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MASTER’S DEGREE IN INDUSTRIAL ENGINEERING

MASTER’S THESIS

CO_2 LIFE CYCLE ASSESSMENT FOR A SOLAR PHOTOVOLTAIC INSTALLATION

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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Academic year 2022/23 is of my authorship, original and unpublished and

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Authorized the delivery of the project

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José Pablo Chaves Ávila

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I would like to thank my family and friends for their help and understanding throughout the completion of this thesis. Especially to those who have shared this year with me in Raleigh, North Carolina. Thank you for putting up with me and supporting me through this journey and bringing out the best in me this year.

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I am deeply grateful to this work for giving me the opportunity to collaborate to improve society and I hope it will be of great use for future studies on this subject.

EVALUACIÓN DEL CICLO DE VIDA DEL CO_2 DE UNA INSTALACIÓN SOLAR FOTOVOLTAICA

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Entidad Colaboradora: ICAI – Universidad Pontificia Comillas

RESUMEN DEL PROYECTO

Este proyecto consiste en el desarrollo de un modelo para la evaluación de las emisiones generadas en la fabricación y desmantelamiento de los paneles PV. Se realiza una aplicación a los paneles situados en la cubierta del edificio de la Universidad Pontificia Comillas que se encuentran en Santa Cruz de Marcenado, definiéndose las emisiones para los escenarios 2022, 2023, 2030 y 2050 en función de su tecnología, tipología y país de fabricación. El modelo permite estudiar todos los posibles escenarios variando los parámetros de entrada. Los resultados obtenidos muestran que, para dichos paneles situados en Madrid, lo óptimo será:

- En 2023: Fabricar paneles de PSC en Canadá.
- En 2030: Fabricar paneles de PSC en España.
- En 2050: Fabricar paneles de cualquier tecnología en España o Alemania.

Palabras clave: Tecnología optima, análisis del ciclo de vida, emisiones CO2, instalaciones fotovoltaicas, balance medioambiental.

1. Introducción

La Universidad Pontificia Comillas está comprometida con la sostenibilidad medioambiental, en línea con el Plan Estratégico 2019-2023 establecido por el Gobierno de España (Universidad Pontificia Comillas, 2019). Además, la Universidad Pontificia Comillas sigue las líneas marcadas por el Papa Francisco en su propuesta de "ecología industrial" (Universidad Pontificia Comillas, 2020).

Dada la importancia de la generación de emisiones según el Pacto Verde Europeo (Comisión Europea, 2019), este trabajo estudia las emisiones generadas al producir y desmontar paneles fotovoltaicos con el fin de encontrar la tecnología, tipología y país de fabricación óptimos para reducir estas emisiones.

2. Definición del proyecto

El trabajo consiste en el desarrollo de un modelo original para el análisis de las emisiones generadas en la fabricación y desmantelamiento de un panel fotovoltaico. Aunque el modelo propuesto es aplicable a cualquier sistema, en este trabajo se analiza el caso específico de la instalación de Santa Cruz de Marcenado. Además, se incluyen la propuesta óptima para los escenarios propuestos: 2023, 2030 y 2050.

El estudio parte del análisis de la energía requerida considerando cada tipo de instalación y para cada tecnología. Posteriormente se realiza una estimación lineal de las emisiones en los distintos países de estudio para poder analizar los escenarios. Con esta información se consiguen las emisiones generadas durante los procesos de fabricación y desmantelamiento, las cuales se estudian para los actuales paneles ya instalados y los que se prevén instalar. El trabajo finaliza con la presentación de los resultados obtenidos, así como un conjunto de conclusiones y unas posibles líneas de desarrollo futuro.

3. Descripción del modelo/sistema/herramienta

La metodología propuesta consiste en simular para las posibles variables de entrada, las emisiones generadas por el sistema. El proceso se muestra en la Figura 1.

En primer lugar, se elige el tipo de instalación: fija, de un eje o de dos ejes. En segundo lugar, se selecciona el tipo de tecnología: Mono-Si, Poli-Si, Ribbon-Si, CdTe, a-Si, CIGS, Orgánica, HCPV, PSC o QD. Una vez conocidos el tipo y la tecnología, es importante conocer el país de fabricación e instalación. Como se explicará en apartados posteriores, entre los países de estudio del modelo se encuentran: China, España, Alemania, Italia, Estados Unidos y Canadá.

Seleccionados todos los parámetros, el modelo predice las emisiones generadas durante la fabricación y el desmantelamiento para los años 2022, 2023, 2030 y 2050. Con estos datos se obtiene un diagrama que muestra la evolución de las emisiones a lo largo de los años. A su vez, el modelo genera un gráfico circular que muestra el porcentaje de uso de las emisiones en 2022.

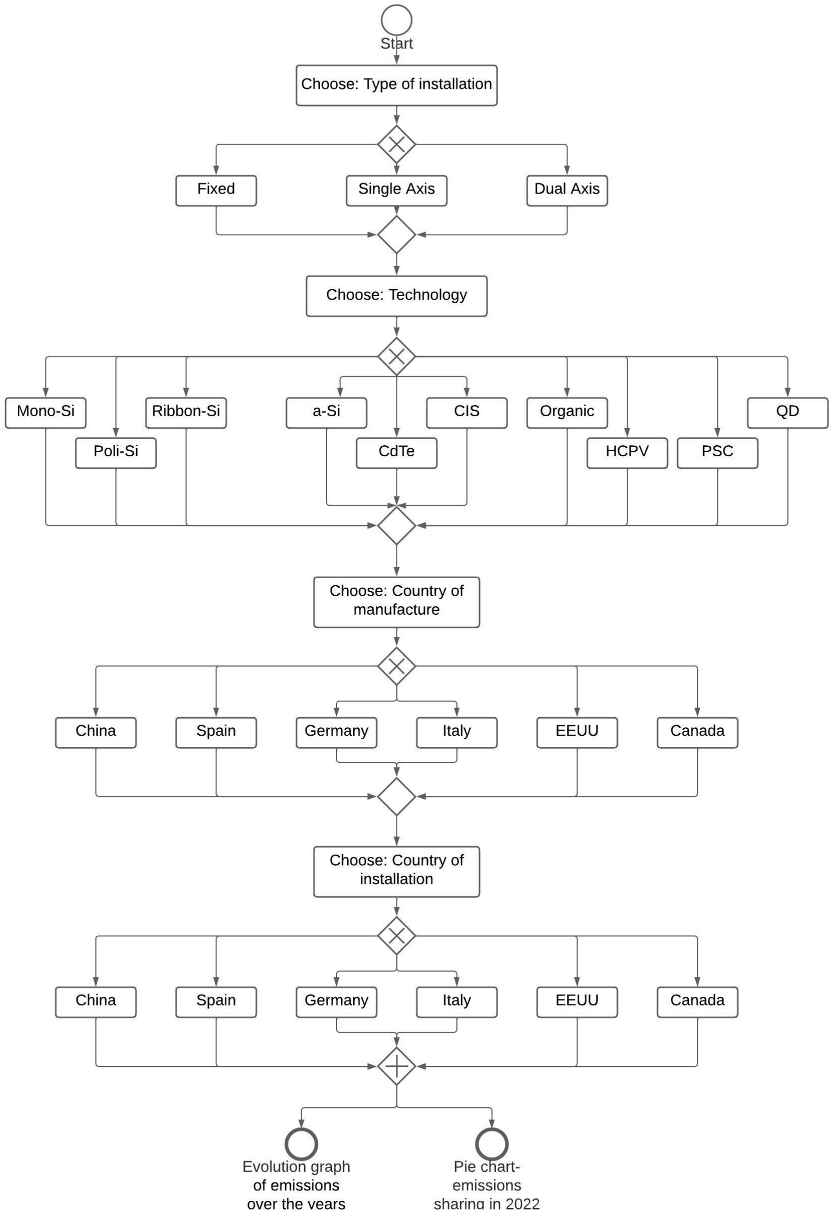

Figura 1. Diagrama de flujo del Proyecto

4. Resultados

Los resultados de los escenarios se muestran en las siguientes tablas: Tabla 1, Tabla 2 y Tabla 3. En ellas se encuentra para la situación de los paneles actuales, los paneles propuestos y los paneles óptimos, las emisiones de CO_2 asociadas a la fabricación, el desmantelamiento y las totales, así como el porcentaje de emisiones evitadas en los tres escenarios: 2023, 2030 y 2050.

	Current Situation	**Future Situation**	**Optimal Situation**
Technology:	Mono-Si	Mono-Si	PSC

Country of manufacture:	China	EEUU	Canada
Manufacturing: CO2 Emissions (kg CO2/kWp)	713,17	466,87	36,13
Dismantling: CO2 Emissions (kg CO2/kWp)	33,74	33,74	7,08
Total CO2 Emissions (kg CO2/kWp)	746,91	500,61	43,21
% of avoided emissions	0%	33%	94%

Tabla 1. Resumen de resultados para el escenario de 2023

	Current Situation	Future Situation	Optimal Situation
Technology:	Mono-Si	Mono-Si	PSC
Country of manufacture:	China	EEUU	Spain
Manufacturing: CO2 Emissions (kg CO2/kWp)	630,42	348,61	20,78
Dismantling: CO2 Emissions (kg CO2/kWp)	12,33	12,33	2,59
Total CO2 Emissions (kg CO2/kWp)	642,75	360,94	23,36
% of avoided emissions	0%	44%	96%

Tabla 2. Resumen de resultados para el escenario de 2030

	Current Situation	Future Situation	Optimal Situation
Technology:	Mono-Si	Mono-Si	All
Country of manufacture:	China	EEUU	Spain/ Germany
Manufacturing: CO2 Emissions (kg CO2/kWp)	393,99	10,71012024	0,00
Dismantling: CO2 Emissions (kg CO2/kWp)	0,00	0,00	0,00
Total CO2 Emissions (kg CO2/kWp)	393,99	10,71	0,00
% of avoided emissions	0%	97%	100%

Tabla 3. Resumen de resultados para el escenario de 2050

5. Conclusiones

Con este trabajo se comprueba que es posible conseguir de cara a 2050 una instalación fotovoltaica con emisiones nulas en el proceso de fabricación y desmantelamiento. A su vez el modelo asegura que con la nueva instalación de paneles fotovoltaicos en el tejado del edificio del IIT de Santa Cruz de Marcenado se reducen las emisiones un 33% en 2023, un 44% en 2030 y un 97% en 2050.

A sí mismo, se puede concluir que la tecnología óptima para reducir la generación de emisiones es la perovskita y la configuración óptima es la de ejes fijos. En cuanto al país de generación para 2023 el país óptimo es Canadá, que produce un 78% menos de emisiones que China, para 2030 el país óptimo es España, que produce un 86% menos de emisiones que China, para 2050 el país óptimo es España o Alemania, que producen un 100% menos de emisiones que China, ya que según el Pacto Verde Europeo las emisiones se verán reducidas a 0 g CO_2/kWh (European Commission, 2019).

De esta manera este proyecto contribuirá a cinco de los objetivos de desarrollo sostenibles como son el 7, "Energía asequible y no contaminante", el 12 "Producción y consumo responsable", el 13 "Acción por el clima", el 15 "Vida de ecosistemas terrestres" y el 17 "Alianzas para lograr los objetivos".

CO_2 LIFE CYCLE ASSESSMENT FOR A SOLAR PHOTOVOLTAIC INSTALLATION

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Supervisor: Chaves Ávila, José Pablo

Collaborating Entity: ICAI – Universidad Pontificia Comillas

ABSTRACT

This project consists of the development of a model for the evaluation of the emissions generated in the manufacture and dismantling of PV panels. It is applied to the panels located on the roof of the Comillas Pontifical University building in Santa Cruz de Marcenado, defining the emissions for the 2022, 2023, 2030 and 2050 scenarios according to their technology, type, country of manufacture and country of installation. The model allows all possible scenarios to be studied by varying the input parameters. The results obtained show that, for these panels located in Madrid, the optimum will be:

- In 2023: Manufacture PSC panels in Canada.
- In 2030: Manufacture PSC panels in Spain.
- In 2050: Manufacture panels of any technology in Spain or Germany.

Keywords: Optimal technology, life cycle analysis, CO2 emissions, photovoltaic installations, environmental balance.

1. Introduction

Comillas Pontifical University is committed to environmental sustainability, in line with the 2019-2023 Strategic Plan established by the Spanish Government (Universidad Pontificia Comillas, 2019). Furthermore, Comillas Pontifical University follows the lines set out by Pope Francis in his proposal of "industrial ecology" (Universidad Pontificia Comillas, 2020).

Given the importance of emissions generation according to the European Green Deal (European Commission, 2019), this work studies the emissions generated when producing and dismantling photovoltaic panels in order to find the optimal technology, typology and country of manufacture to reduce these emissions.

2. Project definition

The work consists of the development of an original model for the analysis of the emissions generated in the manufacture and dismantling of a PV panel. Although the proposed model is applicable to any system, this work analyses the specific case of the Santa Cruz de Marcenado facility. In addition, the optimal proposal is included for the proposed scenarios: 2023, 2030 and 2050.

The study starts with an analysis of the energy required considering each type of installation and for each technology. Subsequently, a linear estimation of emissions in the different countries under study is made in order to be able to analyze the scenarios. With this information, the emissions generated during the manufacturing and dismantling processes are obtained, which are studied for the current panels already installed and those that are planned to be installed. The work ends with the presentation of the results obtained, as well as a set of conclusions and possible lines of future development.

3. Model's description

The proposed methodology consists of simulating the emissions generated by the system for the possible input variables. The process is shown in Figure 1.

Firstly, the type of installation is chosen: fixed, single-axis or dual-axis. Secondly, the type of technology is selected: Mono-Si, Poly-Si, Ribbon-Si, CdTe, a-Si, CIGS, Organic, HCPV, PSC or QD. Once the type and technology are known, it is important to know the country of manufacture and installation. As will be explained in later sections, the model study countries include: China, Spain, Germany, Italy, United States and Canada.

Once all the parameters have been selected, the model predicts the emissions generated during manufacture and decommissioning for the years 2022, 2023, 2030 and 2050. This data is used to produce a diagram showing the evolution of emissions over the years. In turn, the model generates a pie chart showing the percentage of emissions use in 2022.

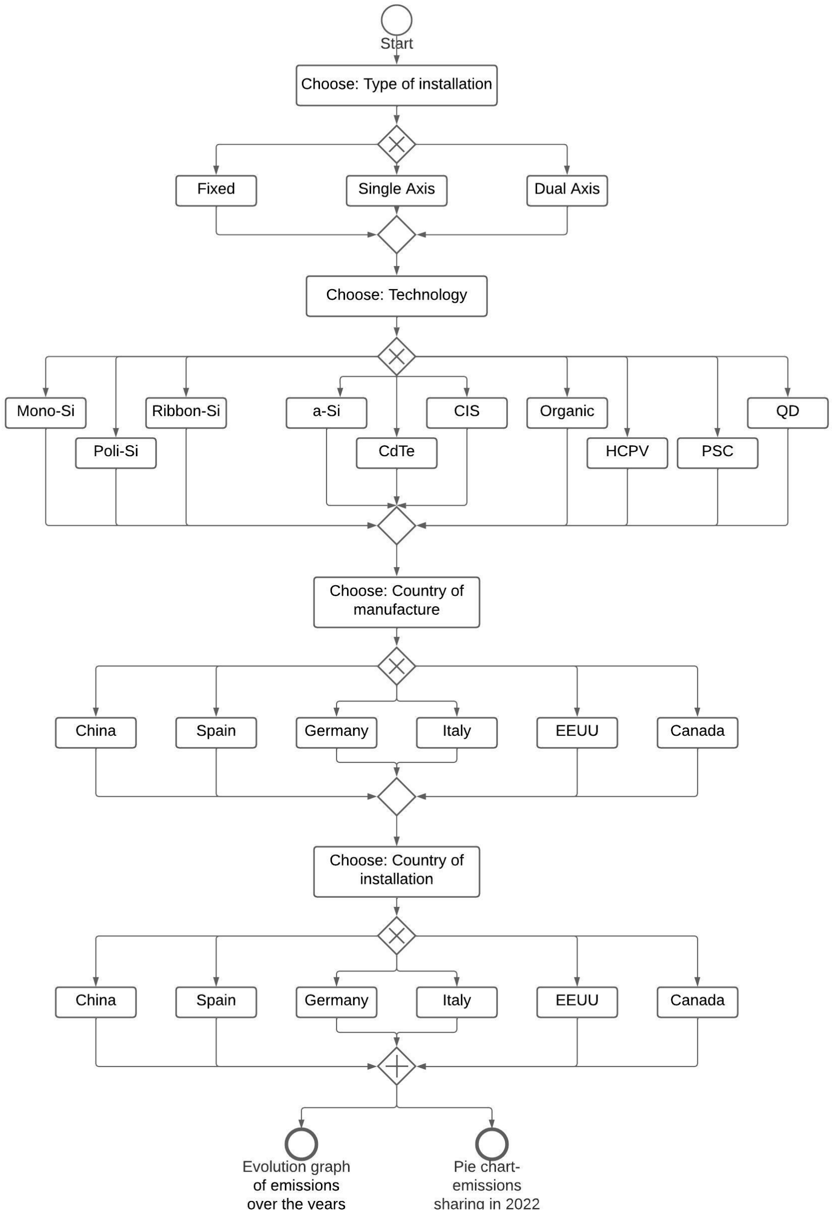

Figure1. Flow Diagram of the project

4. Results

The results of the scenarios are shown in the following tables: Table 1, Table 2 and Table 3. They show the CO2 emissions associated with manufacturing, decommissioning and total emissions, as well as the percentage of emissions avoided in the three scenarios: 2023, 2030 and 2050, for the current panel situation, the proposed panels, and the optimal panels.

	Current Situation	**Future Situation**	**Optimal Situation**
Technology:	Mono-Si	Mono-Si	PSC

Country of manufacture:	China	EEUU	Canada
Manufacturing: CO2 Emissions (kg CO2/kWp)	713,17	466,87	36,13
Dismantling: CO2 Emissions (kg CO2/kWp)	33,74	33,74	7,08
Total CO2 Emissions (kg CO2/kWp)	746,91	500,61	43,21
% of avoided emissions	0%	33%	94%

Table 1. Summary of results for the 2023 scenario

	Current Situation	**Future Situation**	**Optimal Situation**
Technology:	Mono-Si	Mono-Si	PSC
Country of manufacture:	China	EEUU	Spain
Manufacturing: CO2 Emissions (kg CO2/kWp)	630,42	348,61	20,78
Dismantling: CO2 Emissions (kg CO2/kWp)	12,33	12,33	2,59
Total CO2 Emissions (kg CO2/kWp)	642,75	360,94	23,36
% of avoided emissions	0%	44%	96%

Table 2. Summary of results for the 2030 scenario

	Current Situation	**Future Situation**	**Optimal Situation**
Technology:	Mono-Si	Mono-Si	All
Country of manufacture:	China	EEUU	Spain/ Germany
Manufacturing: CO2 Emissions (kg CO2/kWp)	393,99	10,71012024	0,00
Dismantling: CO2 Emissions (kg CO2/kWp)	0,00	0,00	0,00
Total CO2 Emissions (kg CO2/kWp)	393,99	10,71	0,00
% of avoided emissions	0%	97%	100%

Table 3. Summary of results for the 2050 scenario

5. Conclusions

This work proves that it is possible to achieve a photovoltaic installation with zero emissions in the manufacturing and dismantling process by 2050. In turn, the model ensures that with the new installation of photovoltaic panels on the roof of the IIT building in Santa Cruz de Marcenado, emissions will be reduced by 33% in 2023, 44% in 2030 and 97% in 2050.

At the same time, it can be concluded that the optimal technology to reduce emissions generation is perovskite and the optimal configuration is fixed axis. Regarding the country of generation for 2023 the optimal country is Canada, which produces 78% less emissions than China, for 2030 the optimal country is Spain, which produces 86% less emissions than China, for 2050 the optimal country is Spain or Germany, which produce 100% less emissions than China, since according to the European Green Pact emissions will be reduced to 0 g CO_2/kWh (European Commission, 2019).

In this way this project will contribute to five of the Sustainable Development Goals such as 7 "Affordable and Clean Energy", 12 "Responsible Consumption and Production", 13 "Climate Action", 15 "Life on Land" and 17 "Partnerships for the Goals".

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Abbreviations

PV: Photovoltaic systems

Si: Silicon

mono-Si: Monocrystalline silicon

poly-Si: Polycrystalline silicon

a-Si: Amorphous silicon

Ribbon-Si: Silicon ribbon panels

CdTe: Cadmium Telluride

CIS: Copper indium selenium panels

CIGS: Copper Indium Indium Gallium Selenide (CIS) panels

OPV: Organic Photovoltaic Panels

HCPV:

PSC: Perovskite solar cells

QD: Quantum dot cells

RtR: Roll-to-roll

SC: Spray coating

VD: Vapor deposition

1. INTRODUCTION

1.1. MOTIVATION

Photovoltaic (PV) power generation has gradually become one of the fastest developing forms of green energy generation due to its sufficient resource reserves and environmentally friendly method of power generation.

Unlike fossil fuels, solar panels produce no emissions while generating energy, which is why they are such an important component of the clean energy transition.

However, the production steps leading up to solar power generation do cause emissions, from the mining of metals and rare earth minerals to the process of producing the panels and transporting the raw materials and finished panels.

Solar panels require a complex manufacturing process that involves the use of chemicals, heat, and electricity to produce photovoltaic cells made of silicon, a material that melts at 1,414°C. This process releases several pollutants into the atmosphere such as nitrogen oxides (NOx), Sulphur dioxide (SO2), carbon monoxide (CO), volatile organic compounds (VOCs) and particulate matter (PM). In addition to silicon, solar panels use rare earths and precious metals such as silver, copper, indium, tellurium and, for solar battery storage, lithium.

The extraction of all these substances produces greenhouse gas emissions and can pollute air, soil and water. Although there have been technological improvements that have reduced these emissions over time, they remain a concern. (Pescador, 2022).

Taking this into account, on average, during the first years of operation of these panels, the equivalent of about 50 g of CO2 per kilowatt-hour is produced. This is 20 times less than the emissions per kilowatt-hour of coal.

The panels need to be in operation for at least three years to offset their carbon footprint, which is not a problem since their lifetime is more than 20 years.

The European Green Deal has set a target for the EU to reduce its greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels and to achieve climate neutrality by 2050. To achieve these targets, EU Member States must take concrete action to reduce emissions and decarbonize the economy. To make the green transition a reality, new rules are needed, and existing EU legislation needs to be updated.

1.2. PURPOSE OF THE PROJECT

Comillas Pontifical University is committed to environmental sustainability, in line with the 2019-2023 Strategic Plan established by the Spanish Government (Universidad Pontificia Comillas, 2019). Furthermore, Comillas Pontifical University follows the lines set out by Pope Francis in his proposal of "industrial ecology"(Universidad Pontificia Comillas, 2020).

To carry out the reduction of its emissions, 352 photovoltaic panels were installed in the first instance at the Cantoblanco headquarters in Madrid. The second phase of this commitment to the environment took place in the summer of 2019, when photovoltaic panels were installed at ICAI. This resulted in savings of almost 200,000 kWh per year and a reduction of up to 69 tones of CO2. Over the years, the performance of the panels needs to be reviewed to provide an optimal solution.

Given the importance of the European Green Pact to reduce emissions (European Commission, 2019), it is useful to study a model comparing the different technologies, typologies, country of manufacture and country of decommissioning in order to study emissions. This model will allow to deduce the country of manufacture and the optimal technology to reduce emissions.

In this sense, the following research questions can be posed:

1. Which PV plant technology produces the lowest unit emissions (kg CO_2/kWp)?

2. What is the configuration of the installation with the lowest environmental impact?
3. How will the place of manufacture of the components influence the emissions generated?

The aim of this master's thesis is to answer these questions by designing an emissions model that takes into account the technology, typology, country of manufacture and country of installation. From this model, it will not only be possible to study the case studies of the photovoltaic panels located in Santa Cruz de Marcenado, owned by the IIT, but also to consider the emissions of other sites in the rest of the world and over the years.

1.3. STRUCTURE OF THE PROJECT

The structure of the project is as follows:

- Chapter 1: Introduction
- Chapter 2: State of art
- Chapter 3: Methodology
- Chapter 4: Typologies and Technologies of PV Installations
- Chapter 5: Emissions Analysis
- Chapter 6: Case Studies
- Chapter 7: Results
- Chapter 8: Conclusions
- Bibliography
- Annex

Chapter 2 (State of the art) presents a summary of the articles studied for the development of the work. This chapter is divided into plant life cycle analysis, Different types of photovoltaic technology and Typology of installations depending on their assembly.

Subsequently, in Chapter 3 (Methodology) an overview of the project is presented, showing the methodology and structure for easier understanding. It is commented that the methodology to be followed is the one proposed by the ISO 14040 standard, Life Cycle

Analysis of photovoltaic panels. Furthermore, the concept of LCA is explained, as well as process that will be followed through the project.

In Chapter 4 (Typologies and Technologies of PV Installations) the difference between all the installations, such as grounded-mounted and rooftop, are explain. Moreover, the differences in the BOS are developed in this section. Continuedly, the three generations of technology of photovoltaic modules are explained, as well as, compered and contrasted.

In Chapter 5 (Emissions Analysis), the study of the quantification of emissions will be carried out. In order to study the abovementioned, we first summarize the energy required by technology and typology for 1 kWp of installed power. Once this information is available, the emissions generated by each country to generate 1 MWh will be studied. Finally, we obtain the emissions in kg of CO_2/kWp.

During Chapter 6 (Case Studies), we discuss the two-case study. Firstly, applied to the actual photovoltaic panels in Santa Cruz de Marcenado 26, Madrid, Spain. Moreover, (Carbonell de la Cámara, 2023) studies in his thesis the optimal photovoltaic panels that should be installed in this sitemap from the different offers the ITT have received, so this is the second case study. It discusses the context of the panels and inverters, the applied technology and the country of manufacture and dismantling.

In Chapter 7 (Results), the results of both case studies are introduced according to the conclusions drawn in the last section. Tables and graphs show the results obtained.

Finally, in Chapter 8 (Conclusions) the questions proposed in the introduction are answered.

2. STATE OF THE ART

One of the main concerns of today's society is the problems arising from global warming. This process, which began with the Rio Summit (1992), the Kyoto Protocol (1997) and more recently with the Paris Agreement (2015), seeks the sustainable supply of all economic activities in which governments, companies and citizens must be involved.

The first sector that generates emissions (IEA, 2022) is energy, which is why it is important to design an energy system that substantially reduces these emissions.

In order to achieve sustainable energy production, it is essential to know how the energy is generated, and the emissions that are generated when manufacturing, installing and dismantling the energy source. The current state of knowledge on the environmental emissions associated with the manufacture and dismantling of PV facilities suggests that while solar panels are a clean energy source, their production and disposal can result in emissions and environmental impacts.

In terms of manufacturing, studies have shown that the production of PV facilities can result in emissions of greenhouse gases and other pollutants, particularly during the extraction of raw materials and the processing of silicon wafers. The emissions associated with manufacturing can vary depending on the technology used and typology.

The dismantling of PV facilities at the end of their expected life can also result in emissions and environmental impacts. The main concern is the disposal of toxic waste, particularly from the silicon-based photovoltaic panels. Disposal in landfills can lead to the release of toxic chemicals such as lead and cadmium. However, some efforts are being made to recycle and reuse solar panels, which can reduce the environmental impact of their disposal.

While the environmental emissions associated with the manufacture and dismantling of PV facilities are a concern, the emissions are still much lower compared to fossil fuels' emissions.

2.1. BACKGROUND

Following the line of the studies previously carried out by (Cebaqueba et al., 2019) and (Barroso Toro, 2020), this study shows the continuation of those thesis. Although these projects cover energy payback factor, greenhouse gas emissions, energy payback time and emission payback time, this study will focus on the continuation and deepening of the issue of lifetime emissions of photovoltaic technologies. This project develops a model where it is possible to observe how emissions vary depending on different parameters.

First of all, (Cebaqueba et al., 2019)in his master's thesis, covered the years from 2005 to 2018. Secondly, (Barroso Toro, 2020) covered up, in his master’s thesis, until 2020. In this study, the data provided by these two theses are reviewed in order to generate the previously discussed model that quantify the emissions generated during the manufacture and dismantling of the PV facilities. After the revision of these two works and the contribution of data from recent years, the model has data from two decades.

One of the big differences between this study and the two previously mentioned is the addition of third generation technologies such as the Perovskite Solar Cells and Quantum Dot Cells.

Furthermore, this study takes into account not only the direct emissions generated during the production and dismantling of the photovoltaic facilities, but also the indirect emissions generated during the entire life cycle of the PV systems, including the emissions generated during the production of the materials used in the PV facilities. This is a more comprehensive approach to analyzing the environmental impact of photovoltaic technologies than previous studies, which mainly focused on energy payback factor and payback time.

Another important aspect that sets this study apart from previous research is the use of a more advanced modeling technique. This study employs a dynamic model that takes into account changes in the technology, typology, and countries of manufacture and dismantling. This approach allows for a more accurate and realistic assessment of the lifetime emissions of photovoltaic technologies, as it captures the changes in the production processes, energy consumption patterns.

Finally, this study also contributes to the development of a more nuanced understanding of the environmental impact of photovoltaic technologies. While previous studies have generally treated PV technologies as a homogeneous category, this study examines the differences in the environmental impact of different types of PV technologies, such as crystalline silicon, thin-film, and multi-junction technologies. This approach allows for a more nuanced understanding of the strengths and weaknesses of different PV technologies and can help inform policy and investment decisions related to renewable energy development.

2.2. CURRENT SITUATION

The photovoltaic market has experienced enormous growth over the last few years, reaching ever higher power outputs. The European Green Deal (European Commission, 2019) is a set of policies and initiatives proposed by the European Commission to make the European Union's (EU) economy more sustainable and climate-neutral by 2050. The Green Deal includes a wide range of measures, including increasing the use of renewable energy, improving energy efficiency, and reducing greenhouse gas emissions.

Among other objectives, there has been set goals like achieving climate neutrality by 2050, cutting greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels and increasing the share of renewable energy in the EU's energy mix to at least 32% by 2030.

Moreover, the Spanish government developed a 10-year plan known as the National Integrated Energy and Climate Plan 2021–2030 (NIECP), also known by its Spanish abbreviation PNIEC, based on the guidelines of the 2030 European Energy Transition. This plan was approved by the Parliament on March 2021 with the aim of Spain becoming carbon neutral in 2050 and that in 2030 a 73% of the generated power would come from a renewable source. (Gómez-Calvet et al., 2023) states that the large increase of solar PV will surely have a positive impact in the generation of electricity from renewable sources, but it will also imply a higher dependence on backup power plants with very high ramping response as well as massive storage capacity.

In conclusion, the photovoltaic market has experienced significant growth in recent years, and there are increasing efforts to promote sustainable and climate-neutral economies globally. The European Green Deal, the Spanish National Integrated Energy and Climate Plan, and the United Nations' Sustainable Development Goals are just a few examples of the international initiatives aimed at achieving these goals. While the increase of solar PV will positively impact the generation of electricity from renewable sources, it will also require the development of backup power plants and massive storage capacity. It is important to consider the environmental impact of manufacturing and dismantling emissions of solar PV modules and promote sustainable production and consumption practices, such as recycling and reuse. The study of manufacturing and dismantling emissions of solar PV modules is relevant to several Sustainable Development Goals, including Affordable and Clean Energy, Responsible Consumption and Production, Climate Action, Life on Land, and Partnerships for the Goals. Collaboration between governments, industry, and civil society is essential to achieve sustainable and climate-neutral economies by 2050.

Nowadays, three generations of photovoltaic technology can be mentioned: 1st generation: *Crystalline Silicon (c-Si) PV cells*, 2nd generation: *Thin Film PV cells* and 3rd generation: *Multi-junction PV cells*.

According to an article by (Sarah, 2020), the first generation of solar cells, Crystalline Silicon (c-Si) PV cells, were "first developed in the 1950s and 1960s" and remain "the most widely used PV technology today." These cells are "relatively efficient," but they are also "relatively expensive to produce" because they require "high-purity silicon."

Thin film PV cells, which make up the second generation of solar cells, were "developed in the 1970s and 1980s" and are "less efficient than c-Si cells but are cheaper to produce." These cells are made of a "thin layer of semiconductor material, such as cadmium telluride or amorphous silicon, deposited on a substrate." According to an article (Todorov & Mitzi, 2013), the materials used in thin film solar cells are "less expensive and have greater flexibility, which means that more shapes and sizes can be manufactured."

Multi-junction PV cells are the third generation of solar cells and were "developed in the 1990s." These cells are made of "multiple layers of semiconductor materials, each optimized to absorb different parts of the solar spectrum." According to an article (Green et al., 2015), multi-junction cells are "the most efficient PV cells available" but are also "the most expensive to produce." However, the authors note that "the price of these cells is expected to decrease as the technology develops."

In

	Base material	**Efficiency**	**Cost**	**Environmental impact**
1G	Crystalline silicon	15-25%	↑↑	250 kg CO2/kWh
2G	Conductive materials: Cadmium Telluride or Copper Indium Gallium Selenide	10-15%	↓	75 kg CO2/kWh
3G	Perovskites and organic cells	<30%	↑↑↑	75 kg CO2/kWh

Table 1, some characteristics of the different generations are summarized.

	Base material	**Efficiency**	**Cost**	**Environmental impact**
1G	Crystalline silicon	15-25%	↑↑	250 kg CO2/kWh

2G	Conductive materials: Cadmium Telluride or Copper Indium Gallium Selenide	10-15%	↓	75 kg CO2/kWh
3G	Perovskites and organic cells	<30%	↑↑↑	75 kg CO2/kWh

Table 1. Summary of Characteristics of the three generations of PV technologies

Source: (Own Elaboration, 2023)

According to (Gorjian et al., 2022), the most widely used technology today is polycrystalline silicon, followed by monocrystalline silicon. Figure 1 shows the result of the study carried out by (Gorjian et al., 2022).

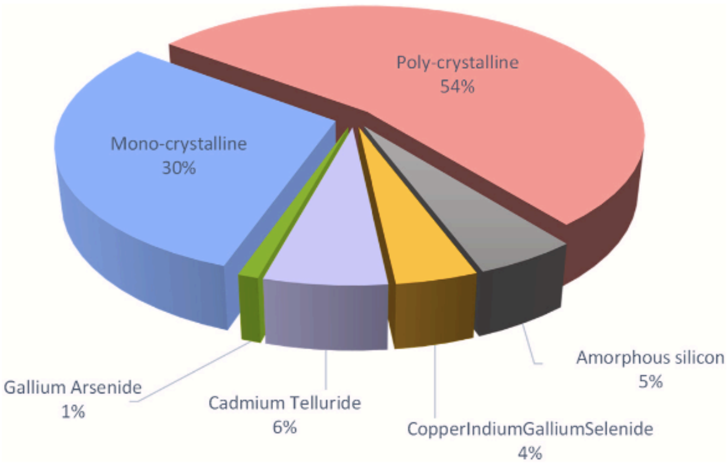


Figure 1. Global market share of the most common PV modules

Source: (Gorjian et al., 2022)

2.3. ALIGNMENT WITH THE SUSTAINABLE DEVELOPMENT GOALS

Furthermore, the United Nations' Sustainable Development Goals (SDGs) are a set of 17 goals adopted by all UN Member States 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 (Figure 2).

Several of these goals are relevant to the study of manufacturing and dismantling emissions of solar PV, including:

- Affordable and Clean Energy (SDG 7): The study of manufacturing and dismantling emissions of solar PV modules is relevant to SDG 7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all. Solar PV is a clean and renewable source of energy that can contribute to achieving this goal.
- Responsible Consumption and Production (SDG 12): The study of manufacturing and dismantling emissions of solar PV modules is also relevant to SDG 12, which aims to ensure sustainable consumption and production patterns. The environmental impacts associated with the life cycle of PV modules can be reduced by promoting sustainable production and consumption practices, such as recycling and reuse.
- Climate Action (SDG 13): The study of manufacturing and dismantling emissions of solar PV modules is relevant to SDG 13, which aims to take urgent action to combat climate change and its impacts. The use of solar PV can reduce greenhouse gas emissions and mitigate climate change.
- Life on Land (SDG 15): The study of manufacturing and dismantling emissions of solar PV modules is also relevant to SDG 15, which aims to protect, restore, and promote the sustainable use of terrestrial ecosystems. The disposal of PV modules at the end of their lifespan can have negative impacts on land, and promoting recycling and reuse can reduce these impacts.
- Partnerships for the Goals (SDG 17): The study of manufacturing and dismantling emissions of solar PV modules can also contribute to SDG 17, which aims to strengthen partnerships for sustainable development. Collaboration between governments, industry, and civil society is essential to promote sustainable

production and consumption practices and reduce the environmental impacts of solar PV.

Figure 2. Sustainable development goals

Source: (SDG,2023)

2.4. LITERATURE REVIEW

This section presents the state of the art, in which different articles and publications related to the following four blocks will be studied:

- Life cycle analysis
- Different types of photovoltaic technology and typology

2.4.1. Life cycle analysis

Life cycle analysis (LCA) is a methodology used to evaluate the environmental impact of a product over its entire life cycle, from raw material extraction to disposal. In the case of solar cells, the life cycle analysis would include the following stages: manufacture, production, and dismantling.

LCA can inform decision-making processes around the sustainable development of solar energy systems by providing a comprehensive and objective evaluation of the environmental performance of different options. It can help to identify opportunities for improvements and inform policy decisions that support the development of more sustainable solar energy systems.

(Brusca et al., 2021) compared the environmental impacts of different photovoltaic technologies, including silicon-based and thin-film solar cells, through a life cycle assessment analysis. The study found that the environmental impacts of PV technologies vary depending on the specific technology and the environmental indicators considered. For example, silicon-based solar cells have a higher impact on certain indicators like ozone depletion potential and eutrophication potential, while thin-film solar cells have a higher impact on other indicators like human toxicity potential and freshwater ecotoxicity potential. The authors also found that the environmental impacts of PV technologies are strongly influenced by the manufacturing phase, which has the highest contribution to most impact categories. The end-of-life phase, including recycling and disposal of PV panels, also has a significant impact on some environmental indicators.

The study published in the International Journal of Green Energy (Soares et al., 2018), used a Life Cycle Assessment (LCA) approach to evaluate the environmental and energy impacts of first and second-generation photovoltaic cell production. The study considered PV technologies based on silicon and CIS thin films. The study found that PV systems made with amorphous silicon had a lower environmental impact and shorter energy payback time compared to those made with crystalline silicon. PV technologies associated with mono-crystal and polycrystalline silicon were found to have a significant environmental impact and fossil fuel demand, making them eco-unfriendly. Ribbon silicon and CIS thin films showed intermediate impact scores, but further improvements are needed before commercial use. The study categorized the technologies into first and second-generation technologies and highlights the need for the development of third-generation PV cells with improved conversion efficiencies and lower environmental impacts.

Moreover, article published in Solar RRL (Shah et al., 2021) provides a review of various comparative Life Cycle Assessment (LCA) studies conducted on different PV technologies. It shows that the environmental impacts of PV technologies vary widely depending on their manufacturing processes, module efficiency, and other factors. The article compares the different studies in terms of their scope, functional units, and indicators used to evaluate environmental impacts. It highlights the need for standardized methods to compare LCAs of different PV technologies. The article also discusses the importance of considering end-of-life management for PV modules, as well as the potential for circular economy approaches in the PV industry. At last, the article provides a comprehensive review of the existing LCAs of PV technologies and emphasizes the need for further research to evaluate the environmental impacts of emerging technologies.

Also, (Suresh et al., 2021) presents a life cycle assessment and energy payback time analysis of different photovoltaic technologies, including Monocrystalline silicon (mono-Si), Polycrystalline silicon (poli-Si), thin film technologies such as Copper Indium Gallium Selenide panels (CIGS), Cadmium Telluride (CdTe), and Organic Photovoltaic (OPV). The study found that thin-film technologies have a lower environmental impact and energy payback time compared to silicon-based technologies. Among the silicon-based technologies, mono-Si showed a lower environmental impact and Energy Payback Time (EPBT) compared to poli-Si. The study also highlights the importance of improving the recycling and end-of-life management of PV modules to reduce their environmental impact.

To sum up, Life Cycle Analysis (LCA) is a methodology used to assess the environmental impact of a product from raw material extraction to disposal and is an essential tool for evaluating the sustainability of PV systems. The environmental impacts of PV technologies vary depending on the specific technology and the environmental indicators considered. For example, silicon-based solar cells have a higher impact on certain indicators like ozone depletion potential and eutrophication potential, while thin-film solar cells have a higher impact on other indicators like human toxicity potential and freshwater ecotoxicity potential. The manufacturing phase has the highest contribution to most impact categories, but end-of-life management is also important. Standardized methods are needed to compare LCAs of different PV technologies, and circular economy approaches show promise in the PV industry. Thin-film technologies have a lower environmental impact and energy payback time compared to silicon-based technologies, with mono-Si showing a lower environmental impact and energy payback time compared to poli-Si. The development of third-generation PV cells with improved conversion efficiencies and lower environmental impacts is needed, as is improving the recycling and end-of-life management of PV modules to reduce their environmental impact.

2.4.2. Different types of photovoltaic technology and typology

There have been several generations of photovoltaic modules, each with its own characteristics and performance improvements that have been mentioned before. It's worth noting that these generations of PV technology are not strictly defined and there is overlap between them. For example, some 2G PV technologies (such as CdTe PV) have achieved efficiencies that are similar to 1G PV technologies. Additionally, there are hybrid PV modules that combine different types of PV technology, such as 1G and 2G PV, in a single module.

Nowadays, the best established and most widely used PV technology is crystalline silicon, which has accounted for approximately 85% of the world's PV power generation capacity in the last decade. The importance of this technology as a low-carbon alternative for electricity production has increased markedly as environmental concerns have grown in the global environment, and this growth can also be attributed to a sharp decrease in production costs and the increasing improvement of yields in these systems (Castillo, 2019).

In Figure 3, it is shown the efficiency of different generations of PV modules. It can be seen that the first-generation technology generates a larger carbon footprint as it has a higher impact score. In turn, Soares et al. make a prediction about the third-generation technologies assuming that they will have a higher efficiency and a lower impact. (Soares et al., 2018).

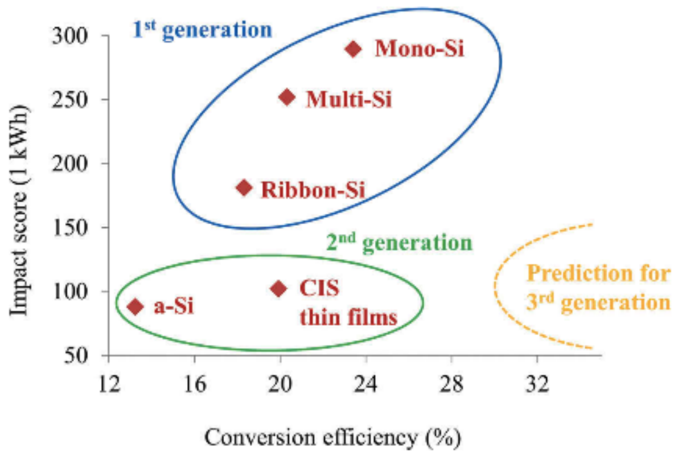


Figure 3. Impact score associated with 1 kWh of energy produced as a function of the conversion efficiency for the PV systems considered herein.

Source: (Soares et al., 2018)

Having a lower impact score in a PV context generally means that the PV technology has a lower environmental impact across its life cycle compared to other PV technologies. This can be due to a number of factors, such as lower material and energy requirements during manufacturing, lower greenhouse gas emissions during production, or higher efficiency leading to lower land use and resource consumption.

In other words, a lower impact score is generally seen as a positive attribute for a PV technology, as it indicates that it has a smaller environmental footprint than other technologies. This is an important consideration in the development of sustainable energy systems, as minimizing the environmental impact of energy generation is a key goal.

The figure mentioned, Figure 3 from (Soares et al., 2018), illustrates the impact score associated with 1 kWh of energy produced as a function of the conversion efficiency for different PV systems. The impact score considers the environmental impact across the entire life cycle of the PV systems, including manufacturing, installation, operation, and end-of-life disposal or recycling. From the figure, it can be observed that as the conversion efficiency of the PV systems increases, the impact score generally decreases, indicating a lower environmental impact associated with each kWh of energy produced. This is because higher efficiency PV systems require fewer materials and resources to produce the same amount of energy compared to lower efficiency PV systems. Additionally, higher efficiency PV systems may require less land use and have lower greenhouse gas emissions during operation.

Years later, in 2021, (Akinoglu et al., 2021)does not give a prediction about the possible module efficiency of 3G PV. Instead, as it is shown in Figure 4, (Akinoglu et al., 2021) presents as a result of the review of numerous articles the relationship between efficiency and cost of the three generations.

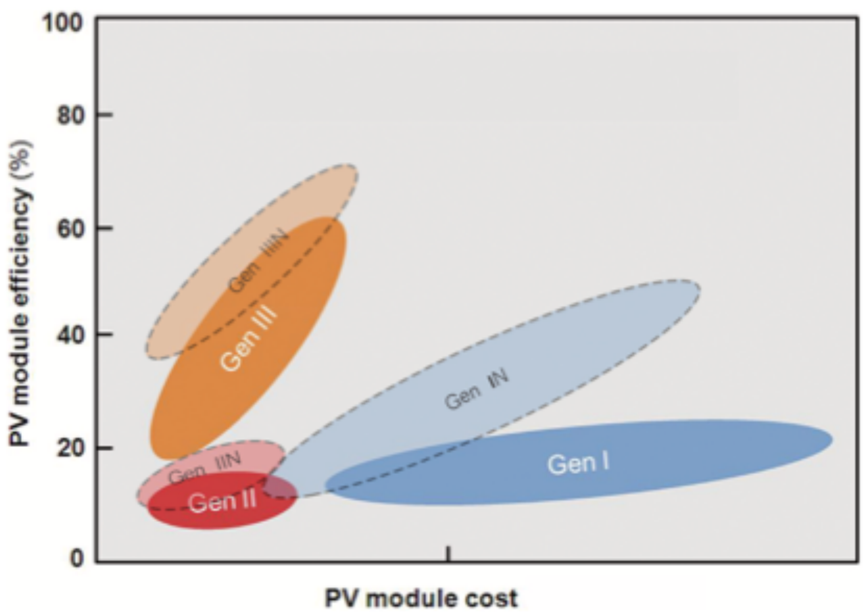


Figure 4. PV module efficiency vs. PV module cost

Source: (Akinoglu et al., 2021)

In the year, in the article "Environmental impacts of solar energy systems: A review" (Rabaia et al., 2021) the following tables are presented. These tables contain the main characteristics of the first, second and third generation technologies.

Type of solar cells	Performance	Merits	Demerits
Mono-Si	- 25-27% on a laboratory scale - 16-22% commercial efficiency - Bandgap between 1.11 and 1.15 eV	High efficiency	Manufacturing is a quite time demanding, and material used are scarce and expensive
Poli-Si	- 15-18% on a laboratory scale - Bandgap is 1.11 eV	Ideal for reducing the market price for a PV module	Efficiency is lower compared to mono-Si cells

Table 2. Characteristics of first-generation PV modules

Source: (Rabaia et al., 2021)

Type of solar cells	Performance	Merits	Demerits
a-Si	- 8% commercial efficiency - Efficiency on a laboratory scale can reach 12%	Cheap on the market	Less material for absorbing the solar radiations because the cells are made up of thinner materials.
CdTe	- 10-15% - 21% record efficiency - Bandgap is 1.45 eV	They give an opportunity of exploiting a broader wavelength spectrum compared to silicone cells. Due to cadmium being abundant, they are also cheap.	Cadmium is toxic and exhibits some harmful characteristics.
Hybrid	- Around 21%	A good compromise between cost and efficiency High carrier mobility of the semiconductor	

Table 3. Characteristics of second-generation PV modules

Source: (Rabaia et al., 2021)

Type of solar cells	Performance	Merits	Demerits
PSC	19-22%	Good efficiency as well as can be enhanced. Cheaper to manufacture compared to the silicone types.	Can easily undergo degradation when exposed to heat, snow, moisture, etc
DSSC	Nearly 10%	Flexibility, not a pollutant, can be recycled. The manufacturing process is cheap. Functional even under small light. High efficiencies at high temperatures.	The electrolyte can become frozen, leading to intermittency in the power supply. The electrolyte is made up of organic solvents; hence sealing becomes very crucial for this type of technology.
QD	1.9%	Easy synthesis as well as preparation.	Lower efficiency

Table 4. Characteristics of third-generation PV modules

Source: (Rabaia et al., 2021)

One of the major challenges in the field of photovoltaic technology is the efficiency of the panels. Researchers and scientists are constantly working towards developing more efficient solar cells that can produce more electricity from the same amount of sunlight. In recent years, there have been significant breakthroughs in this area, with the development of new materials and techniques that can improve efficiency.

For example, a team of researchers at the University of New South Wales in Australia has developed a new type of solar cell that has achieved a record-breaking efficiency of 43%, which is significantly higher than the current industry standard of around 20%. This solar cell is made using a technique called "passivated emitter and rear cell" (PERC), which involves coating the front and rear surfaces of the cell with a thin layer of silicon oxide, which helps to reduce energy losses (Castillo Calderón, 2019).

Another promising approach to improving efficiency is the use of "hot carrier" solar cells. These cells work by capturing the excess energy that is lost as heat in traditional solar cells and using it to generate additional electricity. While hot carrier solar cells are still in the experimental stage, they have shown promising results in laboratory tests (Rabaia et al., 2021).

In addition to improving efficiency, researchers are also working on developing new materials and designs that can make solar cells more durable and resistant to damage. One promising approach is the use of perovskite materials, which have unique electronic properties that make them highly efficient at converting sunlight into electricity. Perovskite solar cells are also relatively inexpensive and easy to manufacture, which makes them an attractive option for large-scale deployment. However, one of the major challenges with perovskite solar cells is their stability and durability over time, as they can degrade quickly in the presence of moisture and oxygen. Researchers are currently working on developing perovskite solar cells that are more stable and durable, which could help to accelerate their adoption in the market (Castillo Calderón, 2019).

In conclusion, photovoltaic technology has evolved significantly over the years, with each generation of PV modules bringing its own unique characteristics and performance improvements. The most widely used technology nowadays is crystalline silicon, which has seen a marked increase in its importance as a low-carbon alternative for electricity production. The issue of efficiency remains a major challenge for researchers and scientists, but recent breakthroughs in materials and techniques have shown promise in improving efficiency. In addition to efficiency, researchers are also focused on developing new materials and designs that can make solar cells more durable and resistant to damage. Perovskite solar cells are a promising option due to their efficiency and relatively low cost, but their stability and durability over time remain a challenge. Minimizing the environmental impact of energy generation is a key goal in the development of sustainable energy systems, and the lower impact score associated with PV technology is seen as a positive attribute. The field of photovoltaic technology continues to evolve, and future breakthroughs are expected to bring even more improvements in efficiency and sustainability.

3. METHODOLOGY

3.1. INTRODUCTION

This chapter explains the methodology of the project.

3.2. METHODOLOGY

The search for information for the development of the project has been carried out through high impact journals in the sector. We have accessed to journals with free access or access guaranteed by the Universidad Pontificia Comillas and North Carolina State University, among which we can highlight *ScienceDirect* or *ElServier*.

For a better understanding of the results, Life Cycle Analysis (LCA) will be used. As discussed below, the ISO 14040 standard will be used. This standard recommends to systematically assess and quantify the inputs and outputs of the process. Furthermore, it will be divided into 4 stages:

- Goal & Scope
- Life Cycle Inventory
- Impact Assessment
- Interpretation

Once the LCA has been completed it is possible to compare the emissions generated in the different technologies and structures.

Last but not least, the project covers the impact on emissions that the panels which are installed in Santa Cruz de Marcenado have and the possible solutions and improvements that could be made.

3.2.1. Life Cycle Analysis

Life cycle analysis (LCA) is a method used to assess the environmental impact of a product or service throughout its entire lifecycle, from raw material extraction to disposal or recycling. This includes assessing the energy and resource inputs, as well as the emissions and waste outputs, at each stage of the lifecycle. The goal of LCA is to identify areas where improvements can be made to reduce the overall environmental impact of a product or service. It is commonly used in the field of sustainability to evaluate the environmental performance of products, processes, and systems.

It is worth noting that there are different methods and standards for conducting LCA, such as ISO 14040 and 14044 standards, and the goal of the LCA can vary depending on the context and the user of the information. According to (Klugmann-Radziemska & Kuczyńska-Łażewska, 2020), the study will be supported by ISO 14040. The objective of this analysis will be to understand the environmental impact of a product and its different stages throughout its life cycle.

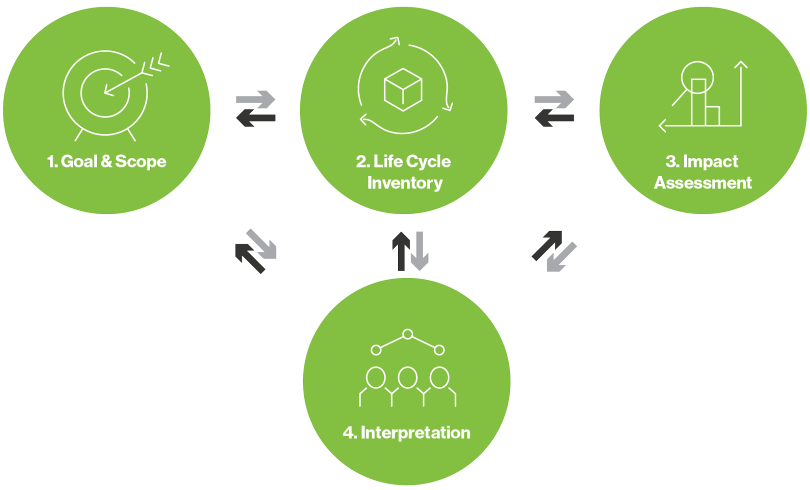


Figure 5. The 4 key steps of LCA

Source: (Rochester Institute of Technology,2020)

In order to study the generated emissions, we differentiate 3 steps during the life cycle of the PV modules. The steps are manufacture, production and dismantling.

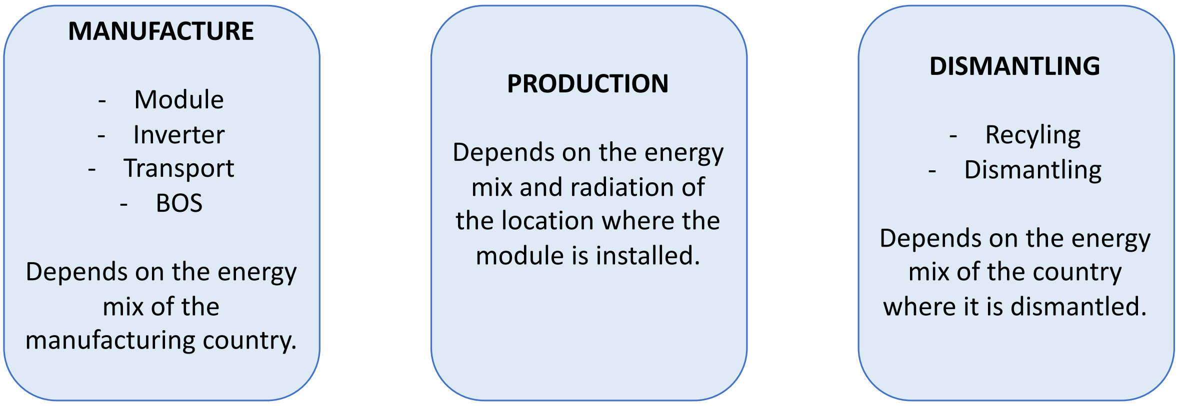


Figure 6. Steps of the LCA

Source: (Own Elaboration, 2023)

The manufacturing of PV modules and other components involves several steps, including the production of silicon (the primary material used in PV modules), the manufacturing of PV cells, and the final assembly and packaging of PV modules. The manufacturing process can generate emissions from the use of fossil fuels and the release of greenhouse gases from the production of certain materials. Efforts to reduce emissions in the manufacturing process include the use of clean energy sources in the manufacturing process and the development of more sustainable materials.

The production of PV modules involves the extraction of raw materials, transportation of materials and finished modules, and the disposal of waste materials. These steps can also generate emissions and have environmental impacts.

The dismantling of PV modules involves the removal of the modules from their installation sites, and the separation and recycling of the materials used in the modules. This process can also have environmental impacts, such as the release of pollutants during the recycling process. However, recycling PV modules can help to conserve resources and reduce the environmental impacts associated with the production of new PV modules.

Overall, the environmental impact of PV modules is highly dependent on the specific manufacturing process and materials used, as well as the disposal or recycling method applied at the end of the module's life. It's important to consider the whole life cycle of PV modules, the emissions generated during the production and dismantling are outweighed by the emissions saved during the operation of the modules throughout their lifetime.

3.2.2. Quantification of system emissions

As it has been said previously, the aim is to quantify the emissions during the manufacture and the dismantling. In order to do that, first, it will be considered the energy required per technology and per structure to produce 1MWh per kWp of installed power. Once the required energy is known, the next step multiplies by the emissions of generate 1 MWh in the country of manufacture or installation.

- $Generated\ emissions = G.E.\ in\ the\ manufacturing + G.E.\ in\ the\ dismantling$
- $G.E.\ in\ the\ manufacturing = \left(E_{module} + E_{BOS} + E_{Transporte} + E_{inverter}\right) * emissions\ when\ generating\ 1\ MWh\ in\ the\ country\ of\ manufacture$
- $G.E.\ in\ the\ dismantling = \left(E_{recycling} + E_{dismantling}\right) * emissions\ when\ generating\ 1\ MWh\ in\ the\ country\ of\ installation$

3.3. FLOW DIAGRAM

Figure 7 shows the block diagram of the proposed case. The procedure consists of evaluating emissions in terms of the different decisions taken.

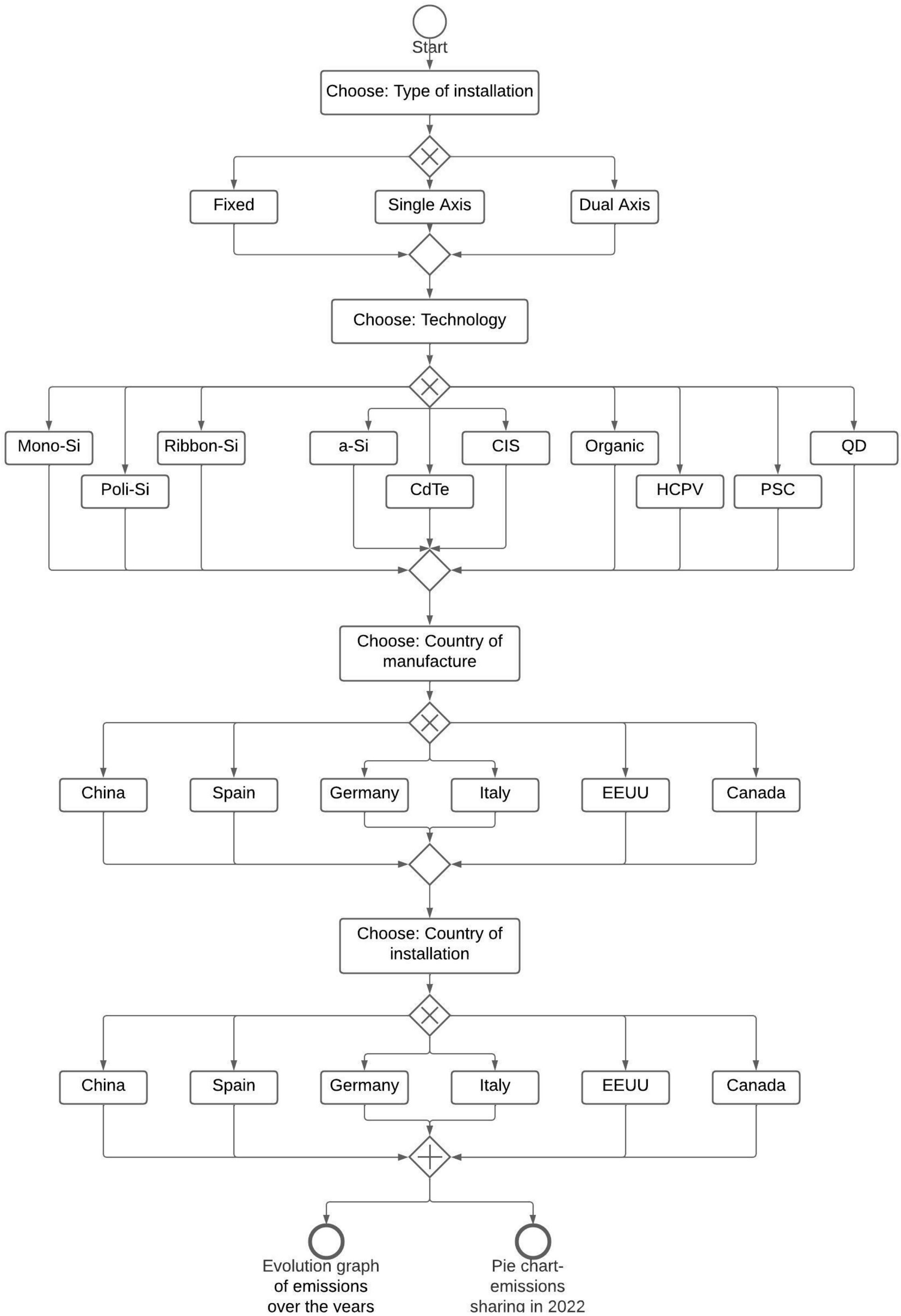

Start
Choose: Type of installation
Fixed
Single Axis
Dual Axis
Choose: Technology
Mono-Si
Poli-Si
Ribbon-Si
a-Si
CdTe
CIS
Organic
HCPV
PSC
QD
Choose: Country of manufacture
China
Spain
Germany
Italy
EEUU
Canada
Choose: Country of installation
China
Spain
Germany
Italy
EEUU
Canada
Evolution graph of emissions over the years
Pie chart- emissions sharing in 2022

Figure 7. Flow Diagram of the project

Source: (Own Elaboration, 2023)

To determine the emissions generated in the manufacture and dismantling of a PV panel, first the type of installation is chosen: fixed, single axis or dual axis. Secondly, the type of technology is selected: Mono-Si, Poly-Si, Ribbon-Si, CdTe, a-Si, CIGS, Organic, HCPV, PSC or QD. Once the type and technology are known, it is important to know the country of manufacture and installation. As will be explained in later sections, among the countries of study of the model are China, Spain, Germany, Italy, United States and Canada.

Once all the parameters are selected, the model predicts the emissions generated during manufacturing and decommissioning for 2022, 2023, 2030 and 2050. This data is used to provide a diagram showing the evolution of emissions over the years. In turn, the model generates a pie chart showing the percentage of emissions use in 2022.

4. TYPOLOGIES AND TECHNOLOGIES OF PV INSTALLATIONS

4.1. INTRODUCTION

In this chapter the different typologies and technologies of photovoltaic modules are explained. Regarding to typologies, the focus is in rooftop and ground-mounted installations. In the other hand, regarding to the technology used we will focus on the three generations:

- 1st Generation: Poli-Si, Mono-Si, Ribbon-Si
- 2nd Generation: CdTe, a-Si, CIGS
- 3rd Generation: OPV, HCPV, PSC, QD

4.2. TYPOLOGY OF PV INSTALLATIONS

In this section, we deal with the differentiation of photovoltaic installations according to the way the PV are assembled. Some common types of PV installations include:

1. Rooftop installations: In this type of installation, the PV modules are mounted on the roof of a building. Rooftop installations are typically smaller in size and are a good option for those who have limited space on their property.
2. Ground-mounted installations: In this type of installation, the PV modules are mounted on the ground, typically using a steel or aluminum frame. Ground-mounted installations are larger in size and are often used in commercial or utility-scale projects.
3. Building-integrated PV (BIPV): In this type of installation, the PV modules are integrated into the building itself, such as by replacing traditional building materials

with PV modules. BIPV installations are a way to generate electricity while also enhancing the aesthetic appearance of the building.

4. Floating PV installations: In this type of installation, the PV modules are mounted on a floating platform, such as a raft or barge, and installed on a body of water, such as a lake or canal. Floating PV installations are a relatively new technology that has the potential to generate electricity in areas where land is scarce or expensive.

We should mention that of all these possibilities, the most common are installations on a fixed support, as well as those with one and two-axis tracking, especially in the case of one axis, since for maintenance reasons they are usually more cost-effective. We focus on grounded-mounted installations and rooftop installations, as they are our point of interest.

4.2.1. Grounded-mounted installations

This is the most common type for large installations. Within these installations there are three different sections: installations with a fixed structure, installations with single-axis trackers and installations with dual-axis trackers.

4.2.1.1. Installations with a fixed structure

These systems typically use solar panels that are fixed in place and do not move with the sun. They are commonly used for residential and commercial properties to generate electricity for on-site consumption or for sending to the grid.

Over the years, PV installations with a fixed structure have evolved in several ways. An increase in the panel's efficiency has been achieved by an improved inverter technology, allowing more compact and cost-effective installations. Also, the cost of PV panels has been declining over time, making PV systems more affordable for homeowners and businesses. Mounting and racking systems for PV panels have become more versatile and durable, allowing for more flexible and robust installations on a variety of structures and in a variety of climates.

On top of everything, the use of energy storage systems, such as batteries, has become more common in recent years, allowing PV systems to store excess electricity for use during periods of low sunlight or high demand.

This type of installation is characterized by being permanently attached to the ground and having a fixed panel orientation, direction, such as south-facing in the northern hemisphere, to maximize the amount of sunlight they receive. Furthermore, these installations are characterized for a regular maintenance, including cleaning the panels, checking the electrical connections, and ensuring that the system is properly grounded.

This type of installations can be placed in roofs, ground-mounted racks, carports and canopies and water surfaces among others. Overall, PV installations with a fixed structure can be installed on a wide variety of structures and surfaces, making them a versatile and flexible energy source. It's important to note that the location and orientation of the panels will affect the system's performance, and a site assessment should be done before an installation is planned.

Fixed-panel systems (Figure 8) tend to have lower efficiency than single-axis trackers, as they are not able to follow the sun's movement throughout the day and capture as much of the sun's energy. The efficiency of a fixed-panel system can range from 10-15% lower than single-axis trackers, depending on the specific location and conditions of the installation.

Figure 8. PV with fixed structure

Source: (Zyrianov, 2017)

4.2.1.2. Installations with single-axis trackers

PV installations with single-axis trackers are a type of fixed-structure PV system that uses a single-axis tracking mechanism to adjust the position of the panels to follow the sun's movement throughout the day. This allows the panels to generate more electricity than fixed-panel systems by capturing more of the sun's energy.

Single-axis tracking systems can be classified as Type A systems, according to the IEC 61215 and IEC 61646 standards, which are designed for use in areas with low wind loads and snow loads. They are commonly used for small-scale residential and commercial installations, and they can be mounted on a variety of surfaces, such as on the ground, on a roof, or on a carport or canopy.

These systems have some benefits such as increased energy production, especially during the morning and afternoon hours, when the sun is at a lower angle in the sky. They also have a relatively low cost of implementation, easy maintenance, and a relatively high level of reliability. However, they have some disadvantages such as the need for more space for the panels to rotate, and the need for more complex and expensive tracking systems.

Different types the single-axis trackers can be found:

Around a horizontal axis (Figure 9), the surface rotates on a horizontal axis oriented in a north-south direction. The rotation is adjusted so that the normal to the surface always coincides with the Earth's meridian containing the Sun.

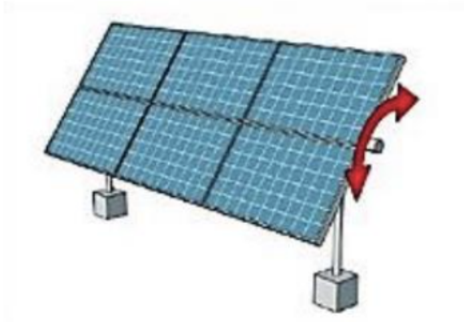


Figure 9. Single-axis tracker around a horizontal axis

Source: (Zyrianov, 2017)

Around the polar axis (Figure 10), the surface rotates about a south-facing axis inclined at an angle equal to the latitude. The rotation is adjusted so that the normal to the surface always coincides with the Earth's meridian containing the Sun. The rate of rotation is approximately 15° per hour, like that of a clock.

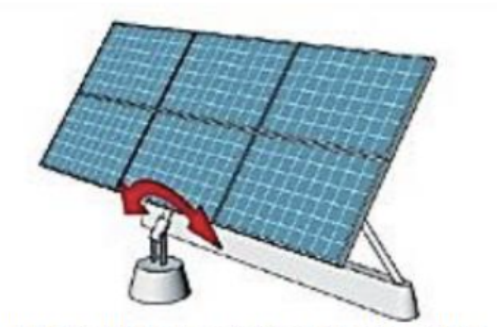


Figure 10.Single-axis tracker around a polar axis

Source: (Zyrianov, 2017)

Around an azimuthal axis, the surface rotates about a vertical axis, the angle of the surface is constant and equal to the latitude. The rotation is adjusted so that the normal to the surface always coincides with the local meridian containing the Sun. The rate of rotation is variable throughout the day.

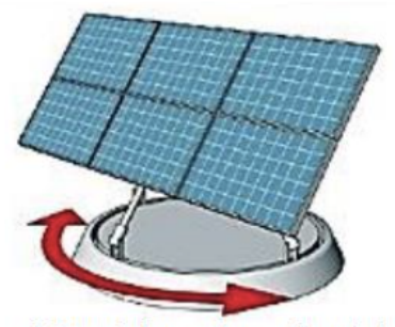


Figure 11. Single-axis tracker around an azimuthal axis

Source: (Zyrianov, 2017)

Single-axis trackers tend to have higher efficiency than fixed-panel systems, as they are able to follow the sun's movement throughout the day and capture more of the sun's energy. The efficiency of a single-axis tracker can range from 10 to 25% higher than fixed-panel systems, depending on the specific location and conditions of the installation.

4.2.1.3. Installations with dual-axis trackers

PV installations with dual-axis trackers are a type of fixed-structure PV system that uses a dual-axis tracking mechanism to adjust the position of the panels to follow the sun's movement throughout the day. This allows the panels to generate more electricity than fixed-panel or single-axis systems by capturing more of the sun's energy.

Dual-axis trackers have two axes of rotation, one that allows the panels to rotate along the east-west plane, and another that allows the panels to tilt and adjust the angle of incidence of the sun's rays on the panels throughout the day. This allows the panels to capture more of the sun's energy, as it can adjust for the sun's elevation and azimuth.

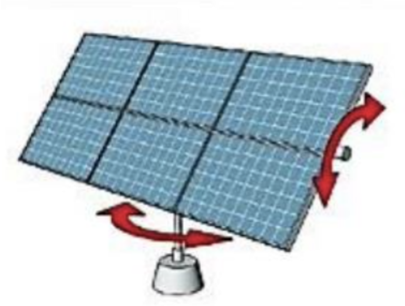


Figure 12. Dual-axis tracker

Source: (Zyrianov, 2017)

Dual-axis trackers can be classified as Type V systems, according to the IEC 61215 and IEC 61646 standards, which are designed for use in areas with higher wind loads and snow loads. They are commonly used for large-scale utility and commercial installations, and they can be mounted on a variety of surfaces, such as on the ground, on a roof, or on a carport or canopy.

These systems have some benefits such as increased energy production, especially during the morning and afternoon hours, when the sun is at a lower angle in the sky and during the whole year, as they can adjust for the sun's elevation. They also have a high level of reliability; however, they have some disadvantages such as the need for more space for the panels to rotate, and the need for more complex and expensive tracking systems. They are also more expensive to install and maintain than single-axis trackers.

The efficiency of a dual-axis tracker can range from 15-30% higher than fixed-panel systems, depending on the specific location and conditions of the installation. It's important to note that while dual-axis trackers have a higher efficiency than fixed-panel systems or single-axis trackers, they also tend to be more complex, expensive, and require more maintenance.

4.2.1.4.Conclusions: Differences in the BOS

The BOS for a solar PV system with fixed structure modules is generally the simplest and least expensive, as the modules are mounted in a fixed position and do not require any mechanical tracking equipment. The BOS for a single-axis tracker system, which uses mechanical equipment to track the sun's movement across the sky, is more complex and typically more expensive than a fixed system, as it requires additional components such as motors, gears, and control systems. The BOS for a double-axis tracker system, which tracks the sun in both the east-west and north-south directions, is even more complex and expensive than a single-axis system, as it requires even more components and control systems.

The components of a Balance of System (BOS) for a solar PV system can vary depending on the specific system design, but generally include the following:

- Inverters
- Mounting hardware
- Wiring and electrical components
- Batteries
- Monitoring and control systems
- Safety devices
- Power electronics components
- Grounding and lightning protection
- Transformers
- Metering and energy management

In general, a BOS for a single-axis tracker system include:

Previous components:
- Inverters
- Mounting hardware
- Wiring and electrical components
- Batteries
- Monitoring and control systems
- Safety devices
- Power electronics components
- Grounding and lightning protection
- Transformers
- Metering and energy management

Additional components:
- Motor and gear drives
- Control systems
- Additional wiring and electrical components
- Structural components to support the tracker

A BOS for a double-axis tracker system include all components in single-axis system, as well as:

Previous components:
- Inverters
- Mounting hardware
- Wiring and electrical components
- Batteries
- Monitoring and control systems
- Safety devices
- Power electronics components
- Grounding and lightning protection
- Transformers
- Metering and energy management
- Motor and gear drives
- Control systems
- Additional wiring and electrical components
- Structural components to support the tracker

Additional components:
- Additional motor and gear drives
- Additional control systems and sensors
- Additional structural components to support the tracker

An estimation for the additional energy required for a single-axis tracker BOS is typically around 5-10% of the total energy produced by the system over its lifetime. This includes the energy used during the manufacturing and transportation process, as well as the energy used by the BOS during operation.

It's difficult to provide an accurate estimation of the additional energy required to construct the BOS for a dual-axis tracker solar PV system without knowing the specific details of the system, such as the size of the system, the specific components used, and the location of the installation. However, the additional energy required for the BOS of a dual-axis tracker system would be higher than for a single-axis tracker system, and it could be around 10-15% of the total energy produced by the system over its lifetime.

To sum up, the BOS of single-axis trackers shall be considered to require 7.5% more additional energy to produce than fixed-axis trackers, and the BOS of dual-axis trackers shall be considered to require 12.5% additional energy.

4.2.2. Rooftop installations

Rooftop solar installations have become increasingly popular in recent years as the cost of solar technology has decreased and the demand for clean, renewable energy has increased. Rooftop solar can provide a significant source of energy for a building or community and can also help to reduce dependence on fossil fuels and decrease carbon emissions.

Rooftop solar installations have several unique characteristics that make them a popular choice for generating renewable energy. First of all, they are space efficient, rooftops are often unused spaces that can be utilized to generate energy, making them a space-efficient option for generating renewable energy. Secondly, they require low maintenance, rooftop solar systems are relatively low maintenance and require only occasional cleaning and inspections. Other advantages that can be found are cost-effective technology, scalable, versatile, net metering, grid independent and environmentally friendly among others.

4.2.2.1. Coplanar rooftop installations

Coplanar rooftop installations can be an efficient way to generate renewable energy, but their efficiency can vary depending on several factors.

One of the main factors affecting the efficiency of coplanar rooftop installations is the angle at which the solar panels are installed. Since coplanar rooftop installations are typically installed on flat or low-sloped roofs, the angle of the solar panels may not be optimal for capturing sunlight. It can be seen in Figure 13 an example of a coplanar rooftop installation.

Another factor that can affect the efficiency of coplanar rooftop installations is shading. If there are nearby buildings, trees, or other structures that cast shadows on the solar panels, it can reduce the amount of sunlight that reaches the panels, reducing the overall efficiency of the system.

Additionally, the orientation of the building, the surrounding climate and weather conditions, the quality of the solar panels, and the overall design of the system can also affect the efficiency of coplanar rooftop installations.

Figure 13. Coplanar rooftop installation

Source: (Google images, 2023)

4.2.2.2. Sloped roof installations

Sloped roof installations (Figure 14) can be an efficient way to generate renewable energy, but their efficiency can vary depending on several factors.

One of the main factors affecting the efficiency of sloped roof installations is the angle of the roof. Sloped roofs are typically installed at an angle that is optimal for capturing sunlight, which increases the efficiency of the system.

Another factor that can affect the efficiency of sloped roof installations is shading. If there are nearby buildings, trees, or other structures that cast shadows on the solar panels, it can reduce the amount of sunlight that reaches the panels, reducing the overall efficiency of the system.

Additionally, the orientation of the building, the surrounding climate and weather conditions, the quality of the solar panels, and the overall design of the system can also affect the efficiency of sloped roof installations.

Overall, sloped roof installations can be an efficient way to generate renewable energy, but their efficiency will depend on the specific site conditions and the design of the system. Sloped roof installations are typically more efficient than coplanar roof installations due to the optimal angle for capturing sunlight and the possibility of using special mounting hardware to adjust the angle of the solar panels according to the location.

Figure 14. Sloped roof installations

Source: (Google images, 2023)

4.2.2.3. Flat roof installations

Flat roof installations are a type of solar panel installation where the solar panels are installed on a flat roof. This type of installation is often used on commercial or industrial buildings and can be less visible from the ground. It can be seen in Figure 15Figure 13 an example of a flat roof rooftop installation.

Figure 15. Flat roof installations

Source: (Google images, 2023)

However, flat roof installations may not be as efficient as sloped roof installations due to the lack of angle adjustment, which is optimal for capturing sunlight. To increase the efficiency of the system, flat roof installations can use special mounting hardware to adjust the angle of the solar panels or use tracking systems that follow the sun's movement during the day.

4.2.2.4. Conclusions on PV installations

To sum up, sloped roof installations are installed at an angle that is optimal for capturing sunlight, which increases the efficiency of the system. Additionally, the use of special mounting hardware can be used to adjust the angle of the solar panels to maximize energy production. Tracking systems that follow the sun's movement during the day can also be added to increase the efficiency of the system.

As in the previous point, it is concluded that depending on the structure (fixed, single-axis tracking and dual-axis tracking) the energy required to manufacture the module was different, in this case the only difference between the PV panels mounted on roofs is the efficiency. All of these panels have a fixed structure, and the big difference is the angle of the tilt. This is not reflected in the energy required, but it does show in the efficiency of the panel.

To sum up, from this point on, the tilt of the panels is not taken into account as we are not focusing on efficiency but on emissions.

4.3. TECHNOLOGY OF PV MODULES

PV modules, also known as solar panels, are devices that convert sunlight into electricity. They are made up of photovoltaic cells, which are made of semiconductor materials such as silicon. When sunlight strikes the cells, it causes a flow of electrons, creating a current of electricity. The cells are connected in series and parallel to create a module, which can then be connected to other modules to create a solar array. PV modules can be used for a variety of applications, including powering homes, buildings, and electronic devices, and can be integrated into building materials such as roofs and walls. Advances in technology have led to the development of more efficient and cost-effective PV modules, and research is ongoing to further improve their performance and durability.

Photovoltaic plants are groupings of photovoltaic panels in series and in parallel until the desired power output is obtained with the appropriate voltage for the required use. If the power generated is to be fed back into the grid, an inverter and a voltage regulator must be installed to maintain synchronization with the external grid, (Sanchez Mingarro, 2020).

For ease of understanding, the following points will consist of an introduction to the technology, historical information, points of interest, and finally, efficiency, life cycle and how temperature affects efficiency. Within each generation, each sub-item will describe the efficiency and the advantages and limitations of each technology.

4.3.1. 1st generation

The earliest and most frequently used type of photovoltaic systems is first-generation PV technology, also referred to as classic crystalline silicon (c-Si) technology. The photovoltaic effect, in which sunlight interacts with semiconducting materials to produce an electric current, is its basis. The silicon solar cell, which turns sunlight into electricity, is the main part of this technology. First-generation PV systems have been widely used in numerous applications and have been crucial in laying the groundwork for the solar industry.

The 1950s saw the development of first-generation PV technology, which received a lot of attention during the 1970s oil crisis. Monocrystalline silicon was used in the early stages of the development of c-Si technology. Polycrystalline silicon was eventually adopted, resulting in cheaper manufacturing costs. Manufacturing procedures have been refined throughout time, increasing efficiency, and lowering prices. Due to a surge in the deployment of first-generation PV systems in residential, commercial, and utility-scale projects, the total installed capacity of these systems worldwide has expanded significantly.

Due to its reliability, durability, and affordability, first-generation PV technology is still in use today. The Earth's crust contains an extremely abundant amount of silicon, which is principally responsible for its broad adoption. Its market supremacy is a result of its established manufacturing procedures, industry standards, and strong supply chains.

With current commercial modules achieving efficiencies of 20% or higher, first-generation PV technology, represented by conventional crystalline silicon (c-Si) systems, has demonstrated considerable gains in efficiency over time. The actual efficiency, however, can differ based on the cell design, manufacturing standards, and environmental circumstances. First-generation PV systems typically have a lifespan of 25 to 30 years, and manufacturers provide warranties to guarantee performance and dependability. First-generation PV system efficiency can be impacted by temperature because high temperatures increase electron-hole recombination rates, which results in decreased energy conversion efficiency. However, the effect of temperature on efficiency can be reduced with good system design, which includes ventilation and temperature management strategies.

4.3.1.1. Monocrystalline silicon (mono-Si)

Monocrystalline silicon (Mono-Si) is a widely used and commercially mature photovoltaic technology belonging to the first generation of PV systems. It is characterized by solar cells made from single-crystal silicon, resulting in a uniform and continuous crystal lattice structure. Mono-Si technology has gained popularity due to its high efficiency, reliability, and widespread availability of raw materials.

Monocrystalline silicon solar cells exhibit some of the highest efficiencies among PV technologies. Current commercial Mono-Si modules can achieve efficiency ranges typically between 19,7% to 27,6%, according to the articles reviewed in the bibliography. This high efficiency is due to the fact that mono-Si PV cells are made from a single, large crystal of silicon, which allows for fewer defects and less recombination of electrons, resulting in higher current and power output.

Mono-Si technology offers several advantages. First off, it has a high energy conversion efficiency, allowing for the best possible use of sunlight to generate electricity. Additionally, Mono-Si modules have a relatively long lifespan, typically lasting 25-30 years, ensuring a stable and reliable energy output over an extended period. Furthermore, Mono-Si modules have a sleek black appearance, making them visually appealing for various applications, such as residential installations.

However, this technology also has some limitations. The manufacturing process for Mono-Si cells is more energy-intensive and expensive compared to other PV technologies, partly due to the production of high-purity silicon required for single-crystal growth. The rigid and square shape of Mono-Si modules limits their design flexibility, making integration into certain architectural designs or curved surfaces challenging. Moreover, Mono-Si technology is susceptible to efficiency losses when subjected to partial shading or high temperatures, which may reduce its overall energy generation capacity.

4.3.1.2. Polycrystalline silicon (poly-Si)

Polycrystalline silicon (Poly-Si) is a widely used photovoltaic technology belonging to the first generation of PV systems. It is characterized by solar cells made from multiple crystal structures, resulting in a less uniform and grainy appearance compared to monocrystalline silicon. Poly-Si technology has gained popularity due to its cost-effectiveness and widespread availability of raw materials.

Polycrystalline silicon solar cells typically have slightly lower conversion efficiencies compared to monocrystalline silicon. The efficiency range for commercial Poly-Si modules is 16.4% in average (Barroso Toro, 2020). The efficiency is lower because there is less quantity of silicon.

In one hand, this technology offers several advantages. Firstly, it benefits from lower manufacturing costs compared to Mono-Si, making it more cost-effective. This affordability makes Poly-Si technology a viable option for large-scale installations and projects with budget constraints. Additionally, Poly-Si modules have good temperature tolerance and can perform well even in high-temperature conditions. The production process for Poly-Si cells is also less energy-intensive compared to monocrystalline silicon, resulting in a relatively lower carbon footprint.

In the other hand, Polycrystalline silicon PV technology also has some limitations. The grain boundaries and non-uniform crystal structure of Poly-Si cells can lead to slightly lower conversion efficiencies compared to mono-Si. Additionally, the lower efficiency may require larger surface areas to achieve the desired power output, which can be a consideration in space-constrained installations. The grainy appearance of Poly-Si modules may not be visually appealing for some applications. Despite these limitations, Polycrystalline silicon technology remains a popular and cost-effective choice for a wide range of solar energy applications.

4.3.1.3. Silicon ribbon panels (Ribbon-Si)

Silicon ribbon panels, also known as Ribbon-Si, represent a first-generation photovoltaic technology that utilizes thin strips of silicon as the primary material for solar cells. Unlike traditional crystalline silicon technologies, Ribbon-Si employs a unique manufacturing process that involves growing thin layers of silicon directly on a substrate, resulting in a ribbon-like structure. Ribbon-Si technology has gained attention due to its potential for cost-effective production and higher material utilization efficiency.

Silicon ribbon panels generally have lower conversion efficiencies compared to monocrystalline and polycrystalline silicon technologies. The mean efficiency of silicon ribbon panels is 14,2% and they have a lifespan of 25-30 years, similar to traditional c-Si PV panels (Müller et al., 2021). While the efficiency may be comparatively lower, Ribbon-Si technology offers advantages in terms of cost-effectiveness and the ability to produce thin and flexible solar panels.

Silicon ribbon panels have several benefits. Ribbon-Si is a potentially cost-effective choice since its manufacturing method uses thinner silicon layers and produces less material waste. Ribbon-Si modules can be more easily integrated into a variety of applications, such as curved surfaces or building-integrated photovoltaics, due to their thin and flexible nature. Additionally, Ribbon-Si technology may increase material use effectiveness, minimizing the environmental impact of silicon consumption.

Ribbon-Si technology does, however, has some drawbacks to take into account. Due to the lower efficiency relative to other PV technologies, bigger surface areas are needed to produce the appropriate amount of power, which might not be feasible in installations with limited space. The cells' ribbon-like shape makes it possible for mechanical stress and fracture to occur more easily. Additionally, the manufacturing process for Ribbon-Si modules can be more complex and sensitive to production variations, which may impact product consistency.

4.3.2. 2nd generation

A variety of thin-film solar cell technologies, such as Cadmium Telluride (CdTe), Amorphous Silicon (a-Si), and Copper Indium Gallium Selenide (CIGS). These technologies use thin layers of semiconductor materials placed on various substrates, which sets them apart from first-generation crystalline silicon. These modules are a type of solar panel technology that offer improved performance and lower costs compared to 1st Generation technologies such as Mono- or Poly-Crystalline Silicon (c-Si).

Second-generation PV technologies have experienced substantial advancement over time. CdTe and a-Si technologies gained prominence in the late 20th century, with CdTe commercialization in the 1990s and a-Si advancements in the 1980s. CIGS technology has experienced steady progress since the 1990s, demonstrating higher efficiencies and improved stability.

Each 2G PV technology has its unique point of interest:

- CdTe technology stands out for its high absorption coefficient, cost-effectiveness, and potential for large-scale deployment.
- A-Si offers flexibility, lightweight design, and good performance in low-light conditions, making it suitable for various applications.
- CIGS combines high efficiency potential, and the ability to be deposited on different substrates, allowing for versatile applications.

Finally, despite these points of interest, 2G PV modules are not without their challenges. For example, some 2G PV technologies use materials, such as cadmium, that can pose a threat to the environment and human health if not handled properly.

4.3.2.1. Cadmium Telluride (CdTe)

Cadmium Telluride (CdTe) is a prominent second-generation photovoltaic technology that utilizes a thin-film solar cell structure. CdTe solar cells consist of a cadmium telluride semiconductor layer deposited on a substrate. CdTe technology has gained significant attention due to its potential for cost-effective production, high absorption coefficient, and suitability for large-scale deployment.

Cadmium Telluride (CdTe) solar cells have achieved remarkable conversion efficiencies, with commercial modules typically ranging from 16% to 22%. Research advancements, such as (Ahmmed et al., 2020) have pushed the upper limits of CdTe efficiency, with some laboratory-scale cells demonstrating efficiencies exceeding 28.04%. These competitive efficiency levels make CdTe technology a viable option for utility-scale photovoltaic installations.

The market for CdTe-based cells has shown high growth in recent years, due to low production costs, as the process is facilitated by the physical properties of its components which, when combined, are able to deposit at the same rate on the surface forming crystalline structures, demanding temperatures that do not exceed 500°C, giving advantages in production and the ease of self-compensation when doping the material. (Ximena & Ramos, 2021).

The advantages of CdTe technology are numerous. It has a high absorption coefficient, which makes it possible to convert energy effectively even with a thin semiconductor layer. CdTe modules are light thanks to this property, making them potentially appropriate for applications that require flexibility and portability. Additionally, compared to other PV technologies, CdTe manufacturing procedures are relatively inexpensive, which increases its cost-effectiveness and potential for large-scale production. CdTe modules are appropriate for a variety of geographical areas since they operate well in low light.

The CdTe technique does have some drawbacks, though. When exposed for an extended period to high temperatures and humidity, CdTe modules may experience potential performance loss. Another issue is the toxicity of cadmium, which calls for careful handling and recycling procedures both during the production and end-of-life stages of the modules.

4.3.2.2. Amorphous silicon (a-Si)

Amorphous Silicon (a-Si) panels are photovoltaic panels that are made from a thin film of non-crystalline silicon. Unlike traditional crystalline silicon (c-Si) PV panels, which are made from silicon wafers, a-Si panels use a thin film of silicon that is deposited on a substrate material, such as glass or metal. As it was said before, a-Si has gained popularity due to its potential for low-cost production, lightweight design, and suitability for various applications. This material currently accounts for more than 10% of international production because it has also proven to be very efficient.

A-Si solar cells typically exhibit lower conversion efficiencies compared to crystalline silicon technologies. Commercial a-Si modules typically achieve efficiencies ranging from 6% to 10% (Avila et al., 2022). While these efficiencies may be lower, a-Si's advantage lies in its superior low-light performance, allowing it to generate electricity even in diffuse or shaded conditions.

Technology based on a-Si has various benefits. Its non-crystalline structure enables flexible and light solar panels, making it appropriate for conformability and aesthetics-sensitive applications like portable electronics or building-integrated photovoltaics (BIPV) (Ghosh, 2022). When compared to crystalline silicon technologies, the a-Si manufacturing process is comparatively inexpensive and uses less material, which increases its cost-effectiveness and potential for large-scale production. Additionally, a-Si modules have a greater temperature coefficient than crystalline silicon, which means they lose less efficiency as temperature rises.

The a-Si technology does have some drawbacks, though. Because a-Si modules have a lower conversion efficiency, they need more surface area to produce the appropriate amount of power, which could be a problem in installations with restricted floor space. Furthermore, the Staebler-Wronski effect, which causes a progressive drop in efficiency, can cause a-Si cells to deteriorate with time (Rubio García, 2022). During the module manufacturing process, gentle soaking procedures can reduce the Staebler-Wronski effect. Despite these drawbacks, ongoing research and development aims to increase the a-Si technology's effectiveness and stability, making it a viable alternative for a range of solar energy applications.

4.3.2.3. Copper Indium Gallium Selenide (CIS) panels (CIGS)

Copper Indium Gallium Selenide (CIGS) is a second-generation photovoltaic technology that utilizes thin-film solar cells composed of copper, indium, gallium, and selenium. CIGS combines the advantages of thin-film technology with the potential for higher conversion efficiencies and improved performance compared to other second-generation PV technologies.

CIGS technology has demonstrated competitive conversion efficiency of 20% with some laboratory-scale cells achieving even higher efficiencies (Avila et al., 2022). Compared to other materials, it provides high efficiency and flexibility, however, its use is limited because it is complicated to manufacture, implementing rare and controversial chemical elements such as cadmium, which is known to cause cancer.

CIGS panels offer several advantages that make them attractive for photovoltaic applications. Firstly, they have the potential for high efficiency, enabling efficient energy production even in limited space. CIGS modules also exhibit good performance in low-light conditions, making them suitable for areas with diffuse sunlight or shading. Additionally, CIGS cells can be deposited on flexible substrates, enabling their use in applications that require curved or flexible surfaces. The material composition of CIGS panels requires less semiconductor material compared to crystalline silicon, resulting in cost savings and a reduced environmental footprint. (Zouache et al., 2022)

Nevertheless, CIGS technology has several limitations to consider. Compared to other thin-film technologies, the manufacturing of CIGS modules can be more time-consuming and expensive. To maintain long-term stability and performance, CIGS panels must be properly encapsulated as they are sensitive to moisture. The performance of CIGS solar cells is mostly dependent on cell efficiency, which is greatly enhanced by a drop in temperature. Therefore, it is suggested that the cell temperature be reduced to 300 K. (Zouache et al., 2022)

4.3.3. 3rd generation

Third generation (3G) PV technologies represent the latest advancements in the field of photovoltaics. These technologies, including Organic Photovoltaic (OPV), High Concentration Photovoltaic (HCPV), Perovskite Solar Cells (PSC), and Quantum Dot Solar Cells (QD), aim to overcome the limitations of previous generations and offer new possibilities for efficient and sustainable solar energy generation.

The development of 3G PV technologies has been ongoing in recent years, with significant progress made in each specific technology. OPV has seen advancements in organic materials and device architecture, leading to improved efficiencies and stability. HCPV has been refined to achieve high concentration ratios and efficient use of sunlight. PSCs have rapidly gained attention due to their high efficiencies and rapid performance improvements. QD solar cells have shown promise in enhancing efficiency and spectral tunability through the use of quantum dots.

Each 3G PV technology has its unique points of interest:

- OPV panels are lightweight, flexible, and can be made transparent, making them suitable for integration into a wide range of surfaces and structures.
- HCPV allows for the concentration of sunlight, reducing the required cell area and potentially increasing efficiency.
- PSCs have gained attention for their rapidly increasing efficiency and the potential for low-cost manufacturing processes.
- QD solar cells have the advantage of tunable bandgaps, enabling them to capture a wider range of the solar spectrum.

3G PV technologies offer promising advancements in solar energy generation, more efficiency at a lower cost.

4.3.3.1.Organic Photovoltaic Panels (OPV)

Organic Photovoltaic Panels (OPV) belong to the third generation of photovoltaic technologies and are characterized by the use of organic materials, such as polymers or small molecules, in the active layer of the solar cells. OPV technology offers unique advantages due to its lightweight, and the potential for low-cost manufacturing processes. These features make OPV panels suitable for applications that require conformability, portability, or integration into various surfaces.

Over time, OPV efficiency range has continually increased. At the moment, commercial OPV modules frequently reach efficiencies between 9% and 10% (Y. Liu et al., 2022). With PM6 as a donor, a high efficiency of 14.3% and a VOC of 0.96 eV were obtained. The goal of ongoing research and development is to improve the conversion efficiency of OPV technology and make it more competitive with other photovoltaic technologies.

OPV offer several advantages that make them appealing for specific applications. Firstly, OPV panels are lightweight, allowing them to be easily integrated into curved or irregular surfaces, and even incorporated into wearable devices or flexible electronics (Riede et al., 2021). Additionally, OPV technology can be manufactured using low-cost, scalable processes, potentially enabling cost-effective mass production. OPV panels also have a lower environmental impact compared to some other PV technologies, as they utilize organic materials instead of inorganic materials such as silicon.

One of the main challenges is achieving higher conversion efficiencies comparable to other PV technologies. Additionally, OPV panels may have limited stability and durability, as the organic materials used in their construction can be susceptible to degradation over time, particularly when exposed to moisture and ultraviolet radiation. In the paper: "Recent Progress and Challenges toward Highly Stable Nonfullerene Acceptor-Based Organic Solar Cells" it has been revealed that many important factors that greatly influence the performance of the OPV, such as NFA molecular design, BHJ morphology, and device engineering, are also found to be important in determining the device stability. (Wang et al., 2021)

4.3.3.2. High Concentration Photovoltaics (HCPV)

High Concentration Photovoltaics (HCPV) is a third generation (3G) PV technology that utilizes optics to concentrate sunlight onto small, highly efficient solar cells. HCPV systems employ lenses or mirrors to focus sunlight onto multi-junction solar cells, enabling the capture of a larger amount of energy from a smaller surface area. The key benefits of high concentrated photovoltaics are their low cost, great efficiency, and environmental friendliness. (Ejaz et al., 2021)

HCPV technology boasts high conversion efficiencies, typically ranging from 30% to over 40% (Cebaqueba et al., 2019). The non-imaging dish concentrator had a peak efficiency value of 38.5%, according to the current investigation (Ejaz et al., 2021). This is significantly higher than the typical efficiency of 15-20% for flat-plate photovoltaic systems. By concentrating sunlight onto small, high-efficiency solar cells, HCPV systems can achieve higher energy output per unit area compared to traditional PV technologies. This makes HCPV particularly suitable for applications where space is limited or where maximizing power output is crucial.

One of the key advantages of HCPV is its exceptional efficiency, which allows to produce more electricity per unit of sunlight. Additionally, the smaller size of high-efficiency cells used in HCPV systems can reduce material costs, making them potentially more cost-effective in certain applications. HCPV also offers the advantage of high energy yield in regions with ample direct sunlight, such as desert areas.

One limitation of HCPV technology is its reliance on direct sunlight. Diffuse or indirect sunlight, which is more prevalent in cloudy or shaded conditions, may not be effectively captured by the concentrated optics, resulting in reduced energy generation. HCPV systems also require accurate and precise tracking mechanisms to follow the sun's movement throughout the day, which can increase complexity and maintenance requirements. Furthermore, the concentrated heat generated by HCPV systems may require additional cooling measures to prevent performance degradation. Due to the high concentration in CPVT, there may be a rise in optical losses, temperature inconsistency, and PV overheating. Only direct solar energy, not diffuse radiation, helps CPVT of more than >10 suns (middle and upward concentration). (Alzahrani et al., 2021).

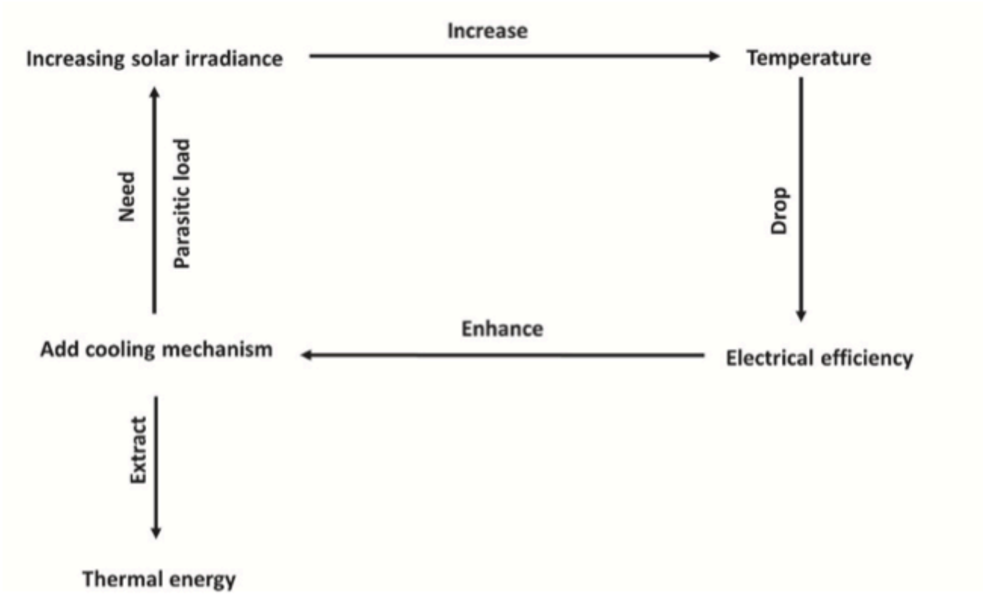


Figure 16. One limitation of HCPV technology is its reliance on direct sunlight.

Source: (Alzahrani et al., 2021)

4.3.3.3. Perovskite solar cells (PSC)

Perovskite Solar Cells (PSC) are a third generation (3G) photovoltaic technology that has gained significant attention in recent years. PSCs are based on a unique class of materials with a perovskite crystal structure, which allows for high-performance light absorption and charge generation. They offer the potential for low-cost, efficient, and lightweight solar energy conversion. (Wu et al., 2021).

Perovskite solar cells have shown remarkable progress in terms of efficiency, with lab-scale devices reaching record efficiencies in the range from 25.5% (Wu et al., 2021) to 26% (Suresh Kumar & Chandra Babu Naidu, 2021). This rapid increase in efficiency has positioned PSCs as one of the most promising emerging photovoltaic technologies. While the efficiencies achieved in the lab are impressive, the challenge lies in maintaining their performance over extended periods and scaling up to large-area production.

PSCs offer several advantages that make them highly appealing for solar energy applications. Firstly, they can be fabricated using low-cost and scalable solution-based processes, allowing for cost-effective production. Additionally, PSCs have a high absorption coefficient, enabling efficient conversion of a broad range of light wavelengths, including low-light and indoor lighting conditions. They also exhibit excellent tolerance to heat and can be manufactured in various forms, such as flexible and semi-transparent devices, expanding their potential applications.

These photovoltaic devices operate much like conventional solar cells by utilizing a perovskite material to generate electrons and holes. What sets PSCs apart is their exceptional efficiency, cost-effectiveness, and ease of production. This novel type of solar cell has garnered considerable interest due to its ability to shift our reliance from finite, non-renewable resources towards the limitless energy provided by sunlight. (Lekesi et al., 2022)

Despite their significant potential, PSCs face certain limitations that need to be addressed for their widespread adoption. One major challenge is their stability, as perovskite materials are sensitive to moisture, oxygen, and UV radiation, which can lead to degradation and reduced device performance over time (Williams et al., 2016). Ensuring long-term stability and durability remains a critical aspect in the commercialization of PSCs. Additionally, the scaling-up of manufacturing processes while maintaining high efficiency and reproducibility poses technical challenges that require further development.

4.3.3.4. Quantum dot cells (QD)

Quantum Dot (QD) cells are a third generation (3G) photovoltaic technology that utilizes nanoscale semiconductor particles called quantum dots to absorb and convert sunlight into electricity. QD cells have garnered attention due to their unique properties, including tunable bandgaps and high absorption coefficients, which make them a promising candidate for efficient and versatile solar energy conversion.

The quantum dots used in these cells are so small that they exhibit quantum mechanical properties, making them highly efficient at converting light into electricity. While the technology is still in the research and development phase, laboratory-scale QD cells have achieved efficiencies exceeding a range from 4% (Rahman et al., 2021) to 13% (Mora-Seró, 2020). The primary reason for this is the limited absorption regions of quantum dots, coupled with the occurrence of charge recombination at the interfaces between QD/electrolyte and TiO2/electrolyte.

QD cells offer several advantages that make them attractive for solar energy applications. Firstly, their tunable bandgap allows for customizing the absorption spectrum to match specific wavelengths of light, enabling efficient harvesting of a broader range of the solar spectrum. QD cells can also be engineered to exhibit superior stability and resistance to degradation caused by environmental factors such as moisture and heat.

Despite their promising features, quantum dot cells face certain limitations that need to be addressed. One challenge is the potential toxicity of certain materials used in QD synthesis, such as cadmium-based compounds (N. Liu & Tang, 2020). Efforts are underway to develop alternative, environmentally friendly materials without compromising performance. Additionally, achieving long-term stability and durability is crucial for commercial viability, as QD cells can be sensitive to environmental factors, including moisture and oxygen (Mora-Seró, 2020).

5. EMISSIONS ANALYSIS

5.1. INTRODUCTION

In this chapter, the study of the quantification of emissions is carried out. In order to study the abovementioned, we will first summarize the energy required by technology and typology for 1 kWp of installed power. Once this information is available, the emissions generated by each country to generate 1 kWh will be studied. Finally, we obtain the emissions in kg of CO_2/kWp.

5.2. ENERGY REQUIRED BY TECHNOLOGY AND TYPOLOGY

The energy required to produce a photovoltaic (PV) module, also known as its embodied energy, can vary greatly depending on several factors, such as the type of materials used, the manufacturing process, and the size and efficiency of the module. However, we will put our focus on the technology and typology.

5.2.1. First and second generation

(Cebaqueba et al., 2019) and (Barroso Toro, 2020) proponed in their thesis a great analysis of the two firsts technologies. In these studies, the required energy and the power output per unit area are provided.

5.2.2. Third generation

- Perovskite:

The articles that discuss the energy required for the manufacture of perovskite solar cells generally conclude that the embodied energy varies depending on the specific manufacturing process and materials used. However, there is a general consensus that the embodied energy of perovskite solar cells is generally lower compared to traditional silicon-based solar cells.

For example, (Guzman-Mendoza et al, 2020) found that the embodied energy of perovskite solar cells ranged from 43 MJ/m2 to 126 MJ/m2, depending on the specific manufacturing process and materials used. The study also found that the major energy-consuming steps in the manufacturing process were the deposition of the perovskite layer and the sintering process required to remove the solvents and create the final structure of the cell.

Similarly, the study by (Li et al, 2018) found that the energy required to produce perovskite solar cells was lower compared to silicon-based solar cells. The study also found that the energy payback time of perovskite solar cells was shorter compared to silicon-based solar cells.

Not many studies have been done regarding the topic of energy required for recycling a perovskite solar cell, so it will be assumed that it is proportional to the other third generation technologies.

Perovskite solar cells are a relatively new technology, and their power output per unit area can vary widely depending on a number of factors, including the specific materials used, the device architecture, and the manufacturing process employed. However, research has shown that perovskite solar cells have the potential to achieve high power conversion efficiencies, which could result in relatively high-power output per unit area.

According to (Preeti Bhavsar et al, 2020), the power output per unit area of perovskite solar cells can range from around 10 to 20 watts per square meter (W/m2) for small laboratory-scale devices to over 20 W/m2 for larger, more efficient devices. In comparison with c-Si modules, this value is lower for several reasons. Among them it can be highlighted, the small size devices and that the efficiency drops when it is considered under real-world conditions. The power output per unit area of a perovskite solar cell with a lab-scale efficiency can vary depending on the specific size and design of the cell. However, as a rough estimate, a perovskite solar cell with a 30% PCE and an area of 1 square meter could potentially produce around 300 watts of power under ideal laboratory conditions.

- Quantum dot cells

(Zhang et al., 2017) estimated the energy required for the manufacture of a quantum dot solar cell to be 25-50 MJ/m2, based on the production process of a specific type of quantum dot solar cell. The study also found that the energy payback time of the quantum dot solar cell was around 2 years. Moreover, (Chen et al., 2017) estimated the energy required for the manufacture of a quantum dot-sensitized solar cell to be around 29-48 MJ/m2, based on a combination of embodied energy and manufacturing energy. The study also found that the energy payback time of the quantum dot-sensitized solar cell was around 2-4 years.

As with perovskite cells, there are not many studies on the recycling energy for Quantum Dot cells, so it is assumed to be proportional to the other third generation technologies.

(Wang et al., 2019) provides the advances and perspectives in the development of quantum dot sensitized solar cells (QDSSCs). In the article, the authors discuss the factors that affect the efficiency of QDSSCs, including the materials used, the device architecture, and the conditions under which the cells are operated. It is noted that the highest reported efficiency for QDSSCs is currently around 14%, which is lower than the efficiency of many other types of solar cells. However, the authors also note that QDSSCs have several advantages over other types of solar cells, including low cost, ease of fabrication, and the ability to use a wider range of solar spectra.

With an efficiency of 14%, and an incident solar power density of 1000 W/m2 (which is approximately the intensity of sunlight at noon on a clear day), it can be estimated the power output per unit area of a quantum dot solar cell as:

Power output per unit area = 0.14 x 1000 = 140 W/m2

5.2.3. Summary

Table 5 shows the required energy per technology in MJ/kWp and Table 6 is the same data but in kWh/kWp. As it has been said before, "the BOS of single-axis trackers considered to require 7.5% more additional energy to produce, and that of dual-axis trackers 12.5%". It is shown in both tables the total energy required for each type of structures.

	Fixed							Single axis	Dual axis
	Required Energy (MJ/kWp)								
	Emod	E bos	E invers	E transport	E rec	E desmant	TOTAL	TOTAL	TOTAL
Mono-Si	3590,18	868,94	190,58	230,86	532,21	144,29	**5557,06**	**5973,84**	**6251,70**
Poli-Si	4200,48	1037,94	227,65	275,76	635,73	172,35	**6549,91**	**7041,15**	**7368,65**
Ribbon-Si	3377,08	1155,50	253,43	307,00	509,73	191,87	**5794,60**	**6229,20**	**6518,93**
a-Si	991,55	1576,01	345,66	418,72	986,28	261,70	**4579,92**	**4923,41**	**5152,41**
CdTe	1111,76	1290,48	283,04	342,86	295,01	214,29	**3537,43**	**3802,73**	**3979,60**
CIS/CIGS	2078,66	1118,25	245,26	297,10	262,41	185,69	**4187,36**	**4501,42**	**4710,78**
Orgánico	4767,88	5743,05	1259,60	1525,83	1265,23	953,64	**15515,23**	**16678,87**	**17454,64**
HCPV	1389,13	538,63	118,14	143,11	163,85	89,44	**2442,30**	**2625,47**	**2747,59**
PSC	281,67	578,13	126,80	153,60	46,02	96,00	**1282,22**	**1378,39**	**1442,50**
QD	271,43	1238,86	271,71	329,14	44,35	205,71	**2361,21**	**2538,30**	**2656,36**

Table 5. Required energy per technology in MJ/kWp

Source: (Own Elaboration, 2023)

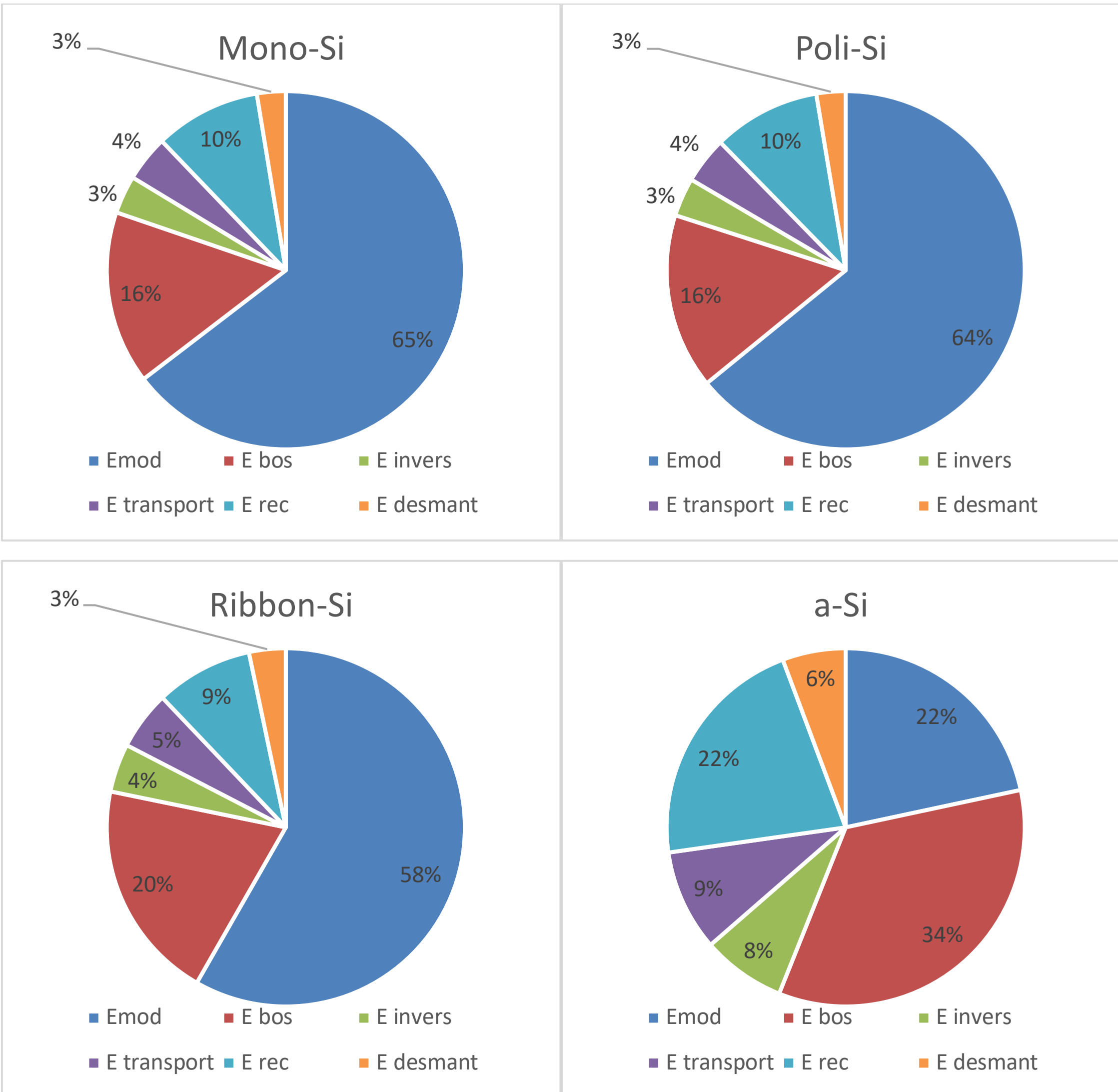
	Fixed							Single axis	Dual axis
	Required Energy (kWh/kWp)								
	Emod	E bos	E invers	E transport	E rec	E desmant	TOTAL	TOTAL	TOTAL
Mono-Si	997,27	241,37	52,94	64,13	147,84	40,08	**1543,63**	**1561,73**	**1573,80**
Poli-Si	1166,80	288,32	63,24	76,60	176,59	47,88	**1819,42**	**1841,04**	**1855,46**
Ribbon-Si	938,08	320,97	70,40	85,28	141,59	53,30	**1609,61**	**1633,68**	**1649,73**
a-Si	275,43	437,78	96,02	116,31	273,97	72,69	**1272,20**	**1305,03**	**1326,92**
CdTe	308,82	358,47	78,62	95,24	81,95	59,52	**982,62**	**1009,50**	**1027,43**
CIS/CIGS	577,41	310,62	68,13	82,53	72,89	51,58	**1163,16**	**1186,45**	**1201,98**
Orgánico	1324,41	1595,29	349,89	423,84	351,45	264,90	**4309,79**	**4429,43**	**4509,20**
HCPV	385,87	149,62	32,82	39,75	45,51	24,84	**678,42**	**689,64**	**697,12**
PSC	78,24	160,59	35,22	42,67	12,78	26,67	**356,17**	**368,22**	**376,25**
QD	75,40	344,13	75,48	91,43	12,32	57,14	**655,89**	**681,70**	**698,91**

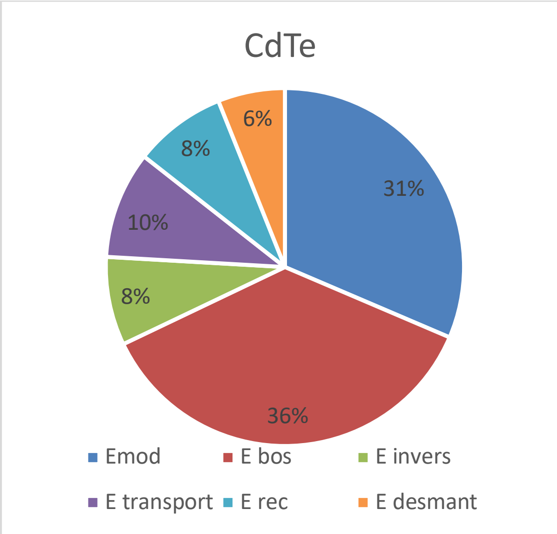
Table 6. Required energy per technology in kWh/kWp

Source: (Own Elaboration, 2023)

5.2.4. Results

Figure 17 shows the results of studying the energy required for each technology with a fixed structure.

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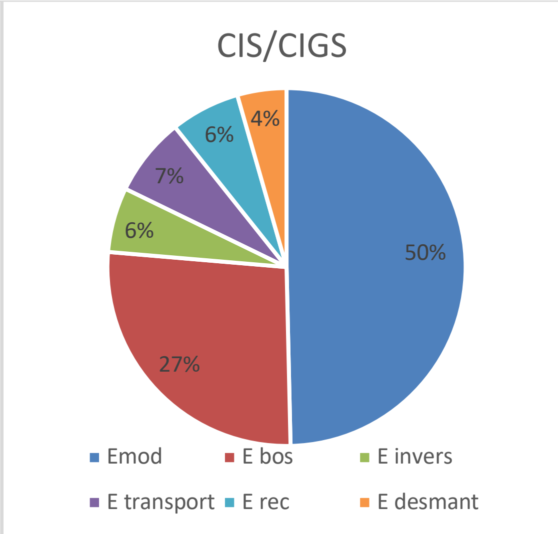
CIS/CIGS
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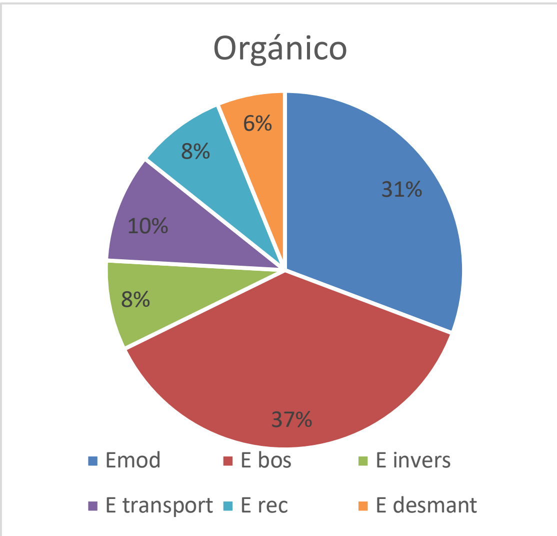
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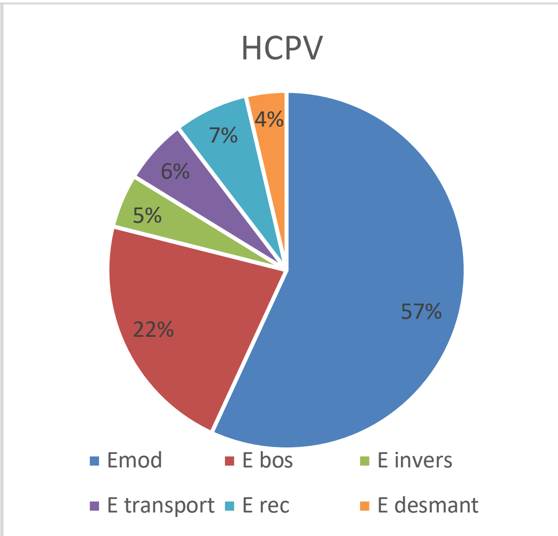
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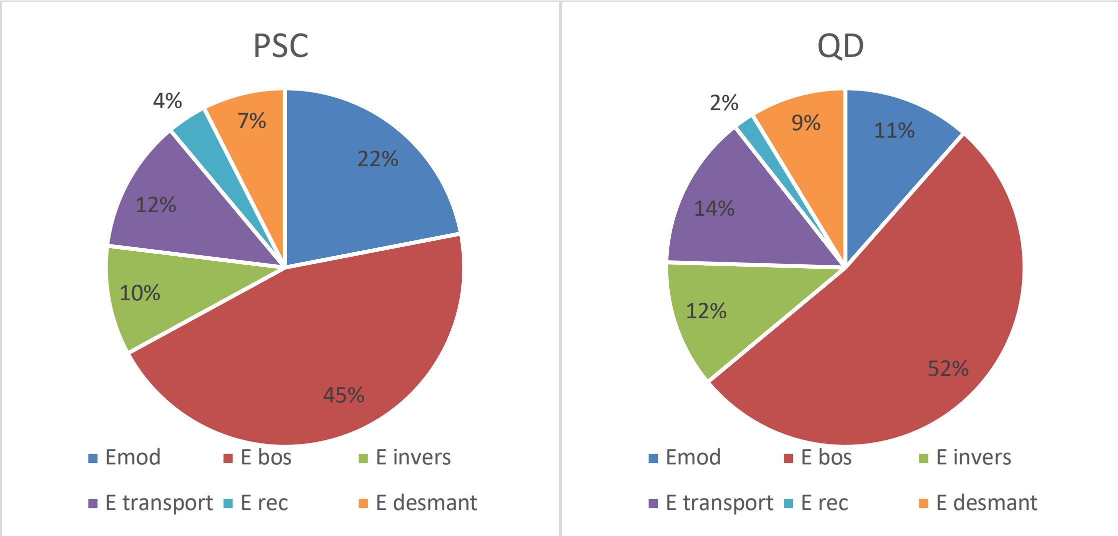

Figure 17. Energy required for a fixed structure depending on the technologies.

Source: (Own Elaboration, 2023)

The data reveals that the amount of energy required per technology varies significantly depending on the type of solar cell technology used. It is important to note that the production of solar panels is not just about the energy generated by the panels, but also about the energy required to manufacture them. Therefore, the energy required to produce solar panels is an important factor to consider when assessing the overall environmental sustainability of solar energy.

The data shows that the energy required for the module itself (Emod) is highest for Mono-Si and Poli-Si technologies, which are the most used types of solar cell technology. This is because these technologies require more energy and resources to manufacture the silicon wafers that form the basis of the solar cells. In contrast, the energy required for the module is relatively low for a-Si, CdTe, and CIS/CIGS technologies, which use thin-film deposition methods that require less material and energy.

The data also shows that the energy required for balance of system (BOS) is highest for a-Si and Organic technologies. BOS includes all the components of a solar energy system that are not part of the solar panels themselves, such as inverters, wiring, and mounting hardware.

The higher BOS energy requirements for a-Si and Organic technologies may be due to their lower efficiency, which means that more solar panels are needed to generate the same amount of electricity, requiring more BOS components and thus more energy.

The energy required for transportation, recycling and dismantling are relatively consistent across all technologies. This suggests that improvements in these areas could have a relatively uniform impact on the overall energy efficiency of solar panel production, regardless of the specific type of technology used.

5.3. EMISSIONS GENERATED ACCORDING TO THE DIFFERENT COUNTRIES

According to Ourworldindata.org, the emissions in g CO_2/kWh are obtained. China, Canada, the USA, and Germany are among the world's leading manufacturers of solar panels. However, China accounts for 70% of the world's photovoltaic cell production. The principles manufacturing companies are presented in Table 7.

Company	Country
Tongwei	China
Long	China
Jinko Solar	China
Canadian Solar	Canada
Aiko	China
Ja Solar	China
Trina Solar	China
First Solar	EE.UU.
Hanwha Q-Cells	Germany
Urec	Taiwan

Table 7. World's leading PV panel manufacturing companies

Source: (Own Elaboration, 2023)

In accordance with (Periódico de la Energía., 2023), Enel has presented its project for Catania, the second most populous city in Sicily (southern Italy), which from 2024 will host the largest solar panel factory in Europe, a center with an annual production capacity of 3 GW.

Although all the world data is acquired, we mainly focus on the principal manufacturers (China, Canada, EE. UU, Germany, and Italy) and the place where the study in being made (Spain).

Yearly emissions (gCO2/kWh)						
Year	China	Spain	Germany	Italy	Canada	EEUU
2000	672,37	425,63	498,51	506,19	214,51	532,61
2001	654,88	385,08	494,35	499,34	222,08	535,38
2002	663,28	439,83	497,08	524,14	213,72	526,75
2003	677,91	392,69	500,05	521,66	219,75	531,99
2004	667,90	410,16	487,04	505,65	203,86	528,83
2005	670,51	436,34	482,56	504,36	200,67	530,55
2006	676,62	404,15	474,40	500,96	189,31	521,93
2007	679,41	407,36	488,67	497,77	195,39	524,97
2008	649,67	372,29	468,49	478,62	185,92	518,42
2009	658,04	342,13	464,67	451,60	173,51	496,26
2010	650,61	280,13	462,20	440,13	175,47	501,34
2011	663,60	319,18	472,59	437,65	165,25	484,12
2012	637,24	328,28	475,15	428,02	155,27	470,47
2013	636,22	270,58	477,54	389,14	149,50	470,62
2014	617,00	271,26	463,10	369,27	147,59	467,31
2015	596,36	307,30	448,40	389,32	147,66	447,66
2016	584,16	268,82	448,03	383,74	144,85	429,44
2017	579,02	309,97	424,13	388,64	136,78	416,78
2018	573,83	275,42	411,56	363,93	132,70	412,06
2019	560,00	243,49	361,57	352,05	130,94	392,78
2020	549,60	199,51	332,58	336,71	119,70	369,39
2021	544,36	193,86	365,98	340,79	128,46	379,38

Table 8. Yearly emissions in g CO2/kWh per country

Source: (Own Elaboration, 2023)

It is of great interest to be able to observe the evolution of emissions according to the different countries, to see how emissions evolve over the years. From the data obtained, the emissions of the last two decades, the emissions in 2022, 2023, 2030 and 2050 have been estimated in a linear way. This will give a clearer picture of how emissions will evolve.

Yearly estimated emissions (gCO2/kWh)						
Year	**China**	**Spain**	**Germany**	**Italy**	**Canada**	**EE. UU.**
2022	534,77	195,84	349,03	344,73	118,12	356,84
2023	526,05	179,56	335,08	338,71	114,06	344,37
2030	465,01	65,60	237,41	296,56	85,62	257,14
2050	290,62	0,00	0,00	176,13	4,37	7,90

Table 9. Yearly estimated emissions per country

Source: (Own Elaboration, 2023)

5.4. EMISSION QUANTIFICATION

For a generic case, which could be a PV module manufactured in China and installed in Spain with a fixed structure, the following results would be obtained.

Figure 18 presents in a bar chart the emissions per technology separating each process that requires energy such as: module energy, BOS energy, inverter energy, energy invested in transport, recycling energy and finally dismantling energy. This figure shows the estimated emissions per technology for solar cell production in China and installed in Spain in 2022. Organic solar cells have the highest emissions due to their energy and resource-intensive manufacturing process. Emissions are lower for technologies such as HCPV, PSC, and QD, which require less energy for manufacturing. Efforts to reduce emissions should focus on optimizing the manufacturing processes for Emod and Ebos, which have the highest emissions.

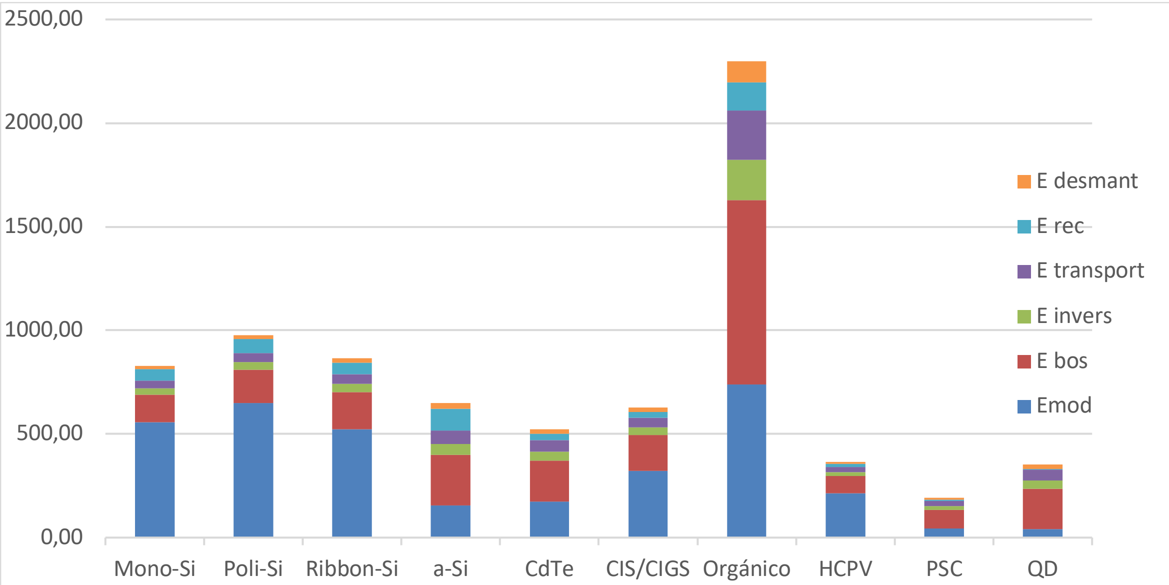

Figure 18. Emissions China-Spain per technology in 2022 for a fixed structure

Source: (Own Elaboration, 2023)

For a more specific example the results of a fixed structure PV plant manufactured in China and installed in Spain which use Mono-Si technology and Perovskite technology are shown.

For a PV plant of Mono-Si:

	Emissions (kg CO2/kWp)						
Year	**Module**	**BOS**	**Inverters**	**Transport**	**Recycling**	**Dismantling**	**TOTAL**
2022	533,31	129,08	28,31	34,29	28,95	7,85	761,79
2023	524,61	126,97	27,85	33,73	26,55	7,20	746,91
2030	463,74	112,24	24,62	29,82	9,70	2,63	642,75
2050	289,82	70,15	15,38	18,64	0,00	0,00	393,99

Table 10. Emissions for a fixed structure, China-Spain, Mono-Si

Source: (Own Elaboration, 2023)

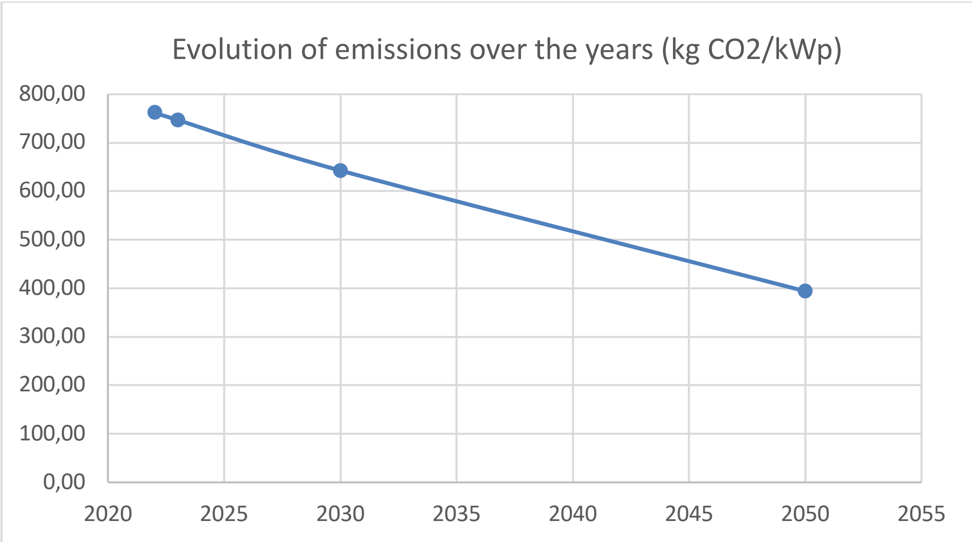

Figure 19. Evolution of the emissions over the years (kg CO2/kWp) for a fixed structure, China-Spain, Mono-Si

Source: (Own Elaboration, 2023)

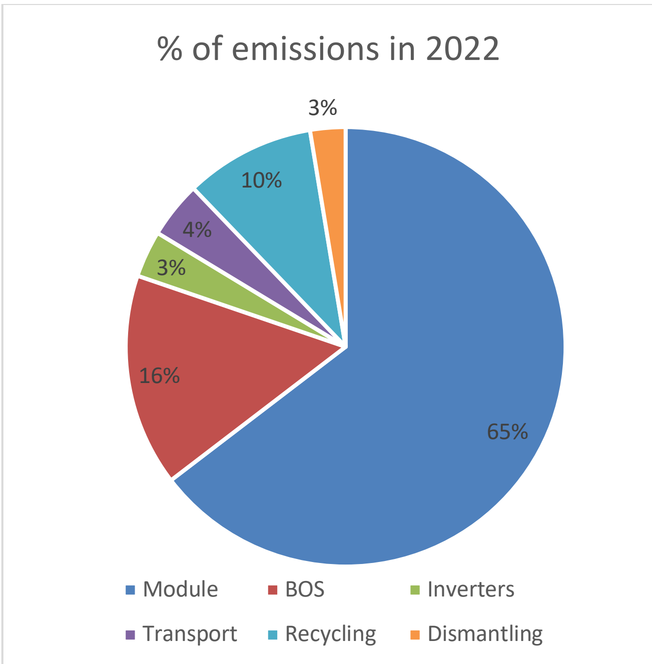

Figure 20. % emissions in 2022 for a fixed structure, China-Spain, Mono-Si

Source: (Own Elaboration, 2023)

For a PV plant of Perovskite:

	Emissions (kg CO2/kWp)						
Year	**Module**	**BOS**	**Inverters**	**Transport**	**Recycling**	**Dismantling**	**TOTAL**
2022	41,84	85,88	18,84	22,82	2,50	5,22	**177,10**
2023	41,16	84,48	18,53	22,44	2,30	4,79	**173,69**
2030	36,38	74,68	16,38	19,84	0,84	1,75	**149,87**
2050	22,74	46,67	10,24	12,40	0,00	0,00	**92,04**

Table 11. Emissions for a fixed structure, China-Spain, PSC

Source: (Own Elaboration, 2023)

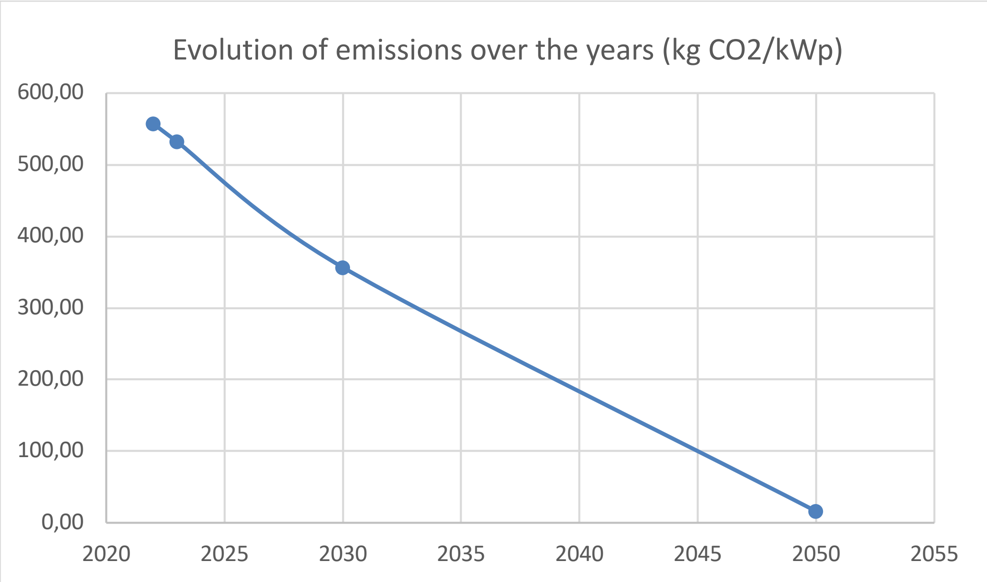

Figure 21. Evolution of the emissions over the years (kg CO2/kWp) for a fixed structure, China-Spain, PSC

Source: (Own Elaboration, 2023)

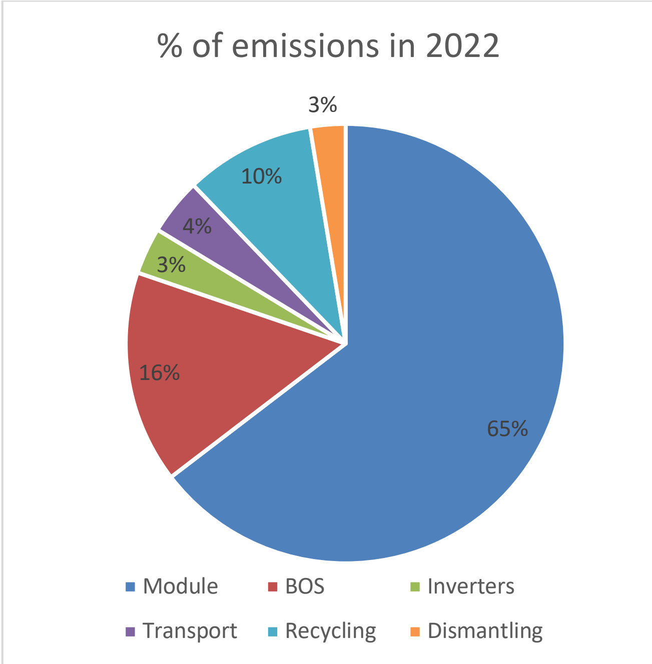

Figure 22. % emissions in 2022 for a fixed structure, China-Spain, PSC

Source: (Own Elaboration, 2023)

The two technologies show the estimated emissions per technology for solar cell production over time. The emissions for Mono-Si are higher than for Perovskite in every year. However, the emissions for both technologies are expected to decrease over time due to advancements in technology and more efficient manufacturing processes. By 2050, the emissions for Mono-Si are estimated to be 376.52 kg CO2/kWp, while for Perovskite, they are estimated to be 29.54 kg CO2/kWp. This suggests that Perovskite technology has a much lower carbon footprint than Mono-Si technology. However, it is important to note that the emissions for both technologies vary depending on the specific year and category.

6. CASE STUDIES

6.1. INTRODUCTION

In this chapter, we will discuss the two-case study. Firstly, applied to the current photovoltaic panels in Santa Cruz de Marcenado 26, Madrid, Spain. Moreover, (Carbonell de la Cámara, 2023) studies in his thesis the optimal photovoltaic panels that should be installed in this sitemap from the different offers the IIT received, so this will be the second case study. It will discuss the context of the panels and inverters, the applied technology and the country of manufacture and dismantling.

6.2. CURRENT PHOTOVOLTAIC PANELS

6.2.1. Modules and inverters background

The planned installation will have a peak power of the photovoltaic field of 4.8 kWp, which will be achieved with 40 monocrystalline silicon modules of 120 Wp manufactured by ATERSA. The photovoltaic modules will be connected to form groups of 8 modules in series to achieve the working voltage of the inverter.

The type of conductor to be used will be 0.6/1 kV, with a suitable cross-section to avoid voltage drops and overheating.

Electrical characteristics	
Maximum power	120 Wp
Current in the point of max. power	7.0 A
Voltage in the point of max. power	16.9 V
Short-circuit current	7.7 A

Open-circuit voltage	21 V
Nº cells	36 of 6"
Measures under the following conditions	
Cell temperature	25 ºC
Radiation	1000 W/m^2
Spectrum	AM 1.5
Physical characteristics	
Length	1477 mm
Width	660 mm
Thickness	35 mm
Weight	11.9 kg
Constructive characteristics	
Roof	Tempered glass
Encapsulant	Ethylene vinyl acetate (EVA)
Backing	White Tedlar
Frame	Anodized aluminum 15 micron

Table 12. Characteristics of PV plates

Source: (ICAI, 2023)

ATERSA's TAURO PRM inverter is a device designed to inject the energy produced by a photovoltaic generator into the commercial electricity grid.

The TAURO system provides a modular solution for grid-connected systems, suitable for use in domestic environments where ease of use, maintenance, low noise level and aesthetics are appreciated.

Inverter TAURO PRM 5000/8	
Nominal power of the installation	4000
Connection	Single-phase
Maximum power in the panel field - W	5000
Open circuit voltage - Voc	176
Maximum power current- Imax/A	37
Maximum power voltage - Vmax/A	136
Maximum short-circuit current- Isc/A	41
Rated AC voltage - Vn/V	230
AC power, Pn- kW	4
Vcc max- V	185
Vcc min- V	105

Table 13. Inverter characteristics

Source: (ICAI, 2023)

6.2.2. Company's background

ATERSA (https://www.atersa.com) is a Spanish company that specializes in the design, manufacturing, and distribution of photovoltaic solar panels. The company was founded in 1992 and is headquartered in Navarra, Spain. ATERSA's primary focus is on the production of high-performance solar panels for both residential and commercial applications. ATERSA manufactures its Optimum range in Taiwan and China as an OEM product"(original equipment manufacturer). The company has also assured that it will continue to manufacture its Ultra range in Almussafes (Valencia) and in the recently inaugurated factory in Mauritania.

The company's product range includes monocrystalline and polycrystalline solar panels, as well as flexible solar panels, which can be used for a wide range of applications, including building-integrated photovoltaics, portable power solutions, and solar-powered vehicles. ATERSA's solar panels are designed to be highly efficient, durable, and cost-effective.

In addition to manufacturing solar panels, ATERSA also offers a range of related services, including project consulting, installation, and maintenance. The company has a strong commitment to sustainability and renewable energy, and its solar panels are designed to help reduce greenhouse gas emissions and promote a more sustainable energy future.

To sum up, ATERSA is a well-established and respected player in the solar energy industry, with a strong track record of producing high-quality solar panels and providing excellent service to its customers.

6.2.3. Technology background

As it has been said before the technology used is monocrystalline silicon. Monocrystalline silicon, often abbreviated as mono-Si, is a type of silicon used in the production of solar cells. Mono-Si solar cells are made from a single crystal of silicon, which is grown in a controlled environment using a process called the Czochralski method.

The Czochralski method involves melting a polycrystalline silicon feedstock in a crucible and then slowly pulling a seed crystal out of the melt. As the seed crystal is pulled, it solidifies the molten silicon, creating a single crystal ingot. This ingot is then cut into thin wafers, which are used as the basis for monocrystalline solar cells.

Mono-Si solar cells have several advantages over other types of solar cells, including higher efficiency and a more uniform appearance. Because they are made from a single crystal of silicon, they have fewer defects and impurities than polycrystalline solar cells, which can reduce their efficiency. Mono-Si solar cells also have a distinctive dark color, which some people find more aesthetically pleasing than the speckled appearance of polycrystalline solar cells.

However, mono-Si solar cells are typically more expensive to produce than polycrystalline solar cells, due in part to the higher cost of the Czochralski method. As a result, they are often used in high-end applications where efficiency is paramount, such as in space satellites and high-performance solar panels for residential and commercial buildings.

6.2.4. Conclusions on current panels

To sum up this point, we can show the results in the following Table 14.

Inputs:	
Type of installation:	Fixed
Technology:	Mono-Si
Country of manufacture:	China
Country of installation:	Spain

Table 14. Inputs for the case study

Source: (Own Elaboration, 2023)

6.3. FUTURE PHOTOVOLTAIC PANELS

6.3.1. Modules and inverters background

The future installation will have a peak power of the photovoltaic field of 11.07 kWp, which will be achieved with 27 monocrystalline silicon modules of 410 Wp manufactured by SUNPOWER. More specifically, it is the SPR-P3-410-COM-1500 model. The photovoltaic modules will be connected as shown in Figure 23 to achieve the working voltage of the inverter.

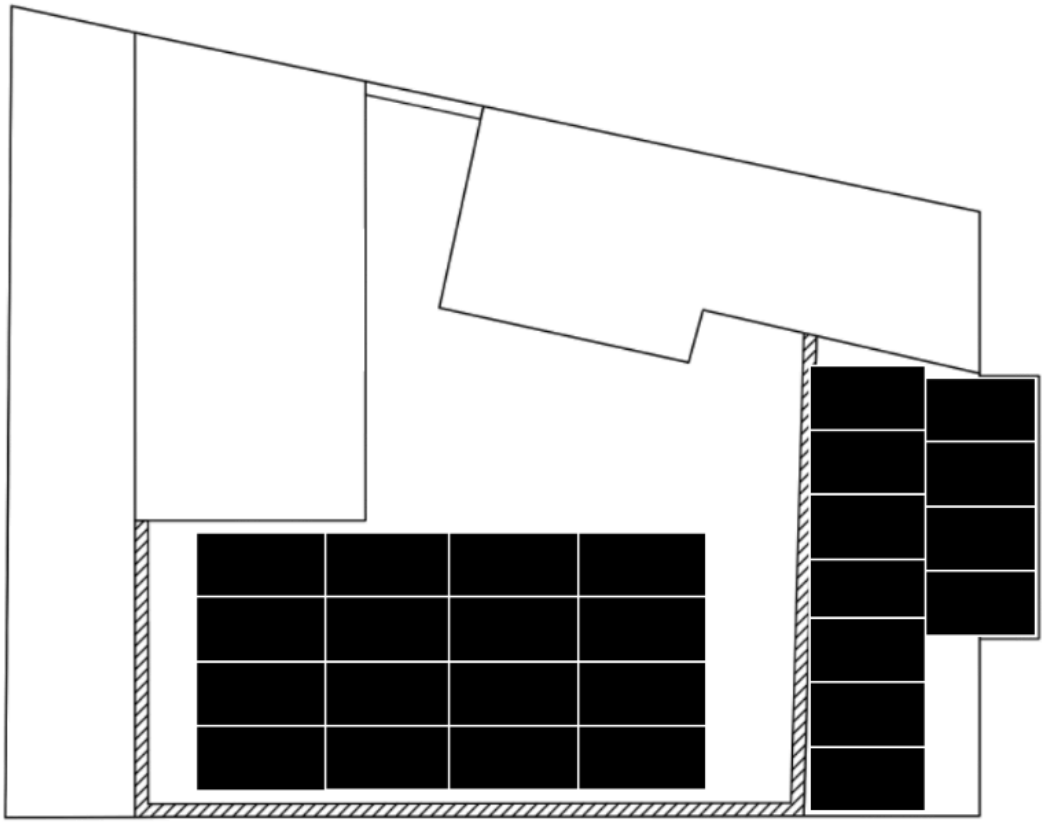

Figure 23. Future Surface Distribution

Source: (Carbonell de la Cámara, 2023)

Huawei inverter, SUN2000-12KTL-M2-3PH, is a device designed to inject the energy produced by a photovoltaic generator into the commercial electricity grid.

The Huawei system provides a modular solution for grid-connected systems, suitable for use in domestic environments where ease of use, maintenance, low noise level and aesthetics are appreciated.

6.3.2. Company's background

SunPower Corporation (https://sunpower.maxeon.com/es/) is an American energy company headquartered in San Jose, California. Established in 1985, the company specializes in designing, manufacturing, and selling solar power solutions for various applications.

One of SunPower's key offerings is its high-efficiency solar panels. These panels utilize the company's proprietary Maxeon solar cell technology, which allows for greater electricity generation in each space compared to traditional solar panels. SunPower's solar panels are widely recognized for their performance and durability.

In addition to solar panels, SunPower offers energy storage solutions. The SunPower Equinox® Storage system allows customers to store excess energy generated by their solar systems. This stored energy can be used during periods of low solar production or during power outages, providing greater energy independence and resilience.

SunPower emphasizes its commitment to sustainability and reducing environmental impact. The company aims to develop clean, renewable energy solutions to address climate change and reduce reliance on fossil fuels. SunPower has formed partnerships with builders, solar installers, and energy service providers to expand its reach and offer comprehensive solar power solutions.

6.3.3. Technology background

The technology used in the new modules is the same one as before monocrystalline silicon (Mono-Si). All the information about this technology is discussed in page 83.

6.3.4. Conclusions of future panels

To sum up this point, we can show the results in the following table, Table 14.

Inputs:	
Type of installation:	Fixed
Technology:	Mono-Si
Country of manufacture:	EEUU
Country of installation:	Spain

Table 15. Inputs for the case study

Source: (Own Elaboration, 2023)

7. RESULTS

7.1. INTRODUCTION

In this chapter, the results of both case studies will be introduced according to the conclusions drawn in the last section. Tables and graphs presented to show the results obtained.

7.2. RESULTS APPLIED TO THE CASE STUDY 1: CURRENT PHOTOVOLTAIC PANELS

After introducing the inputs of the Santa Cruz de Marcenado modules in the model. The following results are obtained:

	Emissions (kg CO2/kWp)						
Year	**Module**	**BOS**	**Inverters**	**Transport**	**Recycling**	**Dismantling**	**TOTAL**
2022	533,31	129,08	28,31	34,29	28,95	7,85	**761,79**
2023	524,61	126,97	27,85	33,73	26,55	7,20	**746,91**
2030	463,74	112,24	24,62	29,82	9,70	2,63	**642,75**
2050	289,82	70,15	15,38	18,64	0,00	0,00	**393,99**

Table 16. Emissions for the current PV panels in Santa Cruz de Marcenado

Source: (Own Elaboration, 2023)

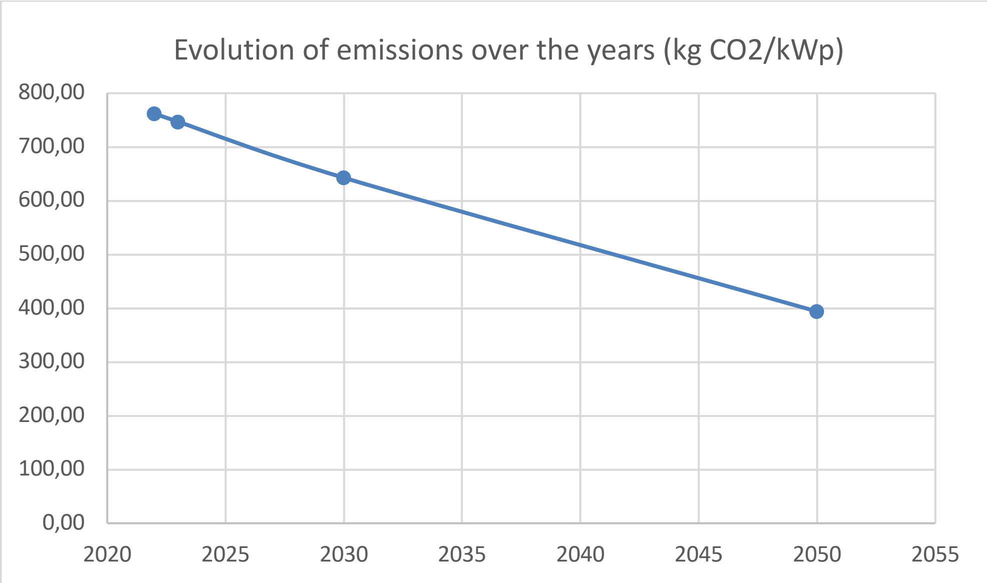

Figure 24. Evolution of the emissions over the years (kg CO2/kWp) for the current PV panels in Santa Cruz de Marcenado

Source: (Own Elaboration, 2023)

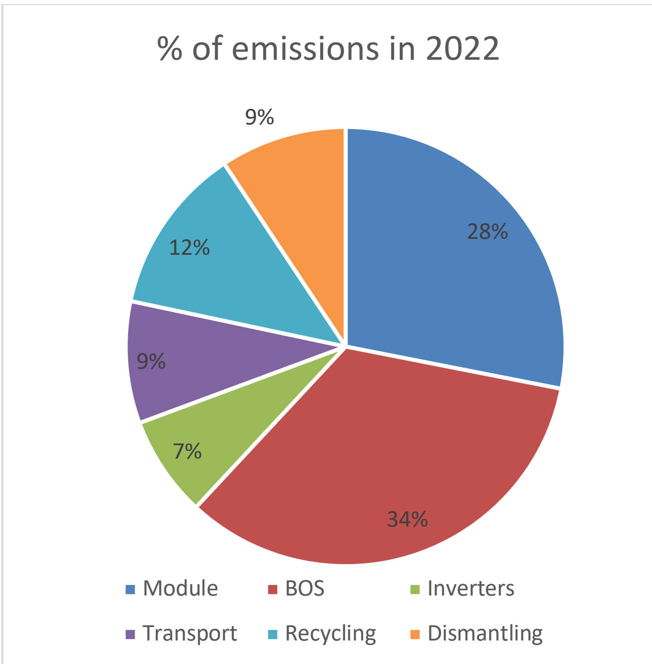

Figure 25. % emissions in 2022 for the current PV panels in Santa Cruz de Marcenado

Source: (Own Elaboration, 2023)

As it was said before the PV module in Santa Cruz de Marcenado, Madrid, Spain has a power of 4.8 kWp.

	Emissions (kg CO2)
Year	**TOTAL**
2022	**3656,60**
2023	**3585,17**
2030	**3085,18**
2050	**1891,15**

Table 17. Emissions in kg CO2 of the current PV modules

Source: (Own Elaboration, 2023)

7.3. RESULTS APPLIED TO THE CASE STUDY 2: FUTURE PHOTOVOLTAIC PANELS

After introducing the future inputs of the Santa Cruz de Marcenado modules, studied by (Carbonell de la Cámara, 2023) in the model. The following results are obtained:

			Emissions (kg CO2/kWp)				
Year	**Module**	**BOS**	**Inverters**	**Transport**	**Recycling**	**Dismantling**	**TOTAL**
2022	355,86	86,13	18,89	22,88	28,95	7,85	**520,57**
2023	343,43	83,12	18,23	22,08	26,55	7,20	**500,61**
2030	256,44	62,07	13,61	16,49	9,70	2,63	**360,94**
2050	7,88	1,91	0,42	0,51	0,00	0,00	**10,71**

Table 18. Emissions for the future PV panels in Santa Cruz de Marcenado

Source: (Own Elaboration, 2023)

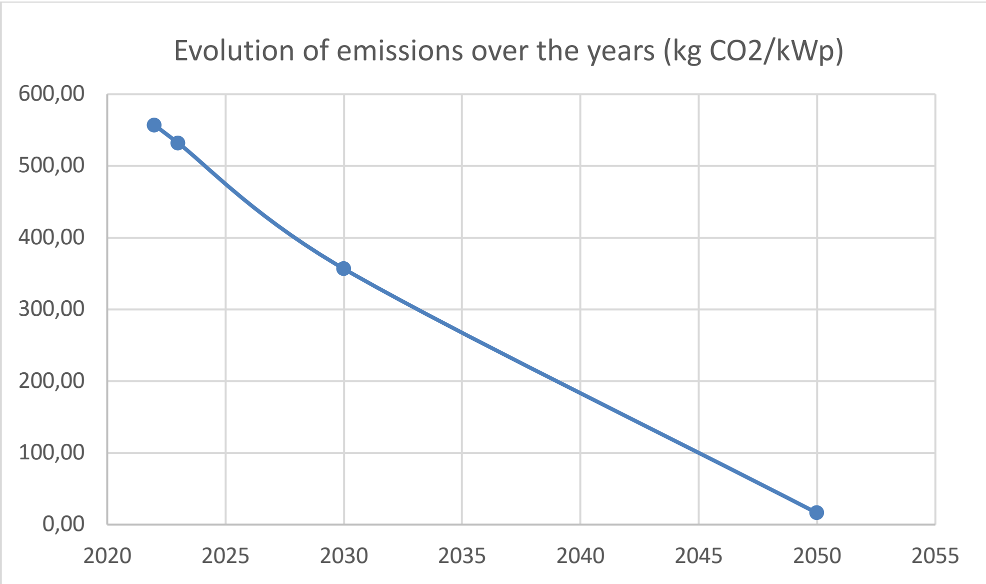

Figure 26. Evolution of the emissions over the years (kg CO2/kWp) for the future PV panels in Santa Cruz de Marcenado

Source: (Own Elaboration, 2023)

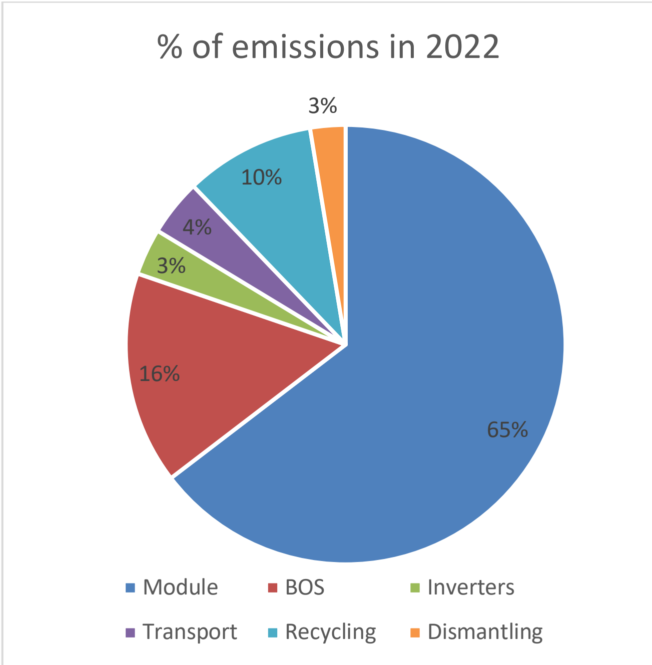

Figure 27. % emissions in 2022 for the future PV panels in Santa Cruz de Marcenado

Source: (Own Elaboration, 2023)

As it was said before the PV module in Santa Cruz de Marcenado, Madrid, Spain has a power of 11.07 kWp.

	Emissions (kg CO2)
Year	**TOTAL**
2022	**5762,69**
2023	**5541,80**
2030	**3995,55**
2050	**118,56**

Table 19. Emissions in kg CO2 of the future PV modules

Source: (Own Elaboration, 2023)

7.4. OPTIMAL SOLUTION

Without considering the bids received for the installation, nor the cost to the IIT, the optimal case will be studied in terms of the years 2023, 2030 and 2050. In other words, considering only the emissions generated.

Given the location in Santa Cruz de Marcenado we can set as a fixed parameter that the installation will be fixed (without tracking to any axis) and the country of installation will be Spain.

The following tables (Table 20, Table 21 and Table 22) show the comparison of the emissions between the country of manufacture and the technology for 2023, 2030 and 2050 in kg CO_2/kWp.

	China	Spain	Germany	Italy	Canada	EEUU
Mono-Si	746,91	277,17	488,02	492,93	188,38	500,61
Poli-Si	879,33	326,69	574,74	580,53	222,23	589,57
Ribbon-Si	779,21	289,02	509,04	514,17	196,36	522,19
a-Si	549,12	228,44	372,38	375,73	167,81	380,98
CdTe	467,88	176,44	307,25	310,31	121,34	315,07
CIS/CIGS	568,75	208,86	370,39	374,16	140,82	380,05
Organic	2053,59	773,87	1348,27	1361,67	531,95	1382,59
HCPV	332,50	121,82	216,38	218,59	81,99	222,03
PSC	173,69	63,95	113,21	114,36	$\boxed{43,21}$	116,15
QD	320,96	117,77	208,97	211,10	79,36	214,42

Table 20. Comparison of CO2 emissions manufacturing country-technology for 2023 with fixed structure in Spain.

Source: (Own Elaboration, 2023)

	China	Spain	Germany	Italy	Canada	EEUU
Mono-Si	642,75	101,26	334,19	414,37	128,41	360,94
Poli-Si	756,39	119,35	393,38	487,72	151,29	424,85
Ribbon-Si	670,64	105,59	348,65	432,33	133,92	376,57
a-Si	453,12	83,46	242,47	297,22	101,99	260,73
CdTe	400,42	64,46	208,98	258,73	81,30	225,57
CIS/CIGS	491,16	76,30	254,76	316,20	97,10	275,25
Organic	1757,91	282,72	917,29	1135,75	356,67	990,16
HCPV	287,37	44,50	148,97	184,94	56,68	160,97
PSC	149,87	23,36	77,78	96,51	29,71	84,03
QD	277,25	43,03	143,78	178,47	54,77	155,35

Table 21. Comparison of CO2 emissions manufacturing country-technology for 2030 with fixed structure in Spain.

Source: (Own Elaboration, 2023)

	China	Spain	Germany	Italy	Canada	EEUU
Mono-Si	393,99	0,00	0,00	238,78	5,92	10,71
Poli-Si	463,52	0,00	0,00	280,92	6,97	12,60
Ribbon-Si	411,14	0,00	0,00	249,18	6,18	11,18
a-Si	268,98	0,00	0,00	163,02	4,04	7,31
CdTe	244,45	0,00	0,00	148,15	3,68	6,65
CIS/CIGS	301,86	0,00	0,00	182,94	4,54	8,21

Organic	1073,37	0,00	0,00	650,52	16,14	29,18
HCPV	176,71	0,00	0,00	107,10	2,66	4,80
PSC	92,04	0,00	0,00	55,78	1,38	2,50
QD	170,42	0,00	0,00	103,29	2,56	4,63

Table 22. Comparison of CO2 emissions manufacturing country-technology for 2050 with fixed structure in Spain.

Source: (Own Elaboration, 2023)

Ideally, PSC panels should be produced in 2023 and 2030. As it shown in the previous tables, according to the emissions, in 2023 panels should be manufactured in Canada whereas in 2030 the optimal manufacturing country would be Spain. For 2050, as the emissions in Spain and Germany go down to 0 because of the European Green Deal, the manufacturing country would not matter or either the technology. Due to their high development over the past few years compared to other technologies, PSC panels would still be the optimal panels. These panels have an efficiency of 26%, have a low price, and unlike silicon panels, perovskite solar cells do not require high-temperature refining and can be produced as inks that can be "printed" on other materials such as plastic.

Although right now Spain is behind other countries in the manufacturing of PV panels, Spain is a country with an impressive photovoltaic production potential, thanks to all the hours of sunshine it receives. However, the penetration of this energy source is much lower than in countries such as Germany or the Netherlands, where production capacity is lower. We have a long way to go.

One positive piece of news is that there are already an increasing number of solar panel manufacturers in Spain. And although they do not reach the international tops, it is a big step for the development of this industry at national level.

7.5. SUMMARY OF RESULTS

For a better understanding of the subsequent results, the following tables (Table 23, Table 24, Table 25) show a comparison of the three proposed scenarios: 2023, 2030 and 2050, comparing the current situation, the future situation and the optimal situation.

	Current Situation	**Future Situation**	**Optimal Situation**
Technology:	Mono-Si	Mono-Si	PSC
Country of manufacture:	China	EEUU	Canada
Manufacturing: CO2 Emissions (kg CO2/kWp)	713,17	466,87	36,13
Dismantling: CO2 Emissions (kg CO2/kWp)	33,74	33,74	7,08
Total CO2 Emissions (kg CO2/kWp)	746,91	500,61	43,21
% of avoided emissions	0%	33%	94%

Table 23. Main results for 2023 scenario

Source: (Own Elaboration, 2023)

	Current Situation	**Future Situation**	**Optimal Situation**
Technology:	Mono-Si	Mono-Si	PSC
Country of manufacture:	China	EEUU	Spain
Manufacturing: CO2 Emissions (kg CO2/kWp)	630,42	348,61	20,78
Dismantling: CO2 Emissions (kg CO2/kWp)	12,33	12,33	2,59
Total CO2 Emissions (kg CO2/kWp)	642,75	360,94	23,36
% of avoided emissions	0%	44%	96%

Table 24. Main results for 2030 scenario

Source: (Own Elaboration, 2023)

	Current Situation	**Future Situation**	**Optimal Situation**
Technology:	Mono-Si	Mono-Si	All
Country of manufacture:	China	EEUU	Spain/ Germany
Manufacturing: CO2 Emissions (kg CO2/kWp)	393,99	10,71012024	0,00
Dismantling: CO2 Emissions (kg CO2/kWp)	0,00	0,00	0,00
Total CO2 Emissions (kg CO2/kWp)	393,99	10,71	0,00
% of avoided emissions	0%	97%	100%

Table 25. Main results for 2050 scenario

Source: (Own Elaboration, 2023)

8. CONCLUSIONS

When this work began, four research questions were posed, which have been answered throughout the course of the project. The questions initially proposed were:

1. Which PV plant technology produces the lowest unit emissions (kg CO_2/kWp)?
2. What is the configuration of the installation with the lowest environmental impact?
3. How will the place of manufacture of the components influence the emissions generated?

In Chapter 5 (Emissions Analysis), the characteristics of the different technologies and typologies of PV panels were analyzed. More specifically, the energy invested in module manufacturing, BOS, inverters, transport, recycling and dismantling in MJ/m^2 was analyzed. Looking at the power per m^2, the energy required per MWh/kWp was calculated.

In order to answer these questions, a model was developed which calculates the emissions in kg CO_2/kWp from the following inputs: type of installation, technology, country of manufacture and country of installation.

- *Which PV plant technology produces the lowest unit emissions (kg CO_2/kWp)?*

According to the results in Chapter 7 (Results), the technology that presents the less emissions are perovskite cells. In 2023, the emissions of these panels are a 75% lower than the mean of emissions. It is true that due to the emissions rate in 2050 in Spain and Germany, it would not matter which cells to use because the electricity system is expected to be decarbonized.

- *What is the configuration of the installation with the lowest environmental impact?*

As it has been said before in Chapter 4 (Typologies and Technologies of PV Installations), the BOS of single-axis trackers shall be considered to require 7.5% more additional energy to produce than fixed-axis trackers, and the BOS of dual-axis trackers shall be considered to require 12.5% additional energy. So just focusing on the emissions, the configuration with less emissions is fixed structure.

- *How will the place of manufacture of the components influence the emissions generated?*

The answer to this question is developed in Chapter 5 (Emissions Analysis). Since the manufacturing technology of the components is assumed to be constant, the energy required will be the same in all the countries analyzed. Thus, those countries that have an electricity sector with lower specific emissions (t CO2/MWh) will produce these components with lower emission levels. Among the countries analyzed, Canada stands out, whose emissions would have been 74.78% lower than in China.

To continue with this study, the analysis of emissions could be carried out taking into account another important parameter: efficiency. This would not only consider the emissions generated, but also the emissions-MWh ratio obtained, in order to achieve lower emissions per unit of energy produced, instead of per installed power, which has been the object of this project.

On the other hand, it would be interesting to analyze the costs associated with each of the above-mentioned combinations, since the effects of tariffs, transport, factor costs, taxes, etc., can substantially modify the decision taken, since this has only been done from a strictly environmental point of view.

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ANNEX I: EMPLOYED MODEL

The model described below follows the methodology explained in Chapter 3 (Methodology) with the required data indicated during the project.

REQUIRED DATA

	Irradiation (MJ/m^2)						
	Emod	**E bos**	**E invers**	**E transport**	**E rec**	**E desmant**	**TOTAL**
Mono-Si	716,60	173,44	38,04	46,08	106,23	28,80	**1109,19**
Poli-Si	701,90	173,44	38,04	46,08	106,23	28,80	**1094,49**
Ribbon-Si	506,90	173,44	38,04	46,08	76,51	28,80	**869,77**
a-Si	109,12	173,44	38,04	46,08	108,54	28,80	**504,02**
CdTe	149,42	173,44	38,04	46,08	39,65	28,80	**475,43**
CIS/CIGS	322,40	173,44	38,04	46,08	40,70	28,80	**649,46**
Organic	143,99	173,44	38,04	46,08	38,21	28,80	**468,56**
HCPV	447,30	173,44	38,04	46,08	52,76	28,80	**786,42**
PSC	84,50	173,44	38,04	46,08	13,81	28,80	**384,67**
QD	38,00	173,44	38,04	46,08	6,21	28,80	**330,57**

Table 26. Irradiation (MJ/m2)

Source: (Own Elaboration, 2023)

m^2 / kWp	
Mono-Si	5,01
Poli-Si	5,98
Ribbon-Si	6,66
a-Si	9,09
CdTe	7,44
CIS/CIGS	6,45
Organic	33,11
HCPV	3,11
PSC	3,33
QD	7,14

Table 27. Power PV density per gross surface

Source: (Own Elaboration, 2023)

	Required Energy (MJ/kWp)						
	Emod	**E bos**	**E invers**	**E transport**	**E rec**	**E desmant**	**TOTAL**
Mono-Si	3590,18	868,94	190,58	230,86	532,21	144,29	**5557,06**
Poli-Si	4200,48	1037,94	227,65	275,76	635,73	172,35	**6549,91**
Ribbon-Si	3377,08	1155,50	253,43	307,00	509,73	191,87	**5794,60**
a-Si	991,55	1576,01	345,66	418,72	986,28	261,70	**4579,92**
CdTe	1111,76	1290,48	283,04	342,86	295,01	214,29	**3537,43**
CIS/CIGS	2078,66	1118,25	245,26	297,10	262,41	185,69	**4187,36**
Organic	4767,88	5743,05	1259,60	1525,83	1265,23	953,64	**15515,23**
HCPV	1389,13	538,63	118,14	143,11	163,85	89,44	**2442,30**

PSC	281,67	578,13	126,80	153,60	46,02	96,00	**1282,22**
QD	271,43	1238,86	271,71	329,14	44,35	205,71	**2361,21**

Table 28. Required Energy (MJ/kWp)

Source: (Own Elaboration, 2023)

	Fixed							**Single axis**	**Dual axis**
Required Energy (kWh/kWp)									
	Emod	**E bos**	**E invers**	**E transport**	**E rec**	**E desmant**	**TOTAL**	**TOTAL**	**TOTAL**
Mono-Si	997,27	241,37	52,94	64,13	147,84	40,08	**1543,63**	**1561,73**	**1573,80**
Poli-Si	1166,80	288,32	63,24	76,60	176,59	47,88	**1819,42**	**1841,04**	**1855,46**
Ribbon-Si	938,08	320,97	70,40	85,28	141,59	53,30	**1609,61**	**1633,68**	**1649,73**
a-Si	275,43	437,78	96,02	116,31	273,97	72,69	**1272,20**	**1305,03**	**1326,92**
CdTe	308,82	358,47	78,62	95,24	81,95	59,52	**982,62**	**1009,50**	**1027,43**
CIS/CIGS	577,41	310,62	68,13	82,53	72,89	51,58	**1163,16**	**1186,45**	**1201,98**
Organic	1324,41	1595,29	349,89	423,84	351,45	264,90	**4309,79**	**4429,43**	**4509,20**
HCPV	385,87	149,62	32,82	39,75	45,51	24,84	**678,42**	**689,64**	**697,12**
PSC	78,24	160,59	35,22	42,67	12,78	26,67	**356,17**	**368,22**	**376,25**
QD	75,40	344,13	75,48	91,43	12,32	57,14	**655,89**	**681,70**	**698,91**

Table 29. Required Energy (kWh/kWp) for Fixed, Single Axis and Dual axis panels

Source: (Own Elaboration, 2023)

Yearly emissions (gCO2/kWh)						
Year	**China**	**Spain**	**Germany**	**Italy**	**Canada**	**EEUU**
2000	672,37	425,63	498,51	506,19	214,51	532,61
2001	654,88	385,08	494,35	499,34	222,08	535,38
2002	663,28	439,83	497,08	524,14	213,72	526,75
2003	677,91	392,69	500,05	521,66	219,75	531,99
2004	667,90	410,16	487,04	505,65	203,86	528,83
2005	670,51	436,34	482,56	504,36	200,67	530,55
2006	676,62	404,15	474,40	500,96	189,31	521,93
2007	679,41	407,36	488,67	497,77	195,39	524,97
2008	649,67	372,29	468,49	478,62	185,92	518,42
2009	658,04	342,13	464,67	451,60	173,51	496,26
2010	650,61	280,13	462,20	440,13	175,47	501,34
2011	663,60	319,18	472,59	437,65	165,25	484,12
2012	637,24	328,28	475,15	428,02	155,27	470,47
2013	636,22	270,58	477,54	389,14	149,50	470,62
2014	617,00	271,26	463,10	369,27	147,59	467,31
2015	596,36	307,30	448,40	389,32	147,66	447,66
2016	584,16	268,82	448,03	383,74	144,85	429,44
2017	579,02	309,97	424,13	388,64	136,78	416,78
2018	573,83	275,42	411,56	363,93	132,70	412,06
2019	560,00	243,49	361,57	352,05	130,94	392,78
2020	549,60	199,51	332,58	336,71	119,70	369,39
2021	544,36	193,86	365,98	340,79	128,46	379,38

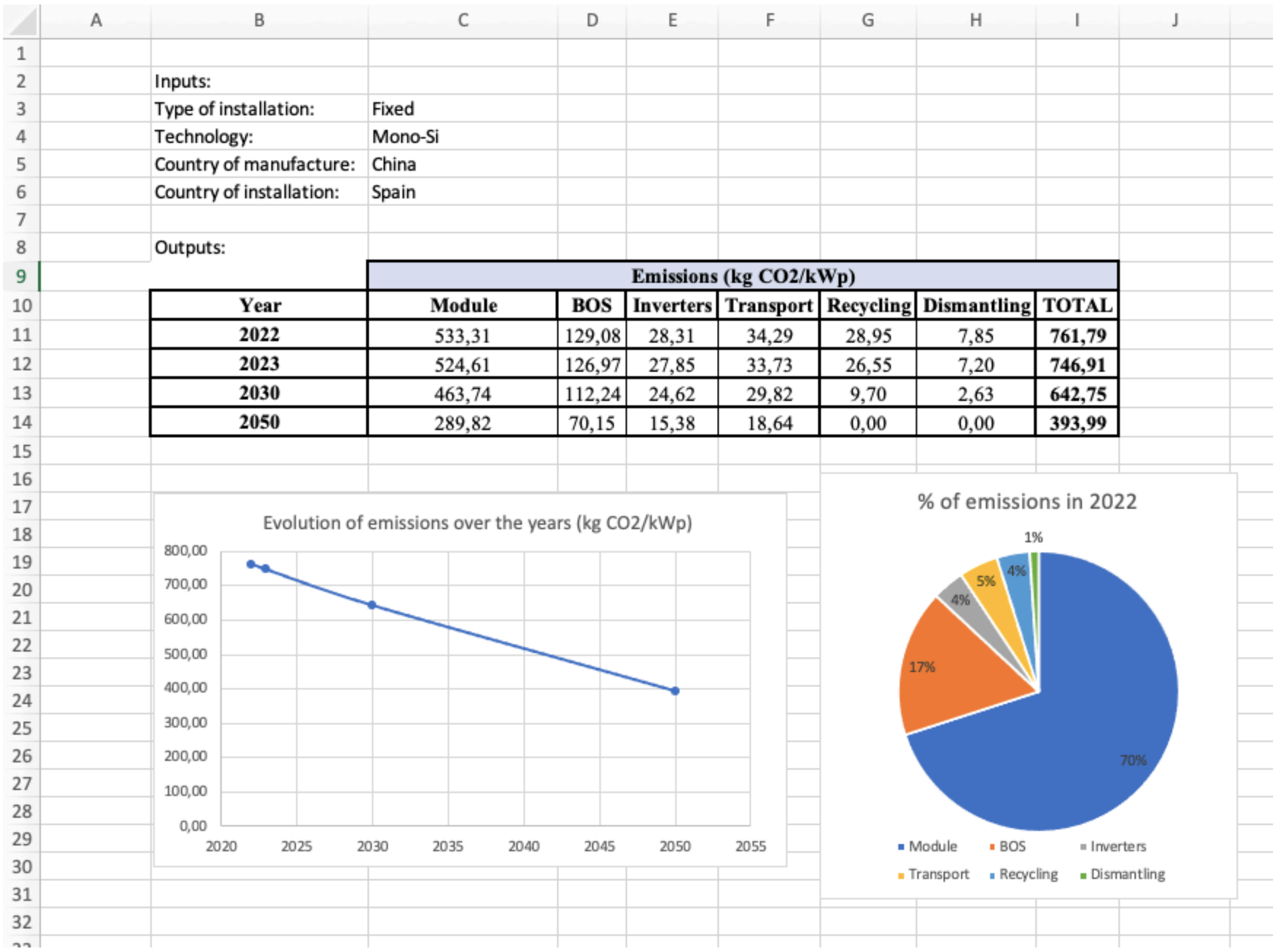
2022	534,77	195,84	349,03	344,73	118,12	356,84
2023	526,05	179,56	335,08	338,71	114,06	344,37
2030	465,01	65,60	237,41	296,56	85,62	257,14
2050	290,62	0,00	0,00	176,13	4,37	7,90

Table 30. Yearly emissions (gCO2/kWh) in China, Spain, Germany, Italy, Canada and EEUU

Source: (Own Elaboration, 2023)

EMPLOYED MODEL

With all the information from the previous tables (Table 26, Table 27, Table 28, Table 29 and Table 30), a model with the following appearance is generated (Figure 28).



Inputs:
Type of installation: Fixed
Technology: Mono-Si
Country of manufacture: China
Country of installation: Spain

Outputs:

	Emissions (kg CO2/kWp)						
Year	**Module**	**BOS**	**Inverters**	**Transport**	**Recycling**	**Dismantling**	**TOTAL**
2022	533,31	129,08	28,31	34,29	28,95	7,85	**761,79**
2023	524,61	126,97	27,85	33,73	26,55	7,20	**746,91**
2030	463,74	112,24	24,62	29,82	9,70	2,63	**642,75**
2050	289,82	70,15	15,38	18,64	0,00	0,00	**393,99**

Figure 28. Employed Model

Source: (Own Elaboration, 2023)

- C3: Drop-down cell for the input of "Type of installation" with the following options: Fixed, Single Axis, Dual Axis.
- C4: Drop-down cell for the input of "Technology" with the following options: Mono-Si, Poly-Si, Ribbon-Si, CdTe, a-Si, CIGS, Organic, HCPV, PSC, QD.
- C5: Drop-down cell for the input of "Country of manufacture" with the following options: China, Spain, Germany, Italy, Canada, EEUU.
- C6: Drop-down cell for the input of "Country of installation" with the following options: China, Spain, Germany, Italy, Canada, EEUU.

- C11:I14 (Emissions kg CO2/kWp): Each cell indicates the emissions generated by that part of the process. (= “Emissions” * “Required Energy”/1000)