-data/tech-specs>

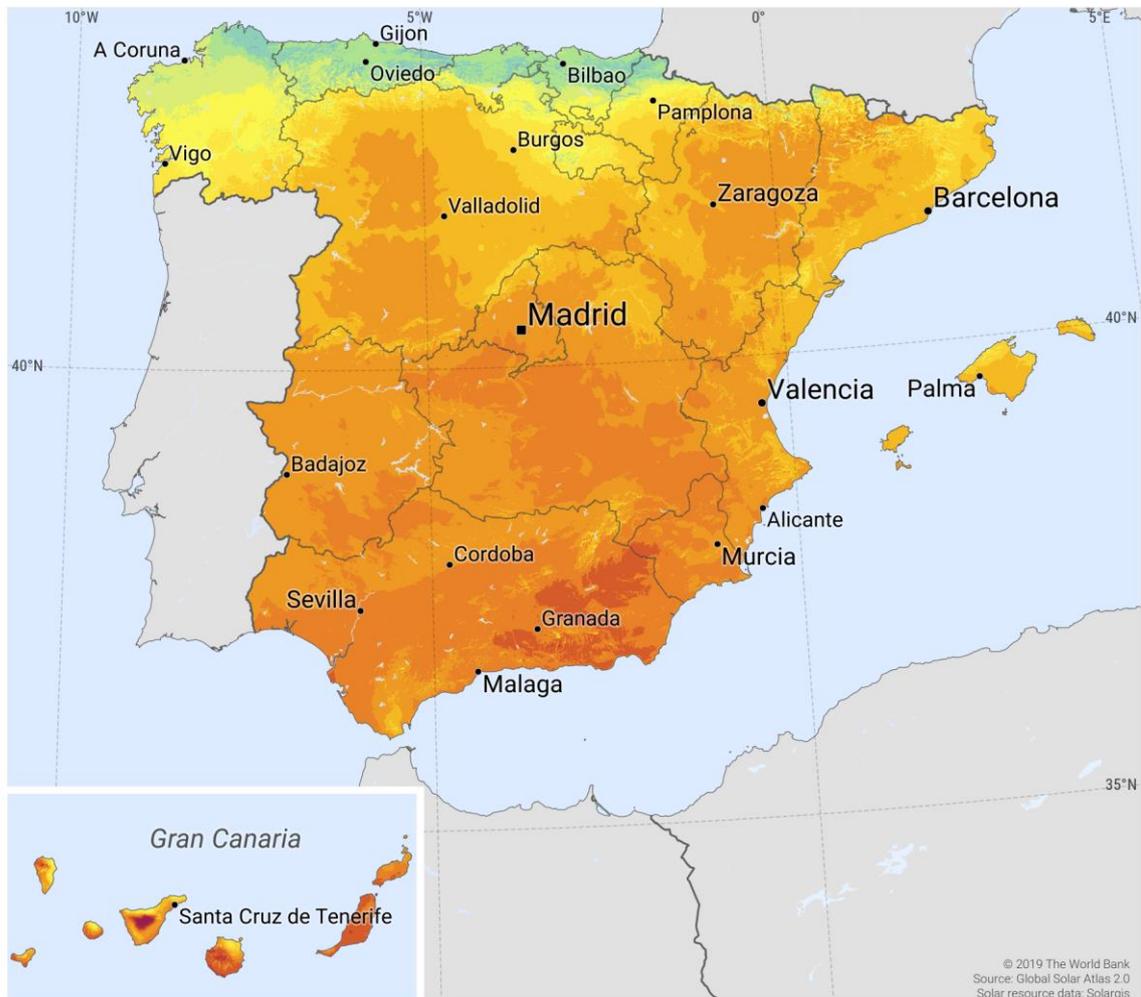
UNEF. (2023). Obtenido de Photovoltaic self-consumption installed in Spain grew 108% over 2021: <https://www.unef.es/es/comunicacion/comunicacion-post/el-autoconsumo-fotovoltaico-instalado-en-espana-crecio-un-108-respecto-a-2021>

# ANNEX I. PHOTOVOLTAIC POWER POTENTIAL (PVOUT)

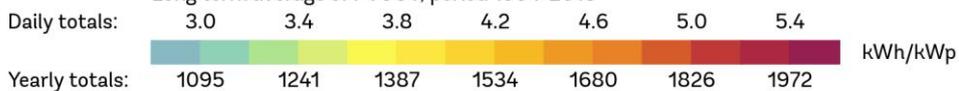
SOLAR RESOURCE MAP

## PHOTOVOLTAIC POWER POTENTIAL

### SPAIN



Long term average of PVOUT, period 1994-2018



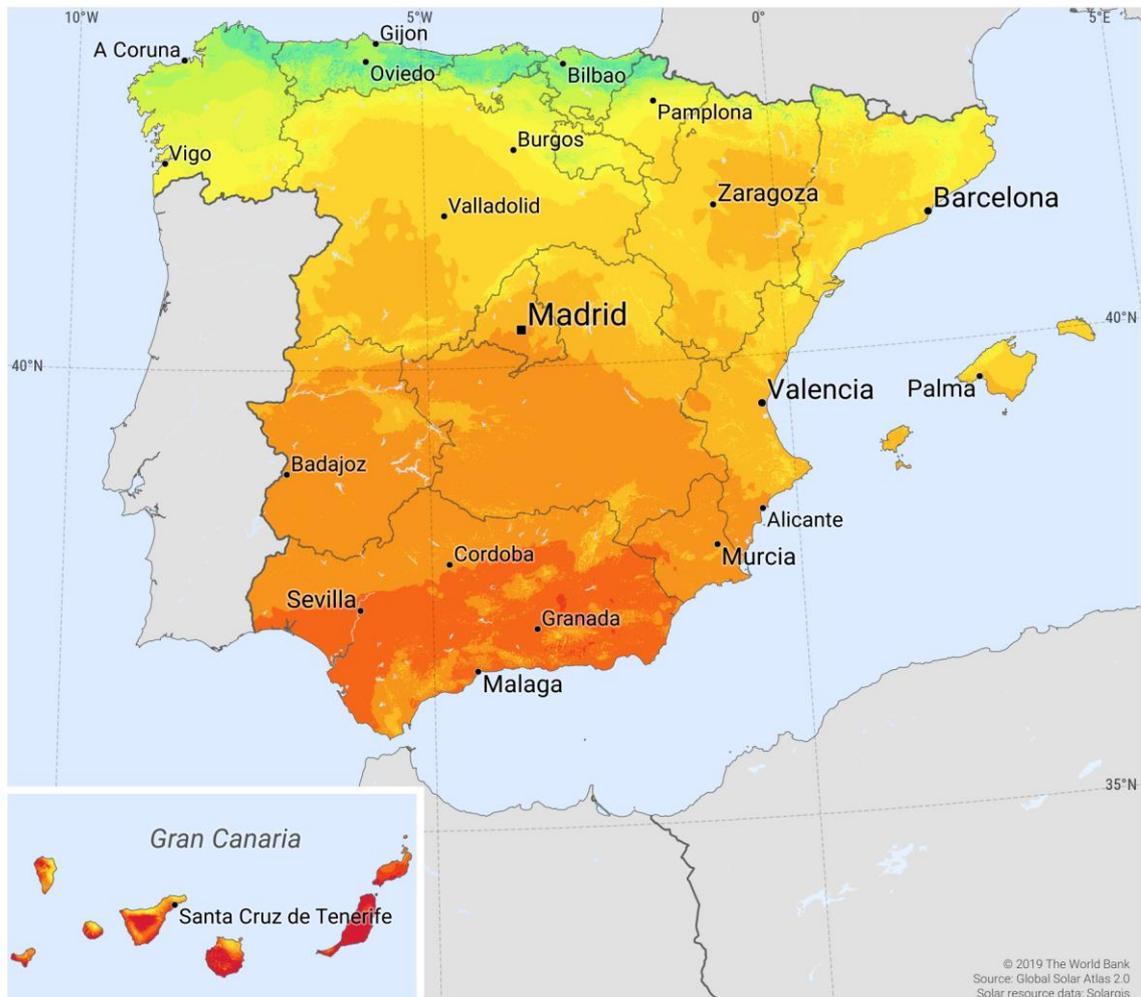
This map is published by the World Bank Group, funded by ESMAP, and prepared by Solargis. For more information and terms of use, please visit <http://globalsolaratlas.info>.

# ANNEX II. GLOBAL HORIZONTAL IRRADIATION (GHI)

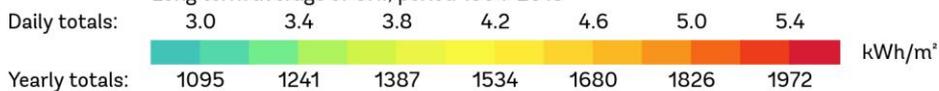
SOLAR RESOURCE MAP

## GLOBAL HORIZONTAL IRRADIATION

### SPAIN



Long term average of GHI, period 1994-2018



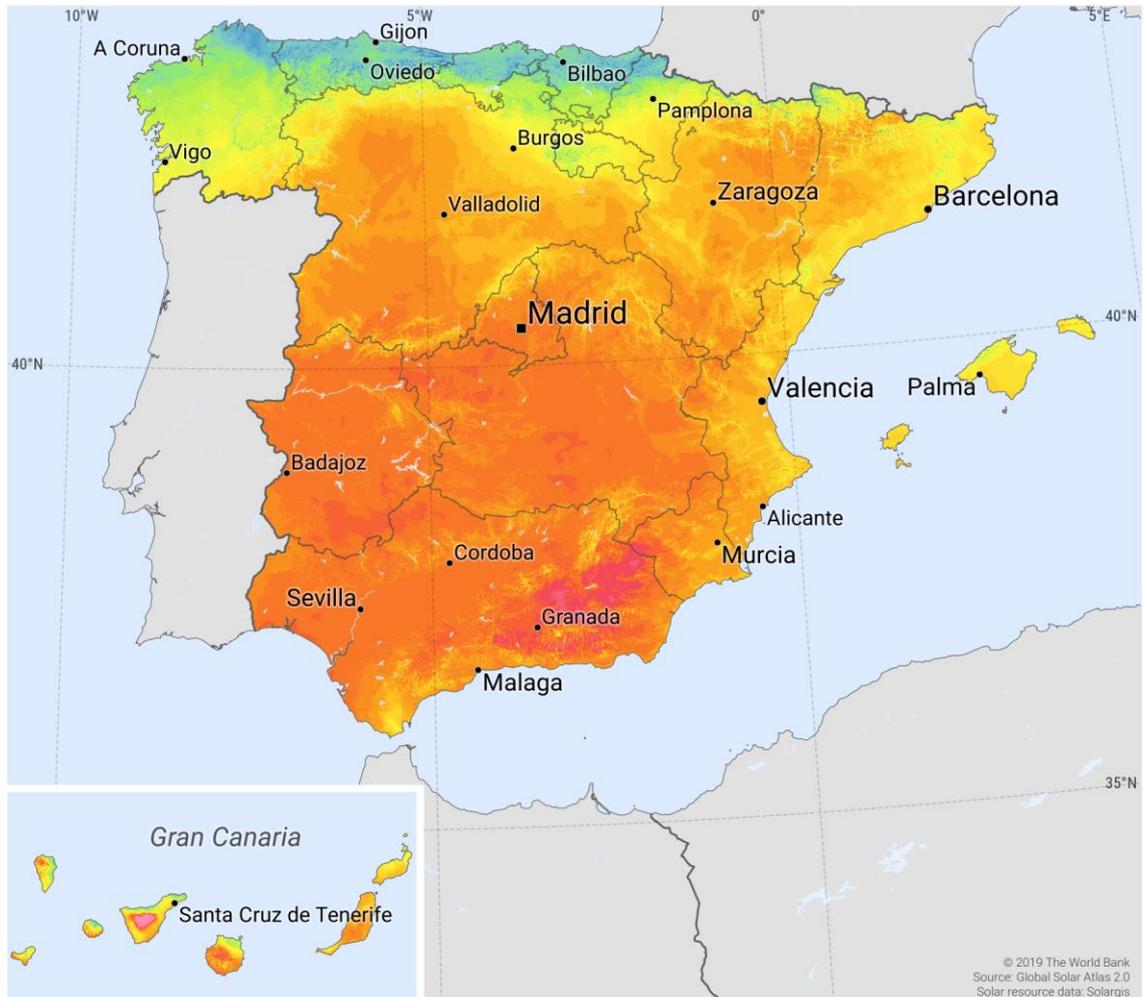
This map is published by the World Bank Group, funded by ESMAP, and prepared by Solargis. For more information and terms of use, please visit <http://globalsolaratlas.info>.

## ANNEX III. DIRECT NORMAL IRRADIATION (DNI)

SOLAR RESOURCE MAP

### DIRECT NORMAL IRRADIATION

### SPAIN



Long term average of DNI, period 1994-2018

Daily totals: 2.0 2.4 2.8 3.2 3.6 4.0 4.4 4.8 5.2 5.6 6.0 6.4 6.8

 kWh/m<sup>2</sup>

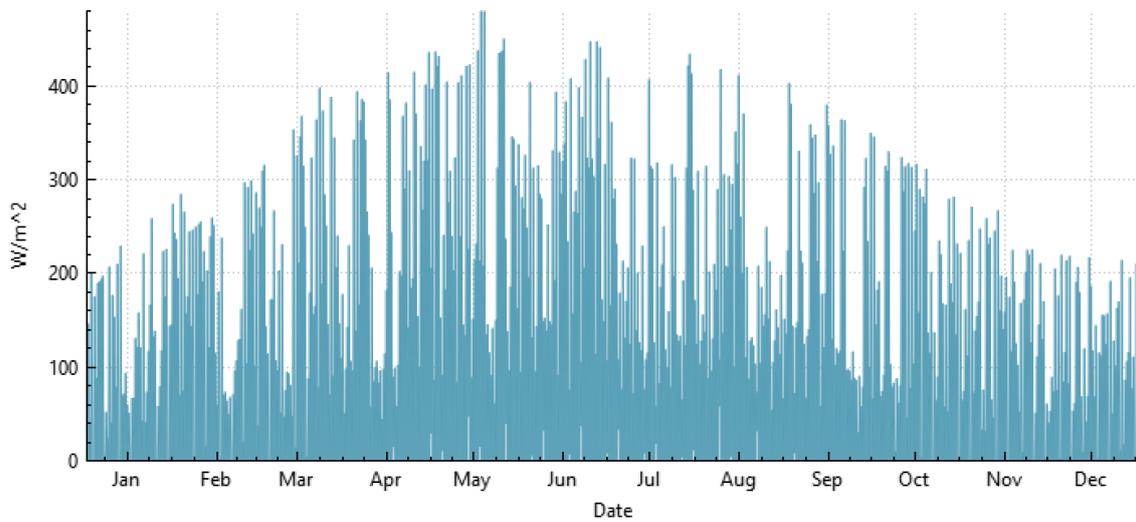
Yearly totals: 730 876 1022 1168 1314 1461 1607 1753 1899 2045 2191 2337 2483

This map is published by the World Bank Group, funded by ESMAP, and prepared by Solargis. For more information and terms of use, please visit <http://globalsolaratlas.info>.

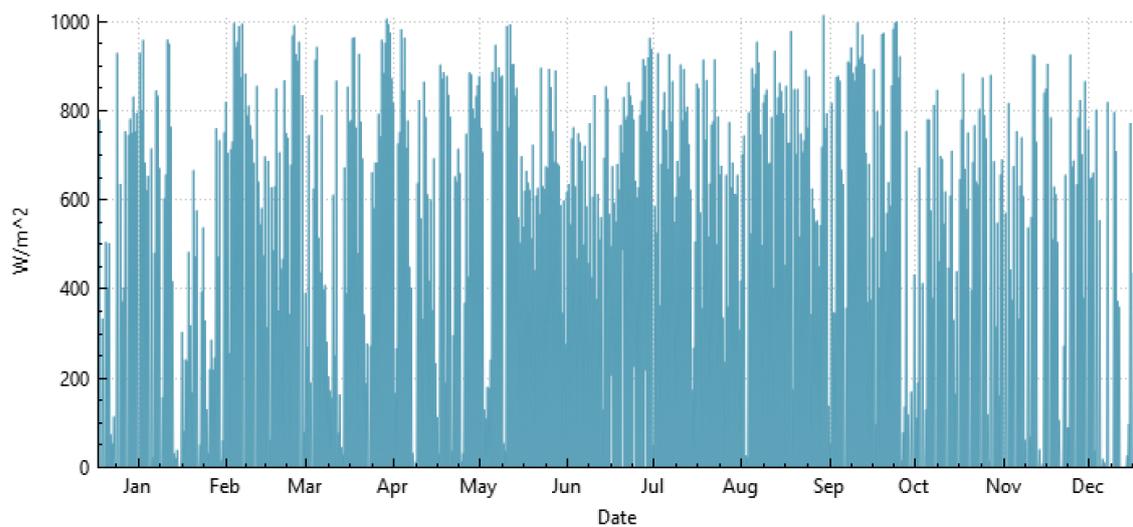
# ANNEX IV. PHOTOVOLTAIC PARAMETERS FOR IIT

BY PSS®DE

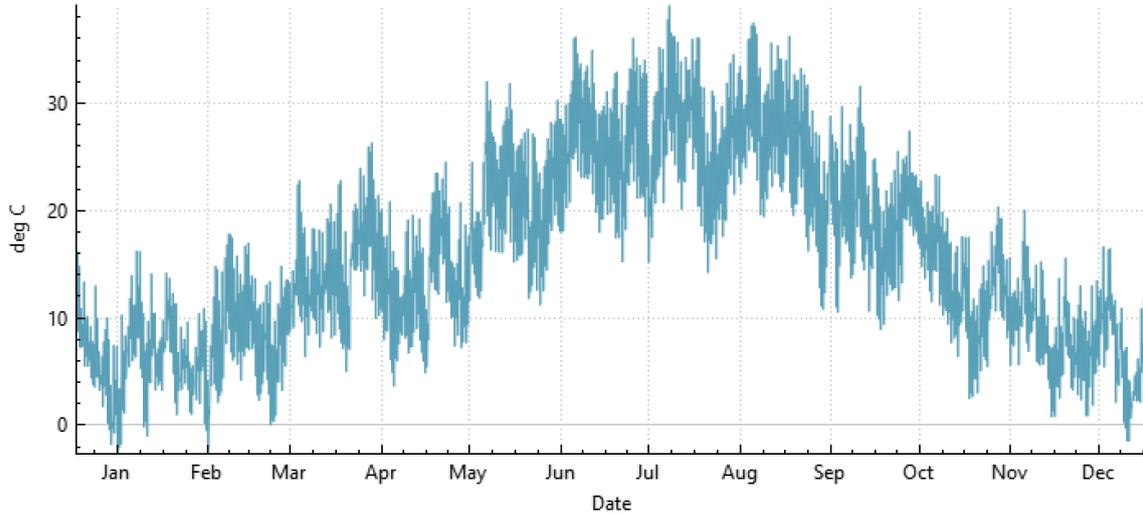
[40.429800 N, 3.712970 W] Diffuse radiation (hr) (unit: W/m<sup>2</sup>)



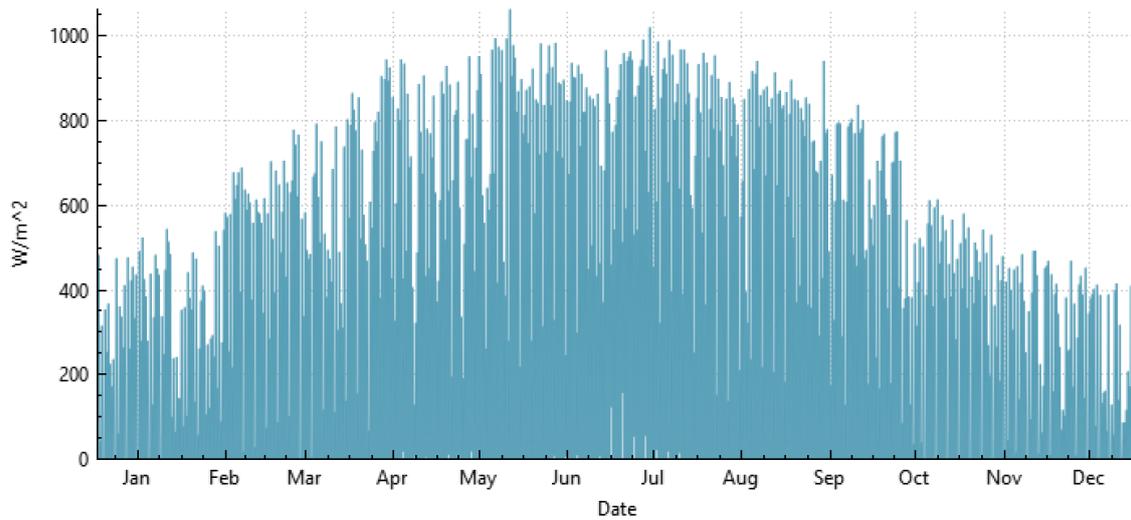
[40.429800 N, 3.712970 W] Direct radiation (hr) (unit: W/m<sup>2</sup>)



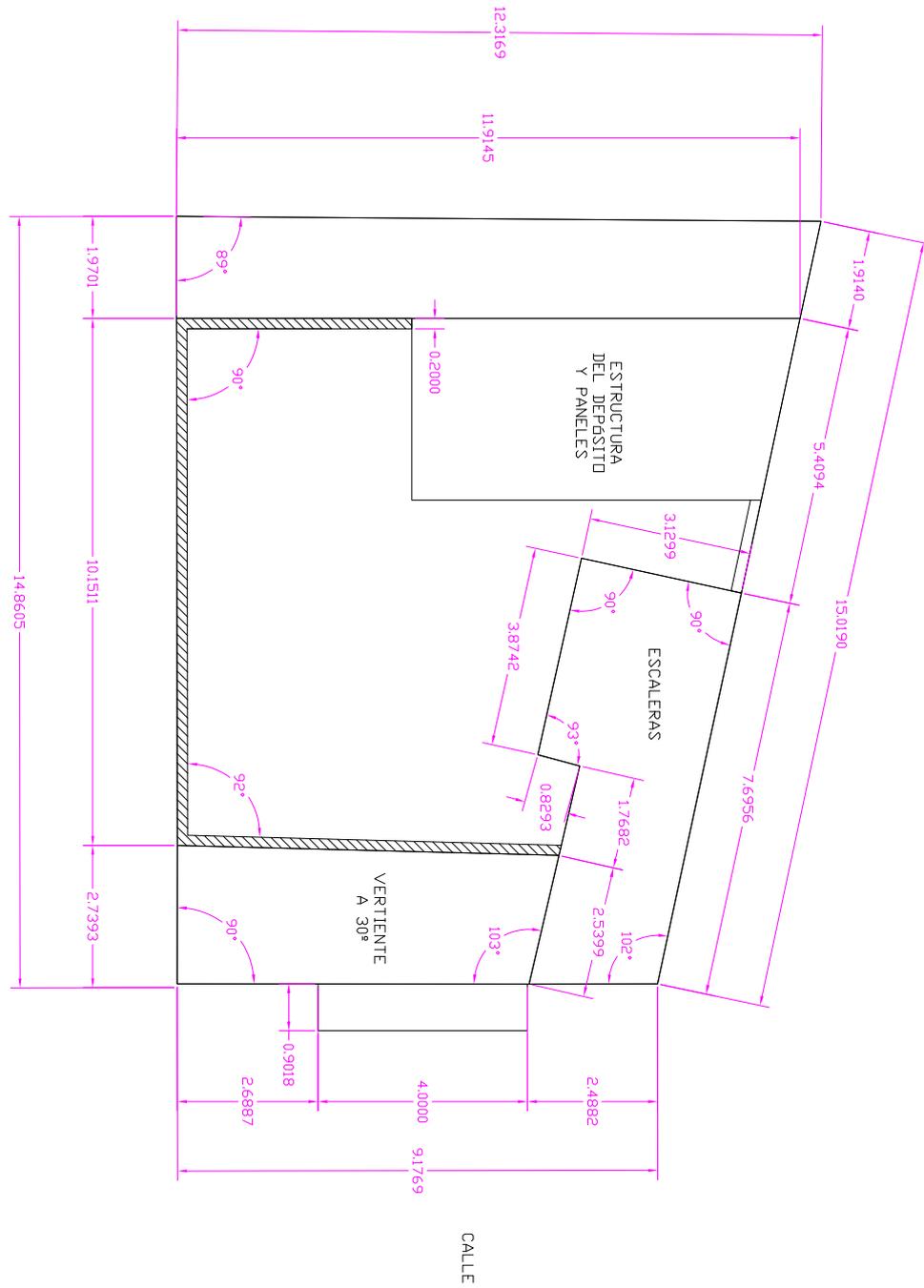
[40.429800 N, 3.712970 W] Ambient temperature (hr) (unit: deg C)



[40.429800 N, 3.712970 W] Global Horizontal Irradiation (hr) (unit: W/m^2)

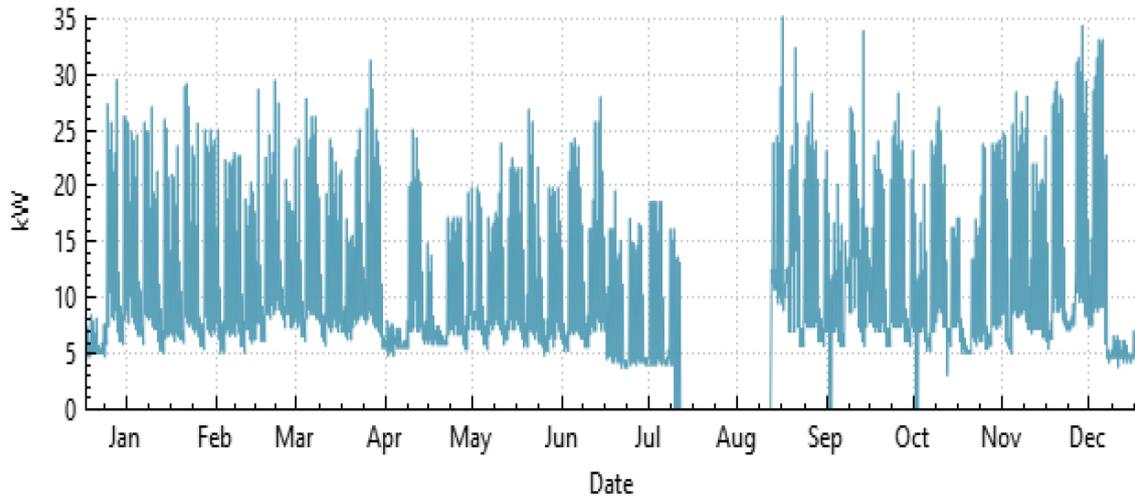


## ANNEX V. DIMENSIONED PLAN OF THE IIT ROOF



## ANNEX VI. ELECTRIC LOAD FOR IIT BY PSS®DE

ElectricLoadIIT2022 (unit: kW)



ElectricLoadIIT2022 (unit: kW)

