COMILLAS
UNIVERSIDAD PONTIFICIA
ICAI

GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

DISEÑO DE UNA INSTALACIÓN SOLAR FOTOVOLTAICA PARA AUTOCONSUMO ELÉCTRICO EN EL SECTOR RESIDENCIAL

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Madrid, 24 de junio de 2025

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Diseño de una instalación solar fotovoltaica para autoconsumo eléctrico en el sector residencial

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

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COMILLAS
UNIVERSIDAD PONTIFICIA
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BACHELOR'S DEGREE IN ENGINEERING FOR INDUSTRIAL TECHNOLOGIES

BACHELOR'S THESIS

DESIGN OF A SOLAR PHOTOVOLTAIC INSTALLATION FOR SELF-CONSUMPTION OF ELECTRICITY IN THE RESIDENTIAL SECTOR

Author: Álvaro Marijuán Garralda

Director: Consolación Alonso Alonso

Madrid, 24th June 2025

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DISEÑO DE UNA INSTALACIÓN SOLAR FOTOVOLTAICA PARA AUTOCONSUMO ELÉCTRICO EN EL SECTOR RESIDENCIAL

Autor: Marijuán Garralda, Álvaro.
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RESUMEN DEL PROYECTO

En este proyecto se ha diseñado una instalación solar fotovoltaica para el autoconsumo de electricidad en una vivienda unifamiliar. Teniendo en cuenta el consumo eléctrico anual de la vivienda, se ha determinado, con la ayuda del software PVsyst, que una instalación fotovoltaica de 5,5 kWp y 5 kWn representa un buen equilibrio entre la cobertura de energía solar y el índice de autoconsumo. Un análisis económico posterior sugiere que, debido al ahorro energético esperado, incluso sin considerar ningún tipo de subvención o incentivo, este proyecto representa una inversión excelente, con un valor actual neto (VAN) positivo, un corto periodo de amortización de entre 5 y 6 años, y una tasa interna de retorno (TIR) del 19 %, muy superior a otras inversiones con riesgos similares.

Palabras clave: Instalación solar fotovoltaica, electricidad, autoconsumo

1. Introducción

En el contexto del aumento de los precios de la electricidad, la creciente preocupación medioambiental y los esfuerzos globales por avanzar hacia una energía limpia, los sistemas fotovoltaicos residenciales para autoconsumo han surgido como una solución prometedora. Estos sistemas permiten a los hogares generar y consumir su propia energía solar, reduciendo significativamente tanto los costes eléctricos como la dependencia de los combustibles fósiles. Más allá de los beneficios medioambientales y técnicos, las instalaciones fotovoltaicas para autoconsumo también representan una inversión económicamente atractiva, ya que ofrecen ahorros a largo plazo con costes operativos mínimos tras la puesta en marcha. Al integrar almacenamiento en baterías y, potencialmente, alimentar vehículos eléctricos, estos sistemas refuerzan aún más la independencia energética y contribuyen a la descentralización de la generación eléctrica. Este proyecto tiene como objetivo diseñar un sistema solar fotovoltaico residencial eficiente y económicamente viable que no solo favorezca la autonomía energética individual, sino que también esté alineado con los objetivos de sostenibilidad más amplios, como el Pacto Verde Europeo y el Acuerdo de París.

2. Definición del proyecto

Este proyecto busca diseñar una instalación solar fotovoltaica para el autoconsumo de electricidad en una vivienda unifamiliar. En función de su demanda energética anual y de las características de la superficie disponible en la cubierta, como la orientación, la inclinación y el área útil, se propondrá un diseño del sistema fotovoltaico basado en los resultados de simulación obtenidos con el software PVsyst. El proyecto describirá detalladamente el diseño y los componentes necesarios para la instalación, así como otros cálculos eléctricos relevantes para la generación de electricidad a partir de la conversión de energía solar en energía eléctrica. Además, se evaluará la viabilidad económica teniendo en cuenta la producción energética de la instalación, la inversión inicial y otros flujos de caja estimados a futuro. En resumen, el objetivo del proyecto es proponer un diseño de instalación solar fotovoltaica y demostrar por qué resulta una inversión financiera inteligente, tanto por razones económicas como medioambientales y geopolíticas.

3. Descripción de un sistema solar fotovoltaico

Una instalación fotovoltaica es un sistema de generación de energía sencillo que requiere solo unos pocos componentes para convertir la energía solar en electricidad, como se muestra en la *Ilustración 1*.

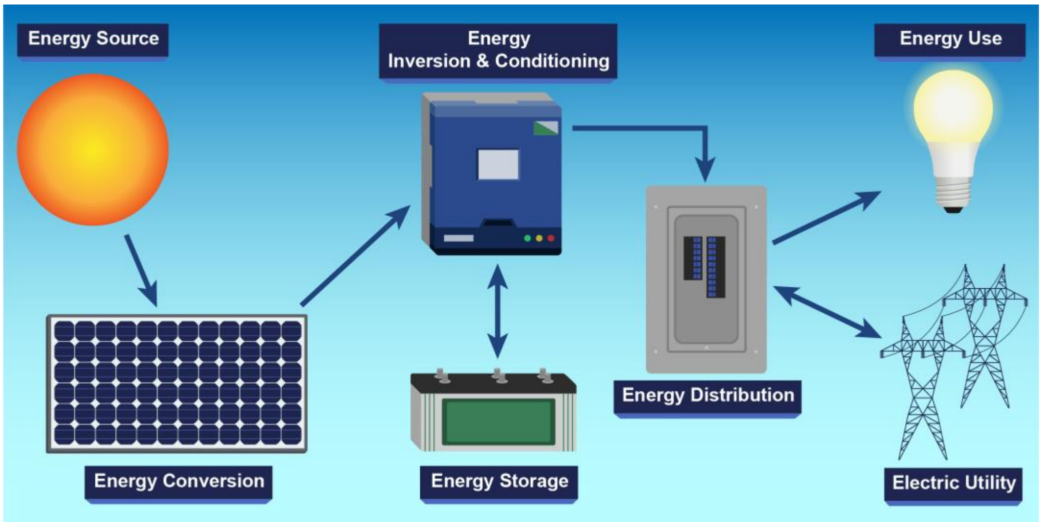

Ilustración 1: Diagrama básico de un sistema fotovoltaico [1]

Los paneles solares están expuestos a la luz solar, compuesta por fotones. Debido a la estructura de una célula fotovoltaica, se genera un campo eléctrico, y cuando los fotones inciden sobre los paneles solares, dicho campo dirige los electrones libres para que fluyan en una dirección específica, generando así una corriente eléctrica. Esta corriente continua se envía al inversor, que la convierte en corriente alterna, adecuada para su consumo en la vivienda o su inyección a la red eléctrica. Además, puede instalarse un sistema de almacenamiento en baterías para guardar el excedente de energía generado por la instalación para su uso posterior, ya que no puede ser consumido instantáneamente por la vivienda y, de otro modo, se inyectaría a la red.

Finalmente, el inversor se conecta al cuadro general de protección de la vivienda, desde donde se distribuye la energía a las cargas o, en caso de que la generación sea superior al consumo, se envía a la red a cambio de una tarifa de compensación.

4. Resultados

Antes de realizar las simulaciones, se analizó el consumo eléctrico de la vivienda. Dado que los datos obtenidos del consumo del año anterior no eran en absoluto representativos del consumo eléctrico futuro, se desarrollaron tres escenarios distintos, considerando cargas adicionales que no estaban incluidas en la tabla de consumo inicial.

Tras ejecutar varias simulaciones con diferentes configuraciones y considerando el Escenario 2 como el más probable de cara al futuro, se obtuvieron los resultados reflejados en la *Tabla 1*, que corresponden a un sistema con una inclinación fija de 35º, orientado al sur, con una potencia instalada de 5,5 kWp y 5 kWn. El grado de autoconsumo es del 38%, lo cual es más que aceptable. La energía solar cubre casi el 40% de la demanda de la vivienda, y el resto deberá ser adquirido de la red, lo cual podría compensarse parcialmente con la inyección del excedente energético a la misma. En conjunto, esta configuración representa un buen equilibrio entre la cobertura de energía solar y el grado de autoconsumo.

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_User kWh	E_Solar kWh	E_Grid kWh	EFrGrid kWh
January	92.5	26.79	11.07	159.8	143.3	736	611	204	492	407
February	104.4	32.72	9.96	155.2	140.3	721	550	188	493	362
March	155.8	52.55	13.89	193.2	179.7	909	580	233	627	347
April	179.9	58.36	14.61	191.3	178.1	899	680	285	566	396
May	226.3	67.68	17.83	213.9	198.7	993	646	297	643	349
June	241.2	61.87	20.70	216.8	201.6	998	983	431	513	552
July	241.1	64.79	25.00	222.6	207.1	1007	1239	520	432	719
August	222.5	56.94	24.38	227.9	213.0	1036	1282	531	450	751
September	167.7	51.31	22.43	196.9	183.7	901	1084	419	434	665
October	136.5	44.01	19.49	189.6	175.4	873	667	258	569	409
November	95.3	32.03	16.15	153.5	139.1	702	585	194	469	390
December	86.0	27.20	13.72	156.2	138.5	707	593	196	472	397
Year	1949.3	576.24	17.49	2276.9	2098.6	10484	9500	3757	6161	5743

Tabla 1: Resultados de un sistema fotovoltaico de 5.5 kWp y 5 kWn

A continuación, se seleccionaron 3 tarifas eléctricas del mercado libre ofrecidas por distintas comercializadoras para analizar cuál de ellas proporcionaría al propietario de la vivienda el mayor ahorro, teniendo en cuenta los resultados energéticos obtenidos en la *Tabla 1*. Considerando tanto los términos de energía y potencia como los peajes de transporte y distribución y los impuestos correspondientes, se obtuvieron los ahorros energéticos del primer año, presentados en la *Tabla 2*.

Ahorros anuales	
Repsol	1247,51 €
Naturgy	1330,94 €
Endesa	1124,03 €

Tabla 2: Ahorros anuales en la factura de la electricidad

A continuación, se obtuvieron algunos indicadores económicos. Para realizar dichos cálculos, se consideraron un coste de inversión inicial de 7250 €, una tasa de descuento del 5 %, una reserva anual para mantenimiento de 50 € y un coste de 700 € por la sustitución del inversor en el año 13. Además, se tuvo en cuenta un incremento anual del 2 % en el precio de la electricidad y un factor de degradación del 0,5 % anual de la instalación fotovoltaica para estimar los ahorros energéticos anuales durante los próximos 25 años. Estos datos de entrada ofrecieron un valor actual neto (VAN) de 14.124,42 €, un periodo de retorno de la inversión entre 5 y 6 años, y una tasa interna de retorno (TIR) del 19 %. Cabe destacar que estos cálculos económicos se realizaron sin tener en cuenta posibles subvenciones o incentivos, los cuales harían el proyecto aún más atractivo desde el punto de vista económico, como se calculó posteriormente al considerar una posible deducción en el impuesto sobre la renta de las personas físicas (IRPF).

5. Conclusiones

En resumen, este proyecto propone una solución energética para un propietario cuya demanda eléctrica aumentará en los próximos años. Al generar electricidad limpia y renovable in situ, el hogar puede reducir su dependencia de la red, disminuir las emisiones de carbono y alcanzar una mayor independencia energética. Con los beneficios adicionales de ahorro a largo plazo y el apoyo a objetivos climáticos más amplios, los sistemas fotovoltaicos residenciales representan un paso clave hacia un futuro energético más resiliente y sostenible.

6. Referencias

[1] Florida Solar Energy Center. (n.d.). *How a PV system works*. University of Central Florida. https://energyresearch.ucf.edu/consumer/solar-technologies/solar-electricity-basics/how-a-pv-system-works/

DESIGN OF A SOLAR PHOTOVOLTAIC INSTALLATION FOR SELF-CONSUMPTION OF ELECTRICITY IN THE RESIDENTIAL SECTOR

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Collaborating Entity: ICAI – Universidad Pontificia Comillas

ABSTRACT

In this project, a solar photovoltaic installation for self-consumption of electricity in a single-family household has been designed. Considering the household electricity consumption throughout the year, a PV installation of 5.5 kWp and 5 kWn has been determined to be a good trade-off between solar energy coverage and self-consumption ratio with the help of PVsyst software. A following economic analysis suggested that due to the energy savings expected, even without considering any subsidies or incentives of any kind, this project represents an outstanding investment with a positive net present value, a short payback period between 5-6 years and an internal rate of return of 19%, much higher than other investments with similar risks.

Keywords: Solar photovoltaic system, electricity, self-consumption

1. Introduction

In the context of rising electricity prices, increasing environmental concerns, and global efforts to transition towards clean energy, residential photovoltaic systems for self-consumption have emerged as a promising solution. These systems allow households to generate and consume their own solar energy, significantly reducing electricity costs and dependence on fossil fuels. Beyond the environmental and technical benefits, self-consumption PV installations also offer an attractive economic investment, providing long-term savings with minimal operational costs after the initial setup. By integrating battery storage and potentially powering electric vehicles, such systems further enhance energy independence and contribute to the decentralisation of electricity generation. This project aims to design an efficient and economically viable residential solar PV system that not only supports individual energy autonomy but also aligns with broader sustainability targets such as the European Green Deal and the Paris Agreement.

2. Project definition

This project seeks to design a solar photovoltaic installation for self-consumption of electricity in a single-family household. Depending on its annual energy demand and the available roof's surface area, orientation and inclination, a design for the photovoltaic system will be proposed based on the simulation results obtained with the PVsyst software. The project will thoroughly describe the design and components needed for the installation as well as other relevant electrical calculations to generate electricity by converting solar into electrical energy. Additionally, the economic viability will be evaluated by considering the energy yield of the PV installation, the initial investment cost and other estimated future cash flows. All in all, the objective of the project is to propose a design of a solar photovoltaic installation and to demonstrate why is it a clever idea to carry out such a financial investment due to economic, environmental and geopolitical reasons.

3. PV installation description

A photovoltaic installation is a simple power-generating system which requires only a few components to convert solar energy into electricity, as shown in *Figure 1*.

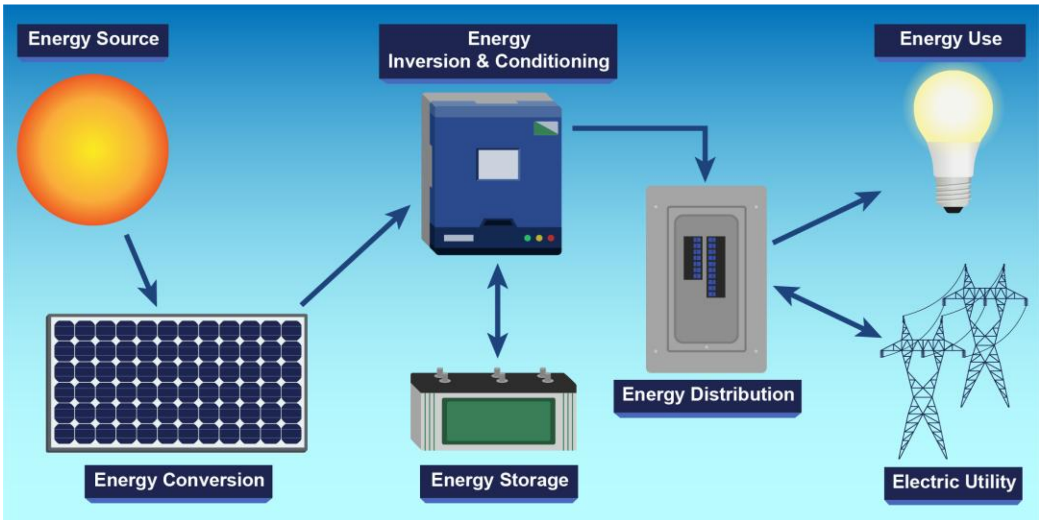

Figure 1: Basic diagram of a photovoltaic system [1]

The solar panels are exposed to sunlight, which is made up of photons. Due to the structure of a PV cell, an electric field is created, and when the photons hit the solar panels, the electric field directs the free electrons to flow in a specific direction, generating an electric current. This direct current is sent to the inverter, which converts it to alternating current, suitable for its consumption in the household or injection into the electric grid. Additionally, a battery storage system could also be installed for storing the surplus energy generated by the installation for its later use, since it cannot be instantly consumed by the household and would otherwise be injected into the grid.

Finally, the inverter is connected to the household main protection board, where the energy is distributed to the loads or, in case the generation is higher than the consumption, sent to the grid in exchange for a feed-in tariff.

4. Results

Prior to computing the simulations, the electricity consumption of the household was analysed. Since the ones obtained from last year's consumption were not representative at all regarding the future electricity consumption, 3 different scenarios were developed, considering additional loads which were not included in the initial consumption table.

After running a few simulations with different configurations and considering the Scenario 2 as the most probable one for the future, the results in *Table 1* were obtained, which correspond to a 35º fixed-tilt South-oriented system with 5.5 kWp and 5 kWn of installed power. The self-consumption degree is of 38%, which is more than acceptable. The solar energy covers almost 40% of the household's demand and the rest of the energy will have to be purchased from the grid, which could be partly compensated with the injection of excess energy to the grid. Altogether, this configuration is a good trade-off between solar energy coverage and self-consumption degree.

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_User kWh	E_Solar kWh	E_Grid kWh	EFrGrid kWh
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Year	1949.3	576.24	17.49	2276.9	2098.6	10484	9500	3757	6161	5743

Table 1: Results for a 5.5 kWp and 5 kWn PV system

Following, 3 free-market electricity tariffs offered by different electricity suppliers were selected to analyse which one would bring the household owner the highest savings taking the energy results obtained in *Table 1* into account. Considering both energy and power terms as well as transport and distribution tolls and taxes, the energy savings for the first year, presented in *Table 2*, were obtained.

Annual savings	
Repsol	1250.84 €
Naturgy	1333.47 €
Endesa	1124.86 €

Table 2: Annual savings on electricity bill

Then, some financial metrics were obtained. To perform such calculations, an initial investment cost of 7250€, a 5% discount rate, an annual maintenance reserve of 50€ and a 700€ cost for inverter replacement in year 13 were considered. Moreover, a 2% annual increase in energy costs and a 0.5% PV degradation factor were also taken into account to estimate the annual energy savings for the following 25 years. Such input data delivered a NPV value of 14,124.42€, a payback period between 5-6 years and an IRR of 19%. It is worth noting that these economic calculations were performed without taking any possible subsidies or incentives into account, which obviously would make the project even more attractive from an economic viewpoint, as it was later calculated when considering a possible deduction in the personal income tax (IRPF).

5. Conclusions

To sum up, this project proposes an energetic solution to a houseowner, who will see the electricity consumption of his household rise in the following years. By generating clean, renewable electricity on-site, homeowners can reduce their reliance on the grid, lower carbon emissions, and achieve greater energy independence. With the added benefits of long-term savings and support for broader climate goals, residential PV systems represent a key step towards a more resilient and sustainable energy future.

6. Bibliography

[1] Florida Solar Energy Center. (n.d.). *How a PV system works*. University of Central Florida. https://energyresearch.ucf.edu/consumer/solar-technologies/solar-electricity-basics/how-a-pv-system-works/

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Table of Acronyms

Acronym	Meaning
PV	Photovoltaic
AC	Alternating current
DC	Direct current
kW	Kilowatt
kWh	Kilowatt-hour
kWp	Kilowatt-peak
kWn	Kilowatt-nominal
GCR	Ground coverage ratio
GHI	Global horizontal irradiance
DHI	Diffuse horizontal irradiance
DNI	Direct normal irradiance
AM	Air Mass
MP	Maximum power
MPP	Maximum power point
MPPT	Maximum power point tracker
SC	Short-circuit
OC	Open circuit
STC	Standard test conditions
FF	Fill factor
MOSFET	Metal-oxide-semiconductor field-effect transistor
PVGIS	Photovoltaic Geographical Information System
NASA-SSE	NASA’s Surface Meteorology and Solar Energy dataset

TMY	Typical meteorological year
NREL	National Renewable Energy Laboratory
IEA	International Energy Agency
PVPC	Precio Voluntario al Pequeño Consumidor
IBI	Impuesto sobre Bienes Inmuebles
ICIO	Impuesto sobre Construcciones, Instalaciones y Obras
IRPF	Impuesto sobre la Renta de las Personas Físicas
NPV	Net present value
IRR	Internal rate of return
PNIEC	Plan Nacional Integrado de Energía y Clima
SDG	Sustainable Development Goals

Chapter 1. INTRODUCTION

1.1. PROJECT MOTIVATION

The increasing global demand for clean and sustainable energy solutions, coupled with rising electricity prices and growing environmental concerns, has led to a significant interest in self-consumption photovoltaic (PV) systems. Residential solar PV installations offer a practical and efficient way to reduce dependence on the grid, lower electricity costs, and contribute to the transition towards renewable energy sources.

This project aims to design a solar photovoltaic installation tailored for residential self-consumption, optimising energy production while ensuring economic feasibility. By leveraging advancements in solar technology and considering local energy policies, the project seeks to maximise energy savings and minimise environmental impact. Additionally, self-consumption systems with battery storage can enhance energy independence, reducing reliance on fossil-fuel-based power generation.

Furthermore, the integration of solar PV systems in residential buildings supports national and international sustainability goals, such as the European Green Deal and the Paris Agreement, which emphasise the need for carbon emissions reduction and increased renewable energy adoption. By designing an efficient and scalable PV system, this project will contribute to promoting cleaner energy solutions and encouraging wider adoption of distributed solar generation in the residential sector.

1.2. OBJECTIVES

First and foremost, this project serves as an economic investment for the customer. Hence, it must bring positive returns to the investor. Otherwise, it would not take place despite all the other advantages and benefits this project brings. The main idea behind it is to reduce the customer's electricity bill by providing the possibility to a household to produce and consume its own electricity with minimal operational costs during the project lifetime once the initial investment has been made, just by taking advantage of the solar energy.

Higher independence from the electrical network and energy markets is also sought with this project. By reducing the amount of electricity required to be purchased from the grid, one also reduces its exposure to the fluctuating electricity prices. Furthermore, should a conventional combustion engine car be substituted with an electric vehicle soon, then one would also become independent from the prices of imported fuels. Instead of refuelling it at a gas station, the car would be powered by cheap, renewable energy coming from the Sun and would not emit greenhouse gases of any kind during its use.

Lastly, this project is also committed to improve the reliability of the electrical network and its security of supply as well as to contribute to the fight against climate change. Solar PV installations play a key role in the so-called decentralisation of energy generation. The larger the amount of renewable energy that is generated and consumed at the same site, the lower the amount of energy that needs to be generated in traditional power plants and distributed through the grid. This way, both saturation of transmission lines and energy generation by greenhouse-gases-emitting sources are avoided.

Chapter 2. TECHNOLOGIES DESCRIPTION

2.1. SOLAR PANEL

2.1.1. PHOTOVOLTAIC EFFECT

The photovoltaic solar panel is the main component of the installation. It is the one in charge of converting the solar energy into electrical energy, process based on the photovoltaic effect. When sunlight, which is made up of photons, hits the solar panel, part of the incident solar radiation is lost by reflexion, another part is lost by transmission, and the remaining is absorbed by the semiconductor material in the PV cells, typically silicon. This element, which belongs to the Group IV, has 4 electrons in its outermost shell. The energy from the photons excites the electrons in the silicon atoms, causing them to break free from their atoms and become mobile. Due to the structure of the PV cell, exposed in *Figure 1*, an electric field is created, which directs the free electrons to flow in a specific direction, generating an electric current.

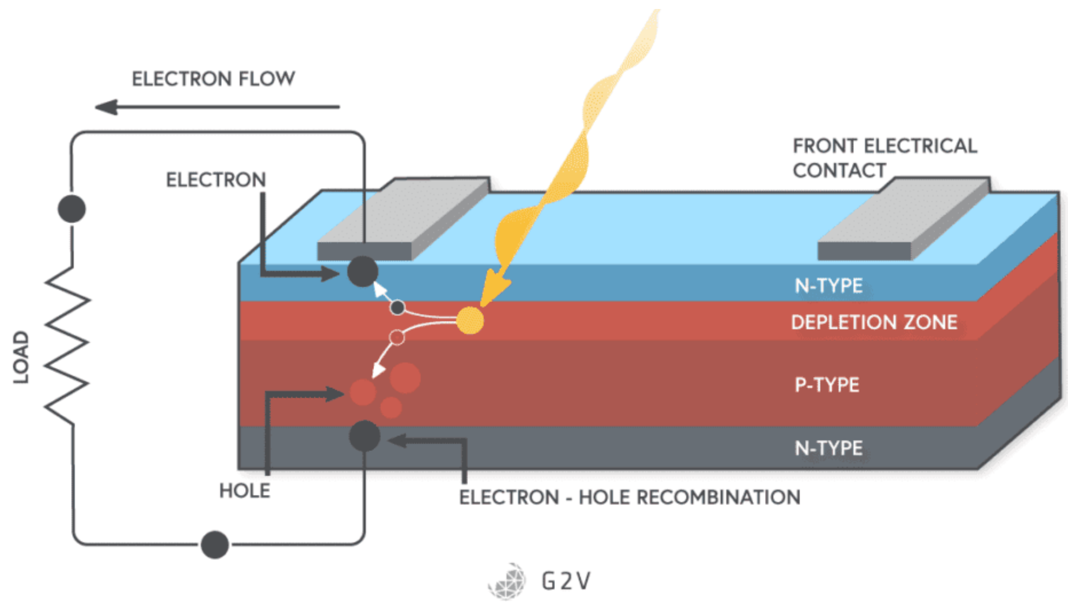


Figure 1: Schematic diagram of a solar cell [1]

This electric field is created by a junction of two layers of silicon, shown in *Figure 2*, which are the N-type silicon, doped with phosphorous to have one extra electron (i.e., 5 valence electrons) and consequently negative charge, and the P-type silicon, doped with boron to have one extra hole (i.e., 3 valence electrons) and therefore positive charge.

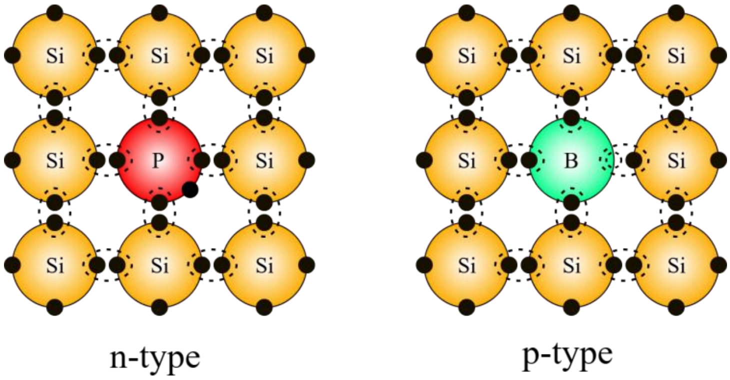


Figure 2: Molecular structure of doped silicon with phosphorous and boron [2]

The interface between these two layers forms a PN junction, which generates the electric field. Consequently, the flow of free electrons creates a direct current (DC) electricity, collected and transferred by metal contacts on the top and bottom of the PV cell. Since nowadays almost all appliances at home use alternating current (AC), the DC electricity produced is sent to an inverter, which converts it to AC.

2.1.2. PV CELL TECHNOLOGIES

The side length of a squared PV cell, illustrated in *Figure 3,* ranges between 160 mm and 210 mm [3], and they are connected in series to assemble a solar panel. The number of cells to connect depends on the voltage the solar panel is supposed to have.

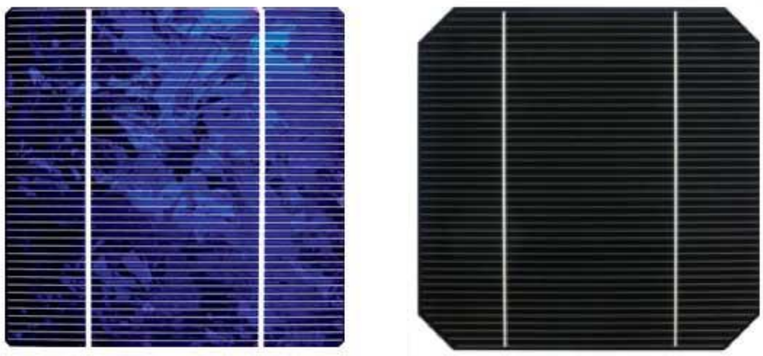


Figure 3: Polycrystalline (left) and monocrystalline (right) cells [4]

The two types of solar cells presented in *Figure 3* are the most common technologies used, accounting for around 97% of the total production in 2023. Monocrystalline silicon cells are characterised for having a homogeneous crystal structure and a record lab cell efficiency of 27.3%, resulting in an energy-intensive and expensive production. Polycrystalline cells, on the contrary, have no uniform crystal direction but different alignment and a lower record lab efficiency of 24.4%. As an advantage, their manufacturing process requires lower energy and is therefore cheaper. However, their production is progressively phasing out, becoming the monocrystalline the most dominant technology in the market [5]. Despite the crystalline silicon cells popularity, in *Figure 4* other different solar cell technologies that have also been developed are introduced.

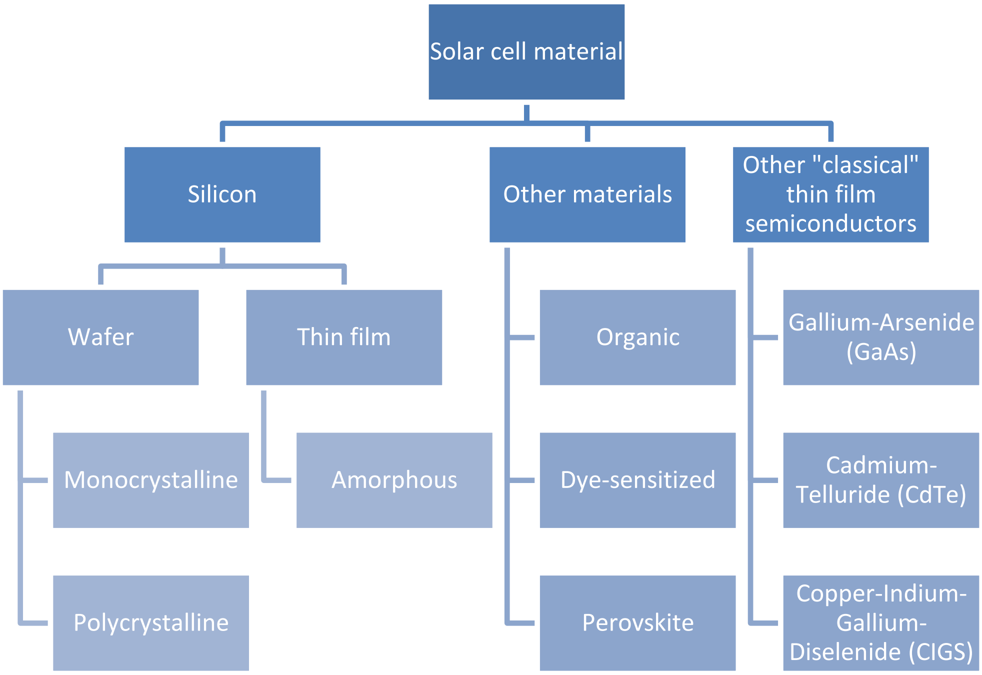


Figure 4: Overview on different solar cell technologies

The advantage of thin film semiconductors lies in the fact that they present widths 100 times thinner than crystalline silicon cells, lowering the amount of semiconductor material needed for their production. As a trade-off, worse efficiencies are obtained. Regarding amorphous silicon cells, hydrogen is added to the silicon during the production process to saturate the open bindings. In this type of technology, as with thin film semiconductors, a strong costs reduction is sought, sacrificing performance. Nevertheless, the high loss of performance over time is slowing its development.

2.1.3. OPERATING PRINCIPLE: I-V CURVE

When a load is connected to a solar cell and the latter is exposed to solar radiation, a voltage difference between both ends of the load is produced and therefore current flows through the closed circuit. It is the net result that it is obtained by subtracting the dark current from the photocurrent. On the one side, the dark current is a small one which flows due to the recombination of charge carriers in the diode, not from light, since the PN junction behaves like a diode even when there is no light, as shown in *Figure 5*. On the other side, the photocurrent is the one dependent on light intensity and is directed from the n-side to the p-side in the external circuit.

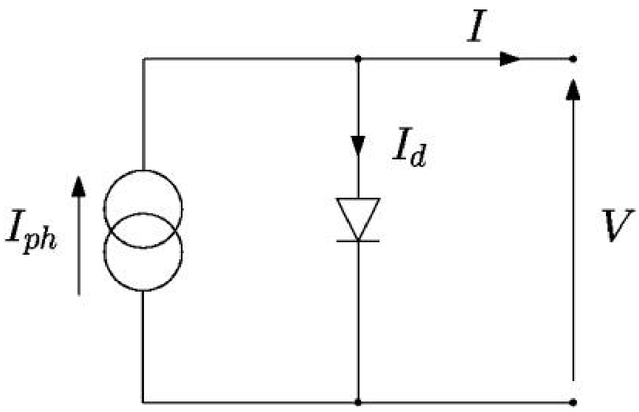


Figure 5: Ideal PV cell equivalent circuit [6]

The dark current increases exponentially with the applied voltage, following the diode equation:

$$I_d = I_0\left(e^{\frac{qV}{nkT}} - 1\right) \tag{2.1}$$

Where:

- I_0: saturation current
- q: electron charge
- V: applied voltage
- n: ideality factor
- k: Boltzmann constant
- T: temperature

Hence, the total current from the solar cell delivered to the load is:

$$I = I_{ph} - I_d = I_{ph} - I_0\left(e^{\frac{qV}{nkT}} - 1\right) \tag{2.2}$$

Plotting equation 2.2 gives an I-V curve as the red one represented in *Figure 6*, which shows the relationship in a solar cell between the output current (I), on the Y-axis, and voltage (V), on the X-axis, under a given level of illumination. In addition, the power output (blue curve) from the solar cell is also plotted. There are three key points on the I-V curve. The short-circuit current (I_{sc}) is the one when the voltage is equal to zero. It is the maximum current output since all the generated photocurrent flows to the load side, as the dark current is zero and therefore no current flows through the diode in the ideal equivalent circuit of *Figure 5*. The open-circuit voltage (V_{oc}) is the one at which the recombination of charge carriers processes equal to the generation ones, not being able to extract current from the solar cell consequently. Thus, it is the voltage built up across the cell when no load is connected. The maximum power point (MPP) is the point on the curve which maximises the product between voltage and current. It is defined by maximum power voltage (V_{MP}) and current

(I_{MP}). There are electronic devices installed in the inverters called maximum power point trackers (MPPT) which try to make the string of solar panels connected to it work at maximum power conditions.

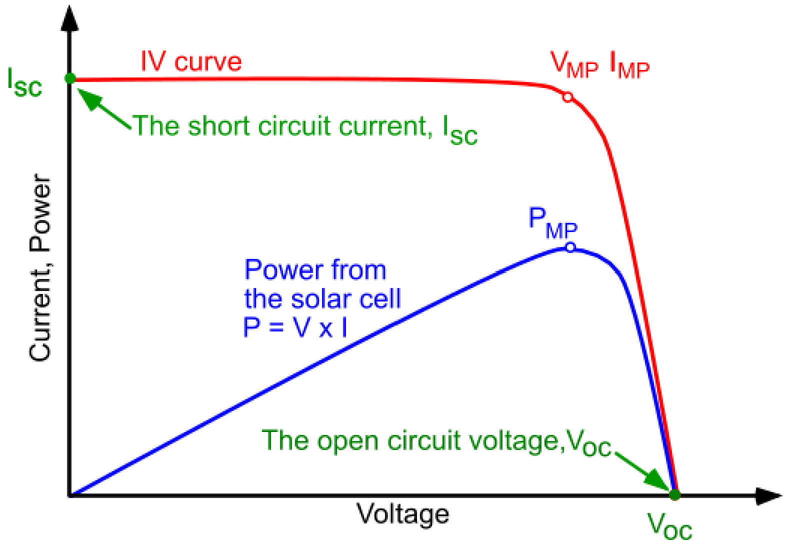


Figure 6: Current-voltage (I-V) curve of a solar cell [7]

Out of these characteristic points one can obtain two common parameters that enable the comparison between solar cells. The fill factor (FF) represents, for standard conditions, the relation between the maximum power of the cell and the theoretical power that one would obtain by using the maximum values of voltage (V_{oc}) and current (I_{sc}):

$$FF = \frac{V_{MP} \cdot I_{MP}}{V_{oc} \cdot I_{sc}} \tag{2.3}$$

It can be graphically deduced by looking at *Figure 7*, that the values of the FF range between 0 and 1, and the closer the FF is to 1, the better is the cell.

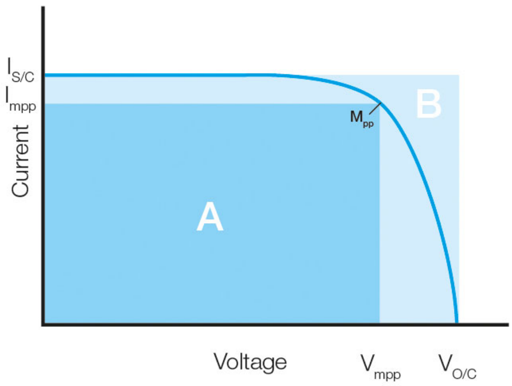


Figure 7: Representation of areas used in calculation of FF [8]

Lastly, the efficiency is the percentage of solar energy received by the cell which is converted to electrical energy under standard irradiance conditions, 1000 W/m^2. This value is part of the Standard Test Conditions (STC) used to rate solar cells and panels. It is obtained by dividing the output and input power:

$$\eta = \frac{V_{MP} \cdot I_{MP}}{G \cdot A_c} \tag{2.4}$$

Where:

- G: 1000 W/m^2
- A_c: solar cell area

The efficiency could be limited by different factors, such as losses due to partial reflection, losses due to recombination, which depends on the presence of defects in the crystalline structure, or losses due to weak electrical contacts and series resistances, among others.

The I-V curve, as demonstrated in equation 2.2, depends both on the temperature and the solar irradiance. On the contrary as one would expect, with a constant solar irradiance, the higher the temperature of the cell, the lower the power output. Higher temperatures increase currents but not enough to compensate the larger decrease in voltages, as it is shown in *Figure 8*.

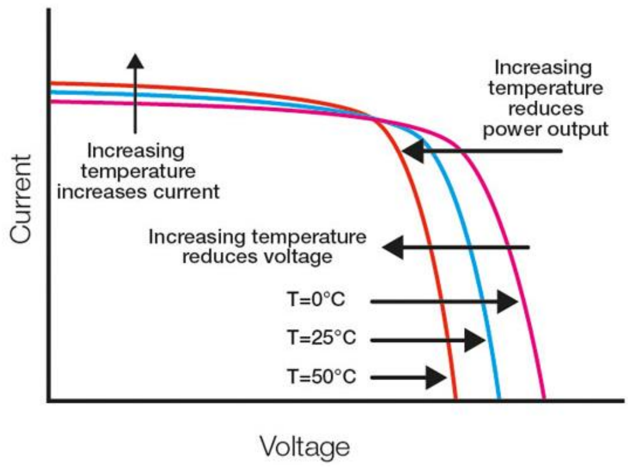


Figure 8: I-V curves with varying temperature and constant irradiance [8]

Switching the role of the two mentioned variables, with constant temperature, *Figure 9* shows that the maximum power increases with increasing radiance, being the current the most affected variable by the variation in solar irradiance.

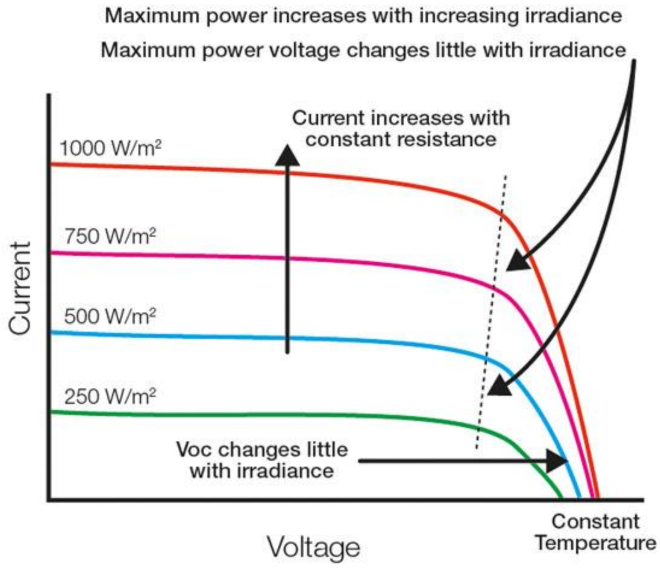


Figure 9: I-V curves with varying irradiance and constant temperature [8]

2.2. INVERTER

As mentioned in section ***2.1.1. Photovoltaic Effect***, an inverter is a power electronics device that converts a direct current (input) into an alternating current (output). It uses electronic switches such as thyristors or metal-oxide-semiconductor field-effect transistors (MOSFETs) to rapidly turn the DC voltage on and off. These pulses are processed and refined to generate a sine wave, closely resembling the AC power supplied by the electrical grid. It must follow the grid's amplitude and frequency voltage and minimise the injection of harmonics.

Maximum power point trackers were also introduced in section ***2.1.3 Operating Principle: I-V Curve***. They are control systems used in photovoltaic installations to ensure the solar panels operate at their most efficient point. Since solar panels have low conversion efficiencies and high initial costs, maximising power extraction is essential. The power output of PV panels is nonlinear and influenced by changing sunlight and temperature conditions, as shown in *Figure 8* and *Figure 9*, which makes it difficult to maintain optimal performance. When solar panels are directly connected to a load, they often do not operate at their peak power point, which can lead to inefficiencies and the need for larger and more expensive systems. MPPT devices solve this by continuously adjusting the operating voltage or current to match the maximum power point, using microprocessors and algorithms that monitor output and adapt accordingly. Because the ideal operating point shifts with environmental changes and cannot be known in advance, tracking it accurately is a complex task and remains an important area of research and development [10].

Figure 10 shows the circuit diagram of a relatively small inverter, from 3 to 10 kilowatts (kW), which has a MPPT for each string of solar panels connected to it. Therefore, it is imperative that all panels connected to the same MPPT and in this case to the same string have the same tilt (inclination) and azimuth (orientation) angles, so that they are all under the same environmental conditions and the MPPT can work correctly in order to maximise the power of the entire string.

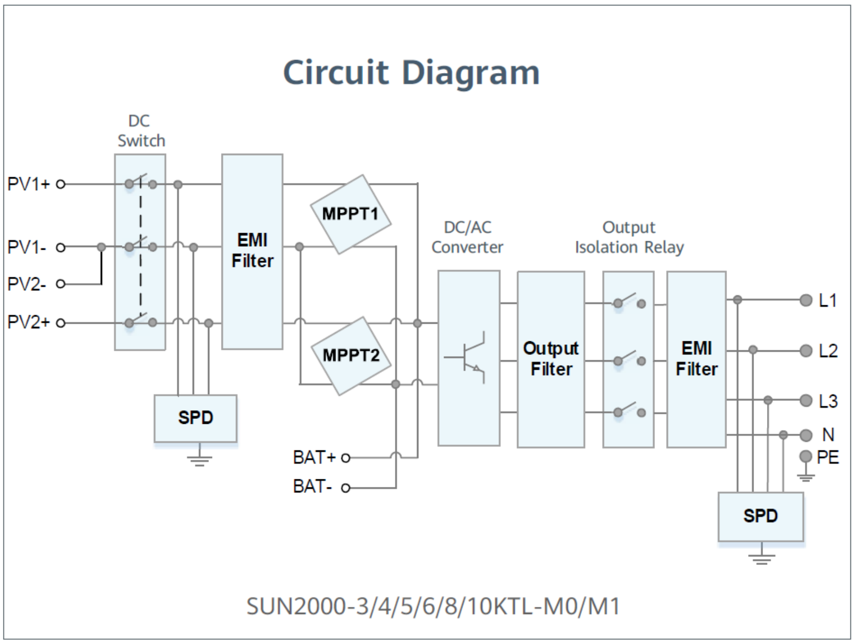


Figure 10: Circuit diagram of a Huawei SUN2000 inverter [9]

Depending on the rated power of the inverter and the total peak power of the solar panels connected to it, different configurations can be deployed. In large photovoltaic plants, located usually in large areas of land or on large roof installations from hundreds to several thousands of kilowatts, a central inverter is installed. In *Figure 11*, one can analyse that all strings of solar panels that compose the PV installation are connected to it to convert the DC voltage generated into AC voltage.

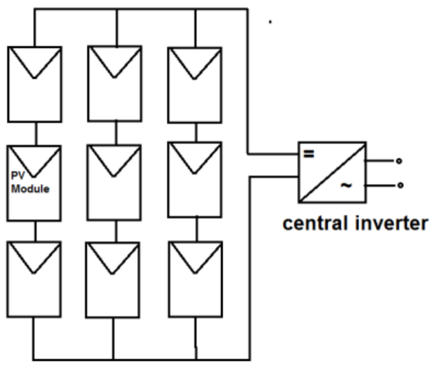


Figure 11: Schematic of a central inverter topology [10]

For large photovoltaic systems, using a central inverter is generally the most cost-effective and easiest solution to install. However, this type of inverter has several disadvantages. First, it is more difficult to maintain compared to other types of inverters. Second, if the central inverter fails, the entire system typically stops working, since there is usually no backup inverter available. Third, if the performance of one panel drops, e.g. due to shading, the overall power output of the system also decreases. For this reason, when choosing a central inverter, it is important to ensure that the installation site is free from potential shading sources like tall buildings or large trees. Additionally, the solar panels should be cleaned regularly to prevent dust accumulation, which can also reduce performance. Nonetheless, for smaller PV systems in the residential sector, central inverters are not usually employed.

String inverters have lower rated power in comparison to central inverters and range from a few kilowatts to hundreds of them. They have lower prices and are easier to maintain, so they are the preferred choice in most grid-connected PV installations. Nevertheless, they still have the same issue regarding the loss of performance of the entire string if just one solar panel is exposed to shades. *Figure 12* shows their different configuration, where each string has its own inverter instead of relying on just one central inverter for all the strings.

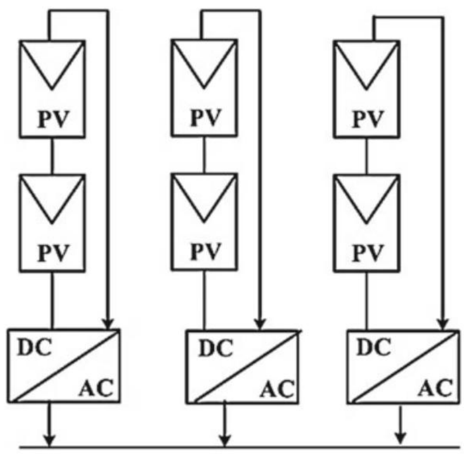


Figure 12: Schematic of a string inverter topology [11]

To solve the problem mentioned of one panel not performing as expected and additionally affecting the whole string it is connected to in case of a string inverter topology or even the whole system in case of a central inverter, microinverters are installed. They are small devices connected to each of the solar panels in the photovoltaic installation, as it can be seen in *Figure 13*, and directly convert the direct current generated by each solar panel into alternating current, making them independent from each other. This way, a shadow in one solar panel will not affect the performance of a whole string or system. Since a microinverter is needed for each of the solar panels of a whole PV installation, they are only used in small systems, such as PV installations for self-consumption of electricity in the residential sector. It would be extremely costly to adopt this kind of topology in large plants where thousands of these devices would be needed [13].

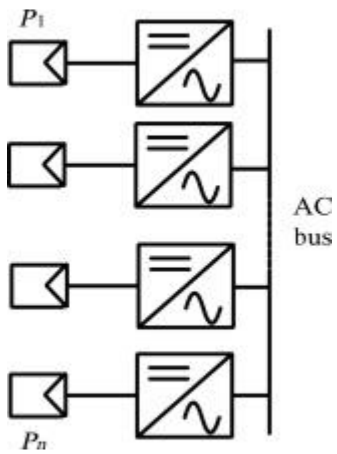


Figure 13: Schematic of a microinverter topology [11]

It is also worth mentioning the existence of hybrid inverters, which, as shown in *Figure 14*, operate using two types of energy sources: solar panels and batteries.

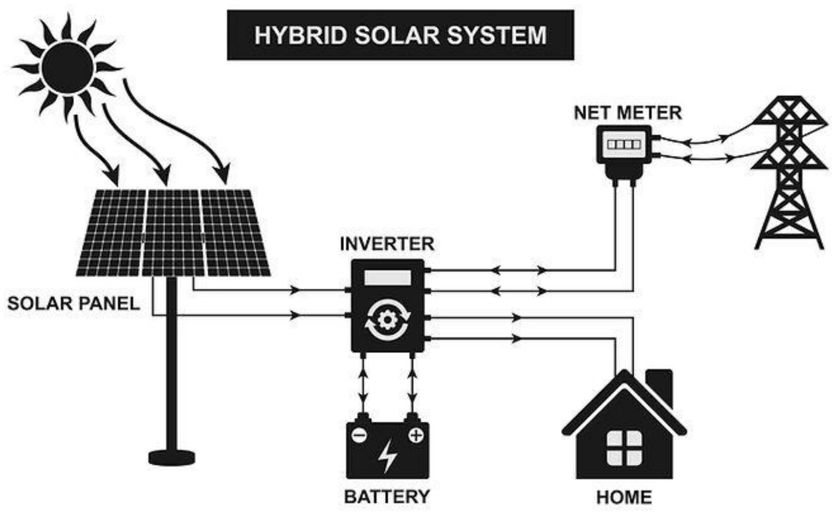


Figure 14: Schematic of a hybrid inverter topology [14]

In this system, a set of solar panels and a set of batteries are connected to the hybrid inverter, which is capable of performing multiple functions. The circuit diagram of a Huawei SUN2000 inverter exposed in *Figure 10* shows how the connection of these two energy sources to the inverter looks like. Just like every other inverter, the hybrid inverter converts the DC voltage produced by the solar panels into AC voltage suitable for household or grid use. In addition, it is able to charge the batteries using both the energy generated by the solar panels or the energy coming from the main electrical network. It does so by converting the grid's AC voltage into DC, i.e., doing the opposite operation and acting as a rectifier instead of an inverter. When the energy of the batteries is required, the device again inverts the DC voltage of the batteries into AC and sends the power to the household or to the grid.

Regarding their technical characteristics, there are a few parameters in an inverter datasheet that are worth highlighting. The nominal power is the maximum AC output power. For legal purposes it defines the power of the PV installation independently of the peak DC power installed. As it is rare to have such environmental conditions that all solar panels are providing their maximum power, the inverter power is normally selected between 5-20% less than the installed PV power. Datasheets also include an efficiency curve such as the one shown in *Figure 15*, where three curves are plotted to show the efficiency of the inverter depending on the input voltage and the load.

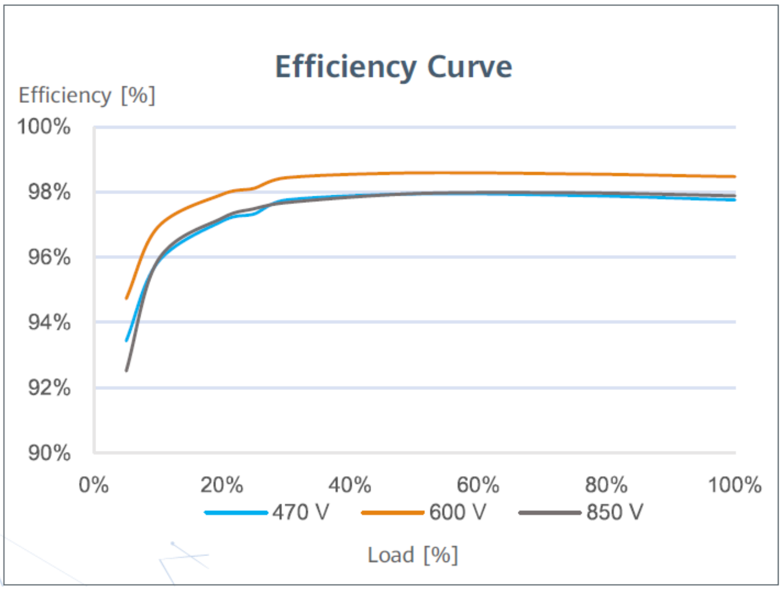


Figure 15: Efficiency curves of a Huawei SUN2000 inverter [9]

Analysing *Figure 15* closely, it could be said that the inverter starts to reach its maximum efficiency when at least 40% of its nominal power is being demanded by the load. In addition, one can perceive a slight increase in efficiency if the input voltage is neither too high nor too low. With the objective of comparing different inverters, the concept of European efficiency is used. It evaluates the inverter behaviour under partial loads, and is defined as:

$$\eta_{EU} = 0.03\eta_{5\%} + 0.06\eta_{10\%} + 0.13\eta_{20\%} + 0.1\eta_{30\%} + 0.48\eta_{50\%} + 0.2\eta_{100\%} \tag{2.5}$$

Datasheets provide an operating voltage range which gives a hint on the minimum and maximum number of PV panels that could be connected in series to form a string. It is important to have this voltage range in mind when designing the installation so as to reach the minimum voltage of the inverter to start working and to keep below the maximum voltage in order not to cause possible terminal damages.

2.3. SOLAR ENERGY AND RESOURCE ASSESSMENT

2.3.1. DEFINITION

The solar resource refers to the amount and availability of sunlight that reaches the Earth's surface, which can be harnessed for energy using technologies like photovoltaics or solar thermal systems. The generation of electrical energy by a solar photovoltaic installation depends directly on the incident solar radiation over the total surface area of the installed panels. This relationship is given by the following equation:

$$E_a = \frac{G_a(\alpha, \beta) \cdot P_p \cdot \eta}{G_{STC}} \tag{2.6}$$

Where:

- E_a: estimated annual energy in kWh
- G_a: global incident radiation on the PV panels depending on their tilt (α) and azimuth (β) angles
- P_p: peak installed power of the solar panels in kW
- η: performance ratio defined as the installation's real efficiency under real working conditions, ranging usually from 0.7 to 0.85
- G_{STC}: standard testing conditions constant (1 kW/m^2)

In the context of solar energy, it is important to distinguish between the terms radiation, irradiance, and irradiation, which are often used interchangeably but refer to different physical quantities. Solar radiation is a general term that describes the electromagnetic energy emitted by the sun. Irradiance refers to the instantaneous power of solar radiation received per unit area and is expressed in watts per square meter (W/m^2). It represents the intensity of solar radiation at a specific moment in time. In contrast, irradiation denotes the accumulated energy received over a period, such as a day or a year, and is measured in watt-hours or kilowatt-hours per square meter (Wh/m^2 or kWh/m^2). For example, solar maps, such as the one presented in *Figure 18*, typically show long-term averages of Global Horizontal Irradiation (GHI), which represent the total solar energy received on a horizontal surface and are crucial for assessing the potential of energy systems.

2.3.2. SOLAR HEIGHT AND AIR MASS

Solar height, also known as solar elevation angle or altitude angle, is defined as the angle that the sun rays form with respect to the horizontal surface. The zenith angle is its complementary one, as it can be seen in *Figure 16*.

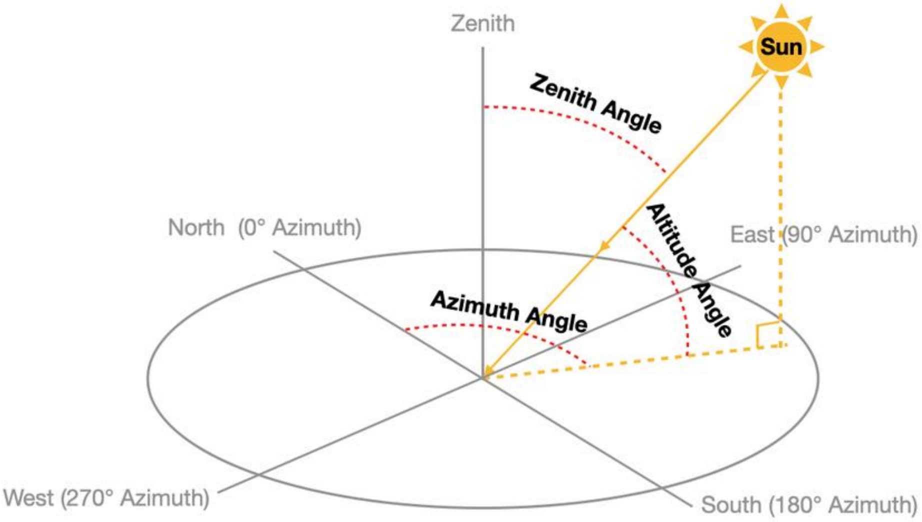


Figure 16: Schematic depicting the altitude, zenith and azimuth angles [16]

The path length of the light through the atmosphere weakens it and changes the spectral composition. When talking about solar cell efficiencies, it is necessary to specify the underlying spectrum. This is done by specifying the Air Mass (AM). When the Sun reaches the zenith height and the rays form an angle of 90˚ with respect to the horizon, being the sun directly overhead, the distance from the sun to an observer placed in the origin is minimal. To this position, an Air Mass of 1 is assigned. Hence, it is normalised to the shortest possible path length. The AM measures how much the atmosphere reduces the intensity of sunlight as it travels through it and gets absorbed by air particles and dust. It is defined as:

$$AM = \frac{1}{\cos(\theta)} \tag{2.7}$$

Where:

- θ: zenith angle

The light source used to measure the maximum power output of a photovoltaic panel has a light spectrum corresponding to AM1.5. This value is one of the parameters that has been adopted as a standard for testing the peak performance of solar panels. Applying the equation 2.7, an AM1.5 corresponds to a cosine value of 0.6, which leads to a zenith angle of around 48˚. Under such conditions, the global solar irradiance that hits the surface of the solar panels is 1000 W/m^2. The value AM0 refers to the solar radiation outside the Earth's atmosphere, and it cannot be calculated using the air mass formula.

2.3.3. TYPES OF SOLAR RADIATION

Solar radiation reaching the Earth's surface can be categorised into three main components: direct radiation, diffuse radiation and reflected radiation, shown in *Figure 17*. The combination of these components determines the global solar radiation, which is a critical parameter in the design and performance assessment of solar energy systems.

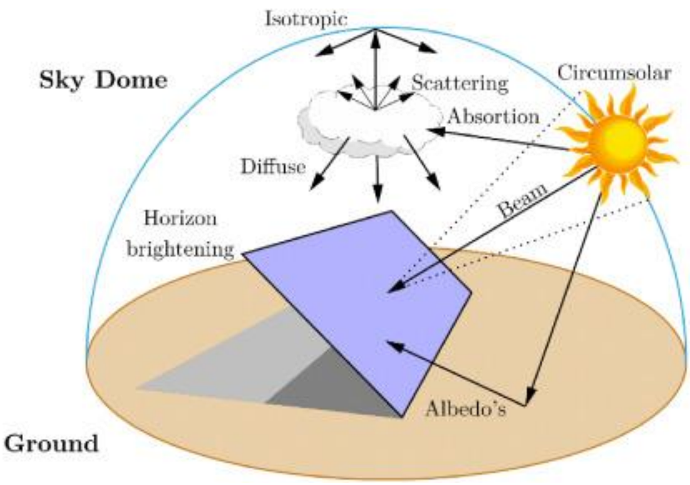


Figure 17: Components of solar irradiance on a tilted surface [17]

Direct solar radiation, also known as beam radiation, is the portion of solar energy that travels in a straight path from the sun to a specific surface without being scattered by the atmosphere. This component is highly directional and is only received when the sun is visible in the sky.

Diffuse solar radiation is the fraction of solar radiation that has been scattered by molecules, aerosols, clouds, and other particles in the atmosphere. Unlike direct radiation, diffuse radiation arrives at the surface from all directions of the sky dome. Although it is less intense than direct radiation, it is available even during overcast conditions and contributes significantly to the energy yield of fixed, non-tracking photovoltaic systems.

Reflected solar radiation, also known as ground-reflected or albedo radiation, is the portion of solar energy that has reached the ground or nearby surfaces and is then reflected onto the receiving surface. The magnitude of this component depends on the reflective properties (albedo) of the surrounding terrain or surfaces, such as snow, sand, water, or buildings.

The global solar radiation is defined as the total amount of solar radiation incident on a horizontal surface and is the sum of the direct, diffuse, and reflected components. Mathematically, it can be expressed as:

$$G = B + D + R \tag{2.8}$$

Where:

- G: global radiation
- B: direct radiation
- D: diffuse radiation
- R: reflected radiation

Understanding and accurately measuring each of these components is essential for the optimal design and operation of solar energy systems, as they influence both the energy yield and efficiency of solar technologies.

2.3.4. SOLAR RESOURCE OPTIMISATION

2.3.4.1. Introduction to the solar resource

The so-called *Sun Belt* refers to a broad geographical zone located roughly between 15° and 35° latitude, both north and south of the equator, where solar radiation levels are exceptionally high throughout the year. This region benefits from consistently clear skies, low precipitation, and high solar angles, making it particularly favourable for solar energy generation. Many of the world's most solar-rich areas, such as the Middle East and North Africa, parts of Sub-Saharan Africa, northern Chile, southwestern United States, and central Australia, are located within this belt. These areas often receive over 2000 kWh/m² per year of global horizontal irradiation, offering ideal conditions for photovoltaic and concentrated solar power systems. *Figure 18* illustrates the global distribution of GHI, clearly highlighting the *Sun Belt* as a continuous band of high solar potential, marked by the red to pink colour range, where values exceed 6.0 kWh/m² per day (or approximately 2200 kWh/m² per year).

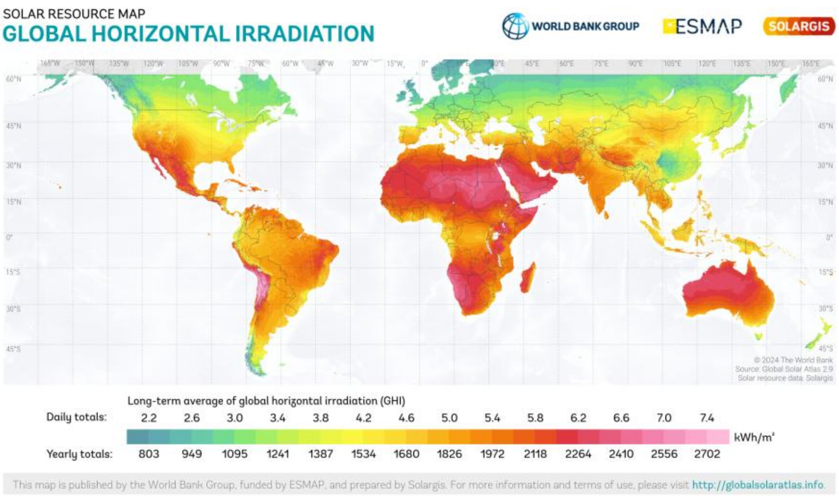


Figure 18: Worldwide solar resource map [18]

In contrast, higher latitudes, especially in Northern Europe, parts of Canada, and Russia, show significantly lower GHI levels (below 1100 kWh/m^2), represented by green to blue shades. This spatial variability in solar resources is crucial for energy planning and investment decisions. High-GHI regions offer greater energy yield potential for PV installations and may support lower Levelised Costs of Electricity (LCOE).

2.3.4.2. Fixed-tilt structures: azimuth and tilt angles

In order to maximise the energy yield of a photovoltaic installation, it is important to keep in mind that the intensity of radiation on a surface decreases proportionally to the cosine of the angle of incidence relative to the normal. The received intensity is maximised when the incident beam is more perpendicular to the receiving surface. In other words, for a PV installation with a fixed structure at a given location, there are two angles that would need to be decided to capture as much solar radiation as possible throughout a year, which are the tilt and azimuth angles, shown in *Figure 19*.

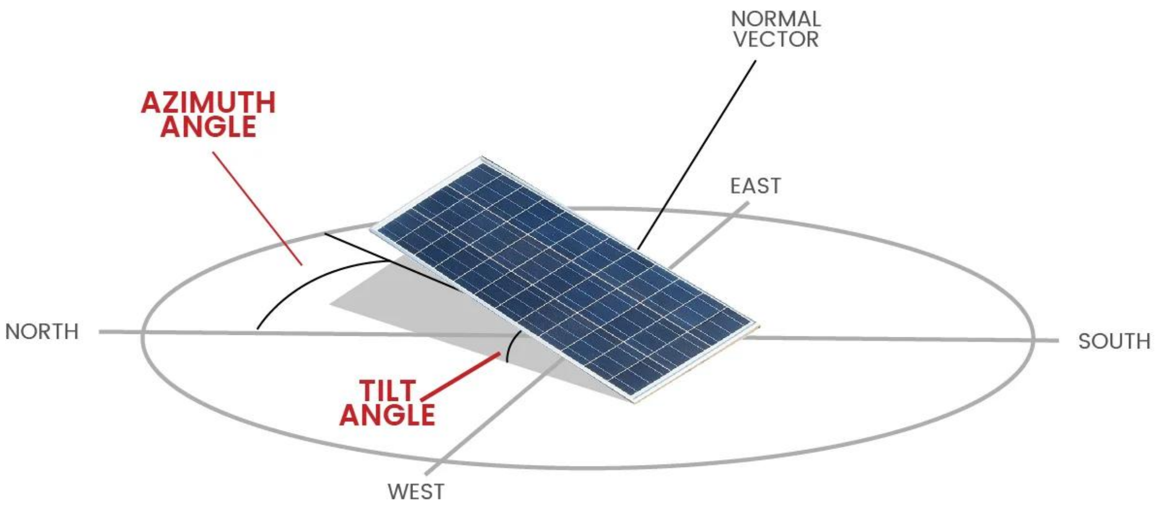


Figure 19: Tilt and azimuth angles in a solar panel [19]

The optimal orientation of a PV panel depends on the geographical location and the specific energy production goals. In general, to maximise solar energy capture, the PV panels should be oriented towards true South (azimuth = 180˚) in the Northern Hemisphere and true North (azimuth = 0˚) in the Southern Hemisphere [20]. This ensures that the panels receive the most sunlight throughout the day. In most experimental studies conducted to determine the optimal tilt angle for PV modules, the panels are oriented towards the South in the Northern Hemisphere [21].

As a result of the translational movement, the Earth's surface receives solar radiation at a different inclination for each season of the year and for each location, as shown in *Figure 20.* Thus, the solar radiation incident on a squared meter of horizontal surface varies continuously month to month since the solar elevation angle is much lower in winter than in summer. Ideally, to maximise the energy generated throughout a year, the tilt angle would be adjusted in such a way that it is reduced during summer months when the sun's altitude angle is higher and increased during winter months when it is lower.

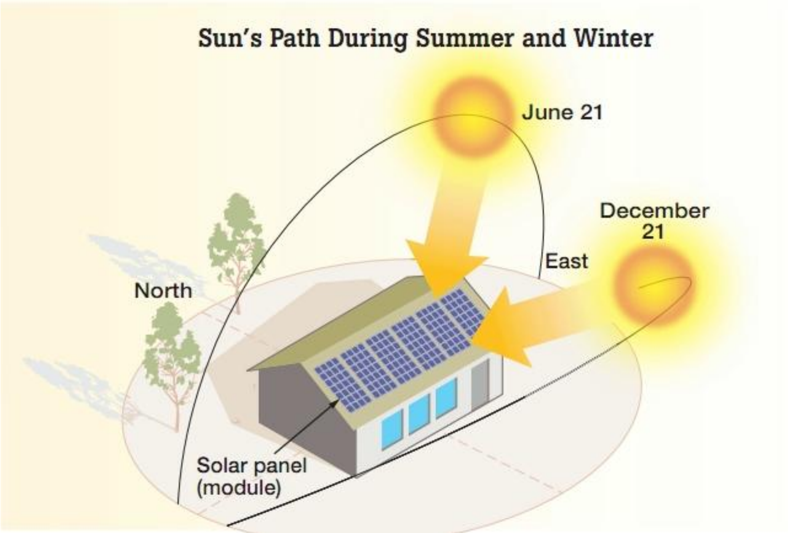


Figure 20: Sun's trajectory during summer and winter in the Northern Hemisphere [22]

Figure 21 gives an insight into the influence the latitude of a location has on the tilt angle needed to maximise the exposure of the solar panel perpendicular to the sun rays. The higher the latitude, the higher the tilt angle needed.

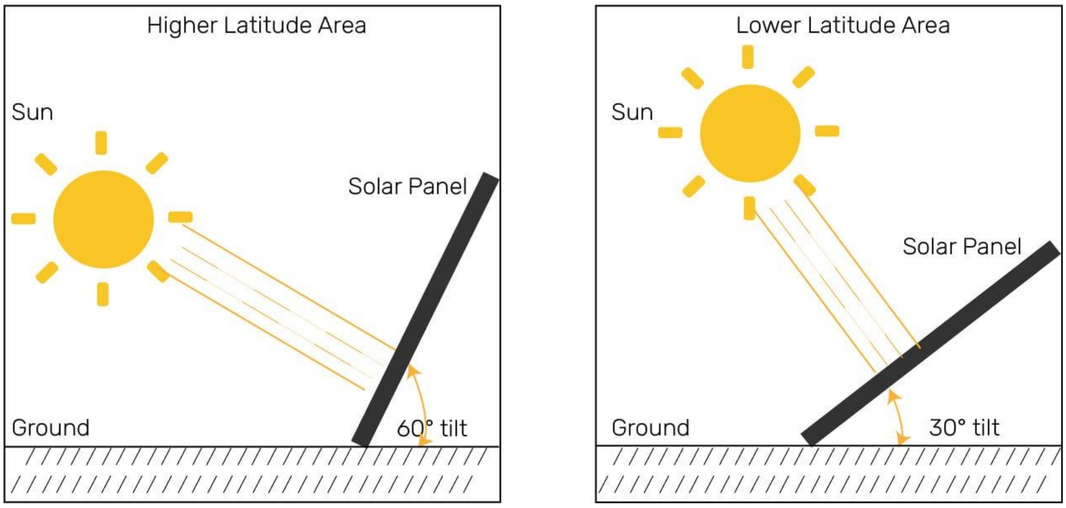


Figure 21: Tilt angles of solar panels depending on latitude [23]

For example, for a solar photovoltaic installation located in Barcelona (Spain) with coordinates 41˚ 22' 56" N, 2˚ 6' 56" E, the optimal tilt angle varies drastically depending on the season. In winter months (December, January and February) it would be 56.4˚, while in summer months (June, July, August) the optimal angle would drop down to 13.76˚. Taking into account also the optimal angles in spring (29.11˚) and in autumn (48.14˚), the annual optimum tilt angle for this latitude would be 36.87°, with which the energy generated by the installation throughout the year would be maximised. As a first order of approximation, research studies suggest that for locations with small values of latitude, the annual optimum tilt angle is close to the location's latitude. It does not apply to locations with higher values of latitude, where the optimum tilt angle is smaller [24]. Nevertheless, for each solar photovoltaic project to be developed, a proper calculation of the optimum tilt angle should be carried out, such as the one shown in *Figure 22*.

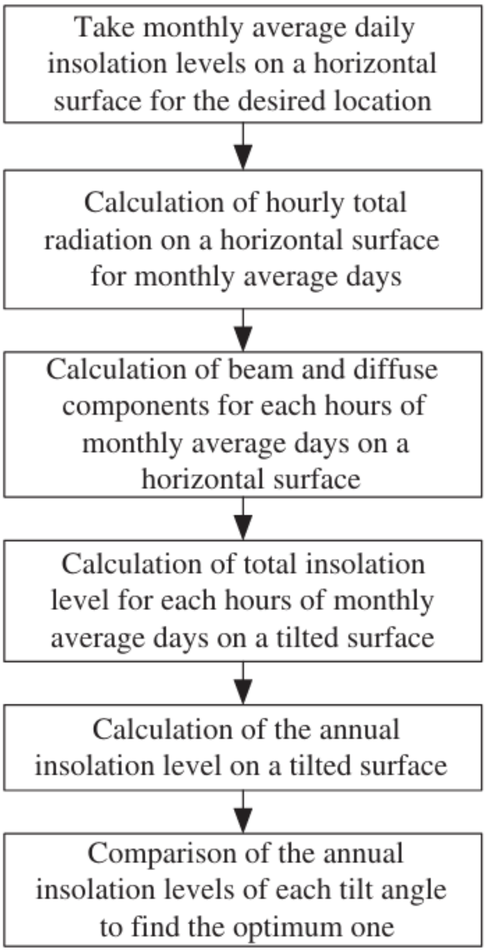


Figure 22: Flowchart of the annual optimum tilt angle calculation algorithm [25]

2.3.4.3. East-West structures

If instead of maximising the total energy production during a day, the objective is to seek a more uniform curve production, east-west structures are the choice, illustrated in *Figure 23*. East-west oriented photovoltaic systems offer several advantages that make them an attractive alternative to traditional south-facing installations, particularly in rooftop and utility-scale applications. By aligning modules in an east-west direction with a low tilt angle, it is possible to reduce the spacing between rows, thereby increasing the ground coverage ratio (GCR) and maximising the installed capacity per unit area. This layout results in a more evenly distributed power generation profile throughout the day, with reduced peak production at noon but increased output during the morning and late afternoon hours. Such a generation profile can better match consumption patterns, especially in commercial or industrial settings, enhancing self-consumption and reducing grid dependency. Additionally, the lower tilt angle leads to reduced wind loads and structural requirements, which can lower installation and material costs. While the energy yield per module may be slightly lower compared to optimally tilted south-facing systems, the overall energy yield per area and cost-effectiveness often compensate for this difference, particularly in space-constrained environments.

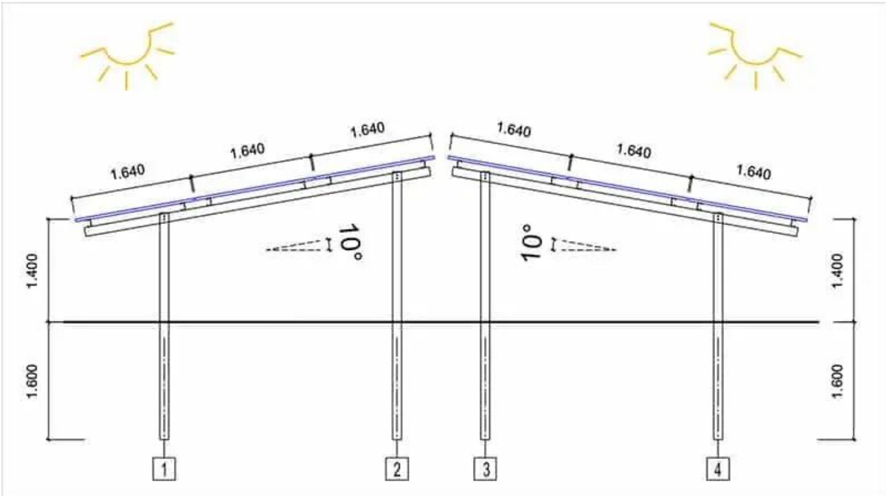


Figure 23: East-West structure system with 10° tilt [26]

Figure 24 shows a comparison between two installations of 1 kWp, whose arrays are facing South and East-West, respectively. It can be analysed that while the East-West system starts generating energy earlier in the morning and finishes later in the afternoon, in total it yields 2.06 kWh less, showing clearly that during the sunny hours it is surpassed by the South facing array as a trade-off.

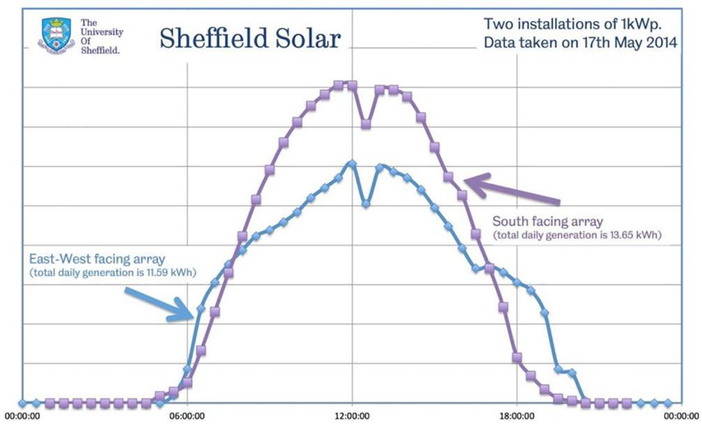


Figure 24: Comparison between East-West oriented and South oriented PV systems [27]

Chapter 3. STATE OF THE ART

3.1. INTRODUCTION TO SOLAR ENERGY FOR SELF-CONSUMPTION

Solar energy for self-consumption refers to the use of electricity generated on-site, through photovoltaic solar panels, to meet the energy demands of a building, facility or house. Instead of relying entirely on the public electricity grid, the user consumes the electricity produced directly from their own solar installation.

Solar panels generate electricity during daylight hours. This electricity is first used to cover the instantaneous consumption of the load connected to the installation. When the solar production exceeds the immediate demand, the surplus electricity can either be stored in a battery system, if available, or exported to the grid, depending on the regulatory framework and grid connection agreements in place.

During periods of low or no solar generation, such as at night or during cloudy weather, when the energy demand is higher than the instantaneous generation of the PV system, the load draws electricity either from the grid or from the battery system, if one has been installed. The use of batteries increases the percentage of self-consumed electricity by enabling energy storage for use outside of generation hours, but it also raises the initial investment cost, significantly extending the payback period of the investment.

Self-consumption offers several advantages. It reduces electricity bills by decreasing the amount of energy purchased from the grid. It can also enhance energy independence, particularly in locations with high electricity prices or unstable grid conditions. Additionally, it contributes to environmental sustainability by promoting the use of clean, renewable energy.

The degree of self-consumption achieved depends on multiple factors, including the size of the PV system, the presence of an energy storage system, and the consumption patterns of the user. In systems without batteries, self-consumption ratios typically range from 25% to 45% of the total solar generation [28]. With battery storage, these ratios can increase to 70% or more, depending on the capacity and management of the storage system.

To maximise self-consumption, it is beneficial to align energy usage with periods of solar production, for instance by running appliances or industrial processes during daylight hours. Accurate system sizing and intelligent energy management strategies are crucial for optimising both economic returns and energy efficiency.

3.2. SYSTEM DESIGN AND SIZING

Regarding the system design, there are multiple options depending on the user's needs. In section ***2.3.4. Solar Resource Optimisation***, tilt and east-west structures were introduced. These ones would be suitable for flat roofs, where the layout of solar panels can be decided. On the contrary, in households with already tilted roofs, the most common and cost-effective procedure would be to install the panels parallel to the roof so that they adopt its tilt angle, as it can be seen in *Figure 25*.

Figure 25: Layout of solar panels on tilted roof [29]

Nonetheless, in case the tilt angle of the roof is not considered as suitable for the maximisation of the energy generation throughout the year, *Figure 26* shows that an additional tilt angle could be added in order to achieve the optimum angle, taking into consideration the sloping roof's angle already in place.

Figure 26: Tilted solar panels on sloping roof [30]

The peak and nominal power to be installed, i.e., the number of solar panels and the rated power of the inverter, are chosen after analysing the household's energy consumption throughout a year and comparing it with the predicted generation of the PV installation. To do so, a software tool such as PVsyst is employed. It is a widely used software tool for the design, simulation and analysis of photovoltaic systems. PVsyst supports grid-connected, stand-alone and hybrid PV systems and allows for a precise system sizing based on energy needs, environmental conditions and component specifications. It turns out to be very useful as it models the performance of PV systems over time, considering various environmental factors such as sunlight, shading and temperature and includes hourly, daily, monthly or yearly simulations to predict energy output. It can do so, since it comes with an extensive database of solar irradiance data, including weather and climate data from multiple sources. Moreover, the software also estimates the economic feasibility of PV systems by calculating payback periods, costs and potential savings.

An Excel file containing the energy consumption in each hour of a day and in each day of a year is requested to the electric energy distribution company and later processed by the software tool. By comparing the expected generation of the PV installation with the household's consumption of each hour of the year, the software determines how much energy is self-consumed by the load and how much of it is sent to the grid. Then, a compromise between a minimum amount of the household's energy demand the installation should cover and a minimum ratio of self-consumption is sought. In other words, the photovoltaic installation is meant to cover the energy demand as much as possible so as to reduce the energy imported from the grid, but at the same time the household should be able to consume at least 30% of the energy generated by the installation. Otherwise, the customer would have paid for an oversized installation which mainly sends the energy generated to the grid due to the load being much lower than the generation, and this is certainly not the purpose of PV installations for self-consumption of electricity.

Table 1 shows how the results computed by PVsyst of the energy management in a photovoltaic installation of 2.2 kWp and 2 kWn would look like, whose purpose is to provide energy for a household with an annual consumption of 4000 kWh. As it can be seen, the net energy produced annually by the PV system after losses is the sum of the energy consumed directly by the load (E_Solar) and the energy injected into the grid (E_Grid), being around 4000 kWh, out of which 38.5% are self-consumed by the load. In this case, the installation covers around 38% of the household's energy demand and therefore it seems to be a good compromise between energy coverage and self-consumption ratio.

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_User kWh	E_Solar kWh	E_Grid kWh	EFrGrid kWh
January	92.5	26.79	11.07	159.8	144.2	295.8	405.9	125.1	157.9	280.8
February	104.4	32.72	9.96	155.2	140.7	288.5	327.1	105.9	170.3	221.2
March	155.8	52.55	13.89	193.2	179.9	363.6	325.3	125.0	223.3	200.2
April	179.9	58.36	14.61	191.3	178.2	359.4	300.0	123.4	220.5	176.6
May	226.3	67.68	17.83	213.9	198.9	396.9	260.0	119.2	260.9	140.8
June	241.2	61.87	20.70	216.8	201.7	398.8	262.4	122.2	259.6	140.2
July	241.1	64.79	25.00	222.6	207.2	402.3	309.8	139.6	245.5	170.3
August	222.5	56.94	24.38	227.9	213.1	414.2	352.9	154.2	242.8	198.7
September	167.7	51.31	22.43	196.9	183.9	360.4	363.1	144.2	201.1	218.9
October	136.5	44.01	19.49	189.6	175.9	349.8	411.8	152.0	183.3	259.8
November	95.3	32.03	16.15	153.5	139.7	281.6	361.2	114.1	155.3	247.0
December	86.0	27.20	13.72	156.2	139.3	284.3	388.5	122.5	149.5	266.0
Year	1949.3	576.24	17.49	2276.9	2102.8	4195.6	4068.1	1547.5	2470.2	2520.6

Table 1: Energy management annual results in a 2.2 kWp PV installation

As a comparison, *Table 2* shows the results obtained from increasing the installed peak power up to 4.4 kWp (4 kWn) while maintaining the same annual energy demand. The most interesting highlight would be that the energy demand's coverage by the photovoltaic system has only increased between 2-3% while the self-consumption ratio has dropped more than 17%, down to values around 21%, which is far from being ideal. This means that most of the energy generation increase by means of installing more solar panels and a higher power inverter, with the costs that this entails, has been injected into the grid rather than taken advantage of by the consumer.

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_User kWh	E_Solar kWh	E_Grid kWh	EFrGrid kWh
January	92.5	26.79	11.07	159.8	144.2	592.4	405.9	137.9	418.3	268.0
February	104.4	32.72	9.96	155.2	140.7	578.1	327.1	115.9	427.1	211.2
March	155.8	52.55	13.89	193.2	179.9	728.3	325.3	136.2	548.3	189.1
April	179.9	58.36	14.61	191.3	178.2	720.0	300.0	133.2	542.7	166.8
May	226.3	67.68	17.83	213.9	198.9	795.1	260.0	125.1	622.2	134.9
June	241.2	61.87	20.70	216.8	201.7	798.9	262.4	129.1	621.7	133.3
July	241.1	64.79	25.00	222.6	207.2	805.9	309.8	149.1	608.2	160.7
August	222.5	56.94	24.38	227.9	213.1	829.6	352.9	164.3	616.2	188.6
September	167.7	51.31	22.43	196.9	183.9	721.8	363.1	159.3	519.4	203.8
October	136.5	44.01	19.49	189.6	175.9	700.8	411.8	163.6	495.4	248.2
November	95.3	32.03	16.15	153.5	139.7	564.1	361.2	123.2	406.3	237.9
December	86.0	27.20	13.72	156.2	139.3	569.4	388.5	130.0	404.6	258.5
Year	1949.3	576.24	17.49	2276.9	2102.8	8404.3	4068.1	1666.9	6230.4	2401.2

Table 2: Energy management annual results in a 4.4 kWp PV installation

In conclusion, a proper sizing of a PV system is critical to maximising its technical, economic and environmental performance. As it has been analysed with the previous example, an oversized system can lead to increased curtailment and unnecessary investment costs. On the other hand, an undersized system may fail to meet the intended energy demand, reducing the system's return on investment and resulting in a low solar fraction, reducing the amount of load covered by renewable generation. Moreover, correct sizing ensures that losses within the system, such as inverter inefficiencies and grid injection limitations, are minimised, enabling more efficient use of the generated solar energy. Hence, a careful balance between generation capacity, load profile, and grid interaction is essential to fully leverage the benefits of solar energy while ensuring system reliability and long-term viability.

3.3. GRID INTERACTION AND REGULATORY FRAMEWORK

This section will be dedicated to explaining the regulatory framework specifically in Málaga, Spain, where the solar photovoltaic project will be carried out.

The deployment of photovoltaic systems connected to the electrical grid in Málaga, Spain, is strongly supported by a favourable regulatory environment and regional initiatives aimed at promoting renewable energy. PV installations operate under different self-consumption modalities. Firstly, they can produce energy but without injecting the surplus into the grid, i.e., cutting the generation short at moments where the instantaneous consumption is lower than the generation. Secondly, PV installations can operate with surplus and simplified economic compensation, the most common modality under rooftop PV installations and briefly illustrated in *Figure 27*, where the surplus energy of installations under 100 kW is not sold directly but discounted on the electricity bill. This means that, in the best-case scenario, just the energy cost of the energy term on the electricity bill can be compensated, and one will still have to face other costs such as the power term or the access and distribution tolls. Therefore, oversizing PV installations is not worth it since once the energy cost is compensated with the surplus energy injected into the grid, any more energy fed into the grid will not be useful to increase savings in electricity costs.

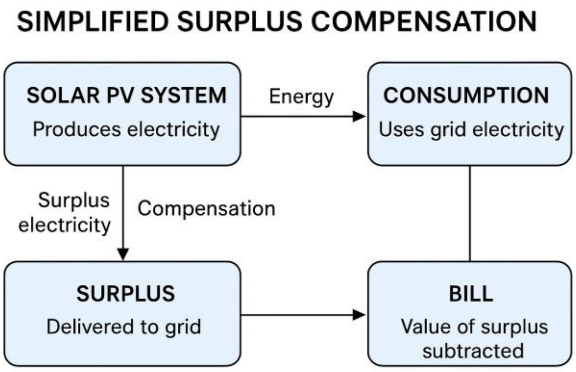


Figure 27: Flowchart of surplus energy compensation in residential solar installations

Finally, the last option would be direct sale of excess energy, generally the case of larger PV power plants whose purpose is the utility-scale generation of electricity rather than self-consumption [31]. The key regulation governing these schemes is Royal Decree 244/2019, which defines the administrative, technical, and economic conditions for self-consumption.

Installations with a capacity below 15 kW benefit from simplified administrative procedures, while systems above this threshold require formal grid access and connection permits, managed by the region's distribution system operator, Endesa Distribución [32]. Royal Decree 1183/2020 further details the general framework for grid connection, ensuring transparency and non-discriminatory access to the network.

From a technical standpoint, PV systems must comply with anti-islanding protection measures and ensure that their inverters are compatible with reactive power control capabilities, as specified in standard UNE-EN 50549-1. In addition, the regulatory framework limits the compensation of surplus energy to a discount on the electricity bill, without permitting net positive remuneration, thus encouraging a balance between self-consumption and responsible grid interaction [33].

At the regional level, Andalusia promotes PV adoption through the Andalusian Energy Agency, which provides subsidies and coordinates strategic plans such as the Plan Integral de Fomento para el Autoconsumo Energético 2021-2030 [34]. Local authorities, including the city of Málaga, have further facilitated PV integration by streamlining the permitting processes for small installations, requiring only minor building permits and standard electrical certifications.

Current trends in Málaga reflect a broader national and European shift towards decentralised energy production [35]. The rise of collective self-consumption models, where multiple consumers share a single generation installation, and the increasing integration of battery storage solutions are key developments. Moreover, Málaga's participation in European initiatives such as GrowSmarter and RENERGRID highlights the city's commitment to modernising its energy infrastructure, enhancing grid flexibility, and increasing the share of renewable energy in the urban environment [36].

3.4. MARKET TRENDS AND ADOPTION

The photovoltaic sector is experiencing a phase of rapid expansion, both globally and within Spain, driven by falling technology costs, supportive policies, and growing societal commitment to decarbonisation. *Figure 28* shows the exponential installed capacity trend this technology has experienced worldwide in the past decade.

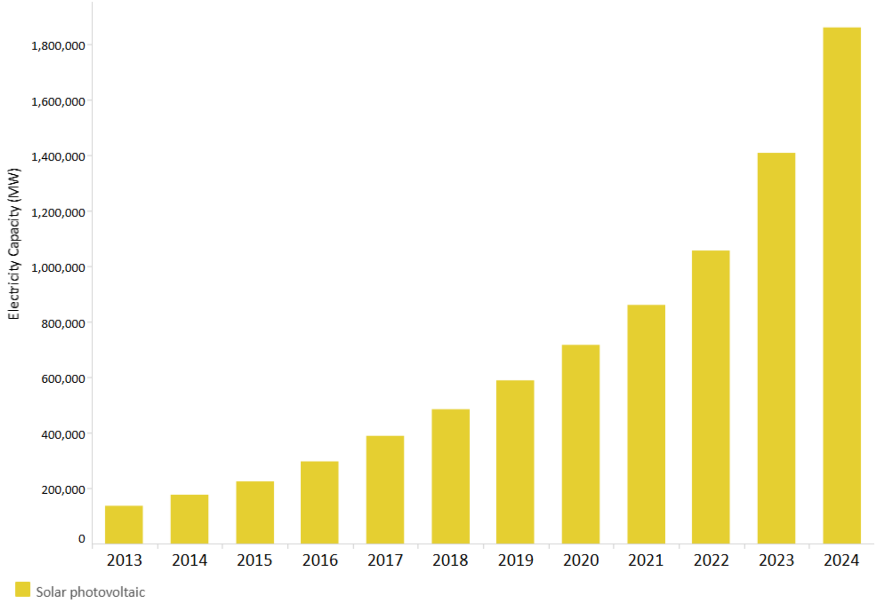


Figure 28: Solar PV installed capacity trend worldwide [50]

In 2023, solar PV accounted for the largest share of new renewable capacity additions worldwide [37]. In Spain, the installed PV capacity has surged significantly, positioning the country among the leading European markets for solar energy deployment [38]. The liberalisation of self-consumption regulations, particularly the approval of Royal Decree 244/2019, has spurred a widespread adoption of distributed PV systems, with residential and commercial rooftop installations becoming increasingly common.

The availability of simplified compensation mechanisms for surplus energy and regional incentives have further accelerated the diffusion of PV technologies among private users and small businesses. The integration of PV systems with battery storage solutions is also gaining momentum, enabling greater energy autonomy and promoting self-consumption even during non-generating periods.

Emerging trends include the proliferation of collective self-consumption projects, allowing multiple consumers to share the benefits of a single generation facility, and the growth of energy communities, which foster local renewable generation and consumption [39]. Additionally, digitalisation is playing a crucial role, with smart inverters, energy management systems, and real-time monitoring platforms enhancing the efficiency and flexibility of PV installations [40].

Spain has become one of the leading countries in Europe for the adoption of solar photovoltaic systems for self-consumption. This trend accelerated particularly after 2018, when the so-called "sun tax" was repealed, removing financial and administrative barriers to small-scale renewable generation. Since then, increasing electricity prices, financial incentives, and growing environmental awareness have further driven uptake in both the residential and industrial sectors.

The installed capacity of solar PV for self-consumption in Spain has grown considerably in recent years. In 2021, the country added approximately 1,203 MW of new capacity. The sectoral distribution was 41% industrial (493 MW), 32% residential (385 MW), and 26% commercial (313 MW) [59].

In 2022, this trend intensified, with installations rising to 2,507 MW. The industrial sector contributed the most with 1,178 MW (47%), followed by residential installations at 802 MW (32%) and commercial at 527 MW (21%) [60].

However, in 2023, the growth rate began to decline, with a total of 1,943 MW installed. Of this, 1,416 MW were in the industrial sector and 527 MW in residential systems. Commercial installations were not separately reported that year [61].

The slowdown became more pronounced in 2024, when the total new installed capacity dropped to 1,182 MW, a decrease of 31% from the previous year. This included 674 MW in the industrial sector, 275 MW in the residential sector, and 207 MW in the commercial sector [62].

Figure 29 illustrates the evolution of annual capacity additions by sector between 2021 and 2024. The industrial sector consistently accounted for the largest share, although the residential segment also played a significant role, especially during peak growth years.

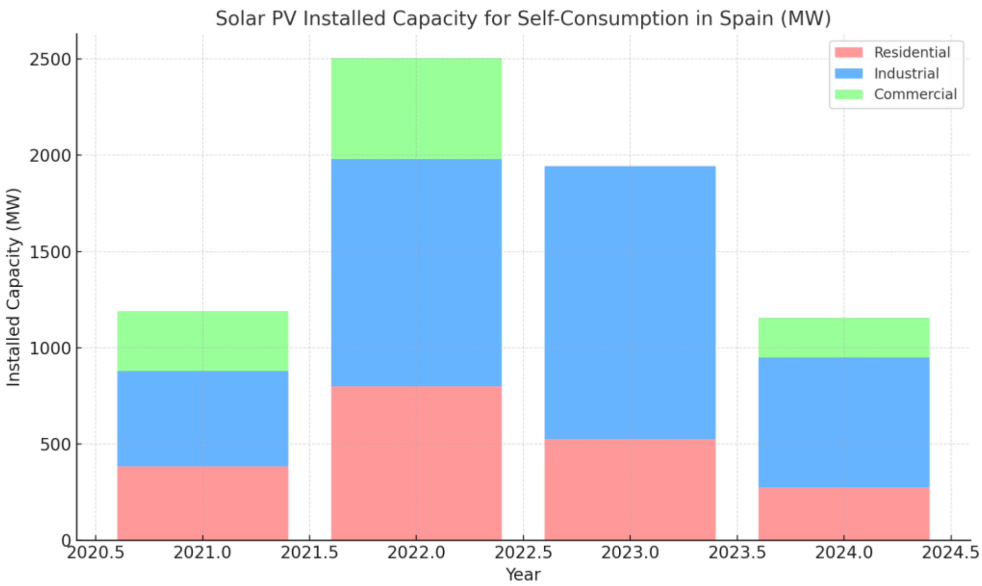


Figure 29: PV installed capacity for self-consumption in Spain

As of the end of 2024, Spain had installed a total of approximately 8.5 GW of solar photovoltaic capacity dedicated to self-consumption [64]. This cumulative figure encompasses both residential and commercial-industrial (C&I) sectors, with the C&I segment accounting for around 6.3 GW and the residential sector contributing approximately 2.2 GW [65].

Spain's Integrated National Energy and Climate Plan (PNIEC) has set an ambitious target of 19 GW of self-consumption capacity by 2030. To meet this goal, annual installations must average at least 1.8 GW. While early progress was promising, the recent decline in new installations puts this target at risk [62].

Administrative hurdles, delays in public subsidies, and the normalization of electricity prices following the 2021–2022 energy crisis have reduced the urgency for new investments. As a result, many households and businesses are postponing decisions to adopt PV systems [63].

Despite the strong growth trajectory, challenges remain, including the need for further grid flexibility, the development of adequate storage solutions, and the adaptation of regulatory frameworks to accommodate the evolving role of prosumers in the energy market.

Chapter 4. PROJECT SCOPE

4.1. JUSTIFICATION

Installing a solar photovoltaic system presents an attractive opportunity for single-family household owners due to its potential to significantly reduce electricity costs, increase property value, and contribute to environmental sustainability.

By generating their own electricity, homeowners can decrease reliance on grid-supplied energy, thereby lowering electricity bills and shielding themselves from future energy price volatility. Furthermore, many regions offer financial incentives, such as tax credits, feed-in tariffs, or net metering programs, which enhance the economic viability of solar PV investments.

Beyond financial benefits, solar energy systems align with growing societal values around sustainability, enabling homeowners to reduce their carbon footprint and support the broader transition towards renewable energy sources. Additionally, the presence of a solar installation can enhance a property's market appeal and resale value, as energy-efficient homes become increasingly attractive to buyers. Taken together, these factors make solar PV systems a highly relevant and beneficial investment for single-family households.

4.2. OBJECTIVES

This project seeks to design a solar photovoltaic installation for self-consumption of electricity in a single-family household. Depending on its annual energy demand and the available roof's surface area, orientation and inclination, a design for the photovoltaic system will be proposed. The project will thoroughly describe the design and components needed for the installation to generate electricity by converting solar into electrical energy. The use of high-quality materials and equipment will allow to assure the security of the people, electric grid and the rest of the systems connected to it.

With all the information available and the required software tools to process it, the objective is to identify which configuration of the solar photovoltaic system is the most suitable one for this case in specific taking the results of the simulations into account. Afterwards, all following calculations, both technical and economic ones, will be based on the designed proposed.

Having decided the peak and nominal power of the installation, this project will go on to perform the electrical calculations such as the sizing of conductors and protections as well as their layout and setup. By doing so, the technical viability of the project will be assured.

Finally, the economic viability will be evaluated by considering the energy yield of the PV installation, the initial investment cost and other estimated future cash flows. Some relevant parameters such as the Internal Rate of Return or the Payback will be calculated to analyse whether the project is viable from an economic viewpoint.

All in all, the objective of the project is to propose a design of a solar photovoltaic installation for self-consumption of electricity in a single-family household and to demonstrate why is it a clever idea to carry out such a financial investment due to economic, environmental and geopolitical reasons.

4.3. METHODOLOGY

First, a preliminary inspection of the house location and structure will be carried out to make sure the project is viable from a technical viewpoint. Starting by choosing a proper location where the solar panels will be installed is important to know whether it will be a limiting factor or not. Then, permission of access to the household's electricity consumption and other important information such as contracted power and voltage connection will be requested to the houseowner, as it will give an insight on how much PV power should be installed.

With all the required information available, different solar radiation databases will be compared to choose which one is the most suitable for the solar resource analysis of the location. The decision will be based on the percentage deviation from the average of all databases compared in the analysis. This will be one of the influencing factors on the performance of the photovoltaic system throughout the year.

The consumption analysis will follow, being quite a relevant one due to the characteristics of this project in specific. The consumption that has been recorded from the past year is not representative at all and different estimations will have to be made in order to achieve a consumption pattern that is similar to the probable household consumption in the future. Therefore, three scenarios will be developed, which represent three possible situations regarding the behaviour of the household loads according to the houseowner.

After having chosen the solar panel and inverter models, one first round of simulations will be run with the PVsyst software to determine which type of structure is the optimal one. Then, the number of panels and the nominal power of the inverter needed will be analysed for each of the consumption scenarios developed before.

Out of the different configurations proposed from the simulations, a final one will be chosen taking the possibility of occurrence of each scenario into consideration. Afterwards, the electrical calculations will take place, where the cross-sectional areas of the conductors and the rating of the protections will be determined. It will all be explained thoroughly and designed in compliance with the Spanish Low Voltage Electrotechnical Regulation. To illustrate such results, a few technical drawings will be attached as an annex to this document.

It is worth mentioning that, as in this project just the electrical side will be designed, there is no convenience on carrying out a comparison between different models of solar panels, inverters or structures considering both their performances and prices. The total cost of the project cannot be calculated just by taking the costs of the electrical side into account, as there are many other aspects that also play an important role in the accomplishment of such a project but are outside of this one's scope. Hence, their selection is just for simulations purposes and will not play a role in the economic viability analysis.

The purpose of this project is to design the electrical side of the solar PV installation, but also to provide the most realistic economic analysis, which ultimately will be the deciding factor for the houseowner to make the investment.

The economic viability of the project will be analysed considering the total cost of a project of such characteristics by requesting budgets to different known companies in the sector. This way, instead of just considering the costs of the electrical side and, consequently, not taking a realistic approach, the analysis is made with an approximate total cost considering other variables outside this project's scope such as the electronics and communications side, the installation by a certified company or the marketing margin of the company designing and developing the project. The analysis will consider possible financial incentives from the public administration.

Looking into the theoretic annual generation of energy by the PV installation, different electricity contracts with several energy suppliers will be studied to determine which is the most suitable one to the customer's new situation. A key factor to consider will be the feed-in tariffs that the electric companies offer to the customer as a compensation for the surplus energy fed into the grid but considering at the same time the electricity prices they offer. Then, the annual savings in electricity costs in comparison with the current situation with no PV system will be calculated and used for further economic calculations, which will ultimately determine the economic viability of the project.

Finally, some conclusions regarding the whole project design and development will be drawn. They will go on to briefly comment on the results obtained and the project's viability from both technical and economic viewpoints.

4.4. ALIGNMENT WITH THE SUSTAINABLE DEVELOPMENT GOALS

The Sustainable Development Goals are a set of 17 global objectives, listed in *Figure 30*, which were established by the United Nations in 2015 as part of the 2030 Agenda for Sustainable Development. These goals aim to address the world's most pressing challenges, including poverty, inequality, environmental degradation and climate change, while fostering peace and justice. They provide a blueprint for governments, organisations and individuals to work together towards a more equitable and sustainable world by 2030.

Figure 30: The 17 Sustainable Development Goals [58]

The primary goal a solar photovoltaic installation aligns with must be **SDG 7: Affordable and Clean Energy**, as the need of ensuring access to affordable, reliable, sustainable and modern energy for all is provided by generating clean and renewable electricity for residential use.

Particularly linked to the one before, this project also directly supports **SDG 13: Climate Action**, which consists of taking urgent action to combat climate change and its impacts. As it is well known, the generation of electricity by solar photovoltaic systems does not emit greenhouse gases of any kind, which are harmful to the atmosphere and contribute to global warming.

The sustainability and resilience of urban and residential communities is also enhanced by this project, aligning with **SDG 11: Sustainable Cities and Communities**. By integrating solar energy solutions, households become less dependent on centralised energy grids and fossil fuels, making cities inclusive, safe, resilient and sustainable.

Homeowners often become more aware of their energy usage when they adopt solar power systems, leading to increased energy efficiency and reduced waste. By promoting self-consumption and reducing the dependence on non-renewable sources, this project aligns with **SDG 12: Responsible Consumption and Production**.

To finish with the environmental and climate action related goals, one could argue that **SDG 15: Life on Land** is also enhanced by solar PV systems. They help protect terrestrial ecosystems by reducing air pollution and environmental degradation associated with traditional energy production.

Moving into innovation and economic matters, it is well known that the solar energy sector is a significant driver of job creation in the green economy. This project supports **SDG 8: Decent Work and Economic Growth** by creating employment opportunities in areas such as system design, installation, maintenance and monitoring.

This project encourages the adoption of renewable technologies in the residential sector, fostering a culture of innovation. It also supports the growth of the green energy industry by stimulating the demand for renewable energy solutions and related services, stating clearly that it is aligned with **SDG 9: Industry, Innovation and Infrastructure**.

In conclusion, this solar photovoltaic installation project contributes meaningfully to multiple Sustainable Development Goals, promoting sustainability, environmental protection and economic growth. The alignment between this project and the SDGs is further analysed in ***Annex V***, where deeper connections to the goals as well as some quantifications obtained from both technical and economic analysis are given. By aligning with these global goals, the project not only addresses immediate energy needs but also supports a more sustainable and resilient future.

Chapter 5. TECHNICAL ANALYSIS

5.1. *HOUSEHOLD CHARACTERISTICS*

The household main electrical characteristics are presented in *Table 3*.

PARAMETERS	
CUPS	ES 0031 1046 8802 5002 PB
TYPE OF CONNEXION	Interior network
VOLTAGE	400 V
CONSUMER	Individual
CONFIGURATION	A (bidirectional metering equipment at the grid connection point)

Table 3: Household electrical characteristics

The solar photovoltaic installation designed in this project will be located in:

- Address of the supply point: Urbanización Cala Golf Resort, Calle Entrelagos 8, 29649 Mijas, Málaga.
- Cadastral address: Calle Entrelagos de Cala Golf 11, 29649 Mijas, Málaga.

Table 4 indicates the location parameters of the project.

LOCATION PARAMETERS	
COORDINATES	36° 32’ 17.69” N / 4° 42’ 50.76” W
MUNICIPALITY / PROVINCE	Mijas / Málaga
COUNTRY	Spain
CADASTRAL REFERENCE	6652110UF4465S0001UZ

Table 4: Location parameters of the project

The project will be held in a single-family household in Málaga, Spain. It consists of 3 floors: underground, ground and upper floors. On the underground, there is a car garage and an office. The ground floor contains a kitchen, a small toilet, a living room and a dining room. Finally, the 3 bedrooms and 2 bathrooms are in the upper floor. Additionally, there is a garden and swimming pool outside. *Figure 31* shows the house seen from the garden, while *Figure 32* illustrates a similar perspective of the house but during the night.

Figure 31: House seen from the garden

Figure 32: Picture of the house at night

Figure 33 shows how the entrance from the street looks like.

Figure 33: Entrance to the house from the street

Finally, *Figure 34* shows the upper view of the house, where it can be seen the available area on the roof for the installation of solar panels.

Figure 34: Upper view of the house

5.2. CONSUMPTION ANALYSIS

5.2.1. INTRODUCTION

In this section, the household's annual consumption is to be analysed. It is of great importance due to the fact that the consumption will determine how much PV power will be needed. It was discussed in section ***3.2. System Design and Sizing***, that accurate sizing of a photovoltaic system is crucial for maximising its technical efficiency, economic feasibility, and environmental benefits.

Oversizing may lead to excessive curtailment and inflated investment costs, while undersizing can result in an inability to meet energy demand, thereby lowering the return on investment and reducing the solar fraction, that is, the proportion of the load met by renewable energy. Furthermore, appropriate sizing minimises internal system losses, such as inverter inefficiencies and grid injection constraints, thus improving the overall utilisation of generated solar power.

Striking an optimal balance between generation capacity, load profile, and grid interaction is therefore essential to fully harness the advantages of solar energy while ensuring long-term reliability and performance of the system.

5.2.2. CURRENT CONSUMPTION

The project will take place in a single-family household, where two people moved in in June 2024. Thus, at the moment of analysis there are two months, April and May, where no consumption is registered, and an approximation has been made to complete the annual consumption based on the consumption of the other months. Also, due to this inconvenience, the simulations will be run with monthly instead of hourly consumptions, which would be the better ones to use to increase precision on results.

Apart from the conventional electric appliances such as an electric oven, a washing machine and a dishwasher, other not so usual ones such as a hot water electric heater, 5 air conditioning systems and a swimming pool water pump are also connected to the household's internal network and make a big impact on the total consumption due to their high electricity demand.

From the distribution system operator (DSO), which in this case is Endesa Distribución Eléctrica, the monthly consumptions shown in *Table 5* were retrieved. To complete April's and May's electricity consumptions, an approximation regarding the consumption of the hot water electric heater was made. As an equivalent system, there is also a thermal solar panel installed which captures the heat received from its exposure to direct radiation from the sun and keeps a water tank hot. In terms of capacity, the hot water electric heater was not even installed from June to October as the solar thermal system was able to provide the household with enough hot water. Hence, with the temperatures and the number of sunny hours rising as the spring goes by, it was fair to assume that the electricity consumption of the hot water electric heater would drop progressively in April and May. In addition, during these two months no other high-electricity-consumption appliance would be used. With not so high temperatures and no use of the swimming pool until June, both the A/C systems and the water pump remain disconnected during April and May.

Current consumption (kWh)	
January	405.943
February	327.085
March	325.292
April	300
May	260
June	262.416
July	309.846
August	352.888
September	363.13
October	411.788
November	361.165
December	388.544

Table 5: Household's current electricity consumption

However, after talking to the owner, it was clear that these consumptions are not representative at all. To start with, the water pump had only been running half of the time it was supposed to during the summer months. Moreover, the A/C systems were barely used due to the uncertainty of how the electricity bill would look like in summer months, as they had just moved in. Also, the solar thermal system used to provide the house with hot water will be removed due to construction works. Finally, there is also a desire in changing an old diesel car with a brand new electric one, taking advantage of the PV installation.

Therefore, three possible scenarios have been developed, which represent different consumption situations so as to give the project a more realistic view on the future consumption of the household.

5.2.3. FUTURE CONSUMPTION: SCENARIO 1

The Scenario 1 represents the most probable situation, i.e., the one where it is known that the electric appliances already in place will increase their consumption. All the following estimations have been done according to the information provided by the house owner.

The summer months in *Table 5* contain only half of the electricity consumption expected by the swimming pool water pump, as it was stated by the owner that the pump is supposed to run 8 hours per day from June to September, both included, while last summer it ran 4 hours per day, sometimes even less. Taking the pump's characteristics shown in *Figure 35* into consideration, it can be seen that its power consumption is of 1.3 kW, which multiplied by the increase of time usage, 4 hours, the expected consumption increase of the water pump to be added to the total consumption of the household can be calculated, and those results are shown in *Table 6*.

Figure 35: Water pump electrical characteristics

Water pump	
Power	1.3 kW
Usage time increase	4 h/day
To add in June (30 days)	156 kWh
To add in July (31 days)	161.2 kWh
To add in August (31 days)	161.2 kWh
To add in September (30 days)	156 kWh

Table 6: Consumption increase by water pump

The air conditioning system is another high-electricity-demanding appliance whose consumption during last year's summer months is far from being representative. According to the owner, an increase in its usage for better comfort and lower indoor temperatures is desired. There are two A/C systems in the living room and one A/C system in each of the three bedrooms of the first floor. Nevertheless, as there are only two people living on a daily basis in the house, just the A/C system of the principal bedroom will be considered. With the same procedure as before, knowing the average power consumption, the number of A/C systems and estimating the additional hours they will be used, the amount of energy to be added to the total count can be calculated. The results of such calculations are shown in *Table 7*.

Air conditioning systems	
Average power consumption	1.23 kW
A/C systems in living room	2
Usage time increase in living room	4 h/day
A/C systems in bedroom	1
Usage time increase in bedroom	2 h/day
To add in June (from 15th to 30th)	184.5 kWh
To add in July (31 days)	381.3 kWh
To add in August (31 days)	381.3 kWh
To add in September (until 15th)	184.5 kWh

Table 7: Consumption increase by A/C systems

It was also mentioned that the solar thermal system used to provide the household with hot water, mainly during summer months, will be permanently removed. Hence, there will be a consumption increase by the hot water electric heater, which approximately from April to September would be barely used with the solar thermal system. However, it is difficult to estimate how much does the system contribute to providing hot water during colder months. On average, modern shower heads drain around 10 litres per minute. Considering a shower time of 5 minutes, 50 litres of hot water per person are required just for showering. Taking other possible hot water usage situations into account, such as washing one’s hands or cookware which does not fit into the dishwasher, 60 litres per person per day of hot water will be considered in the calculations of consumption increase by the hot water electric heater.

With the objective to calculate the amount of energy needed to heat up a determined amount of water, the specific heat formula (5.1) will be employed:

$$Q = m \cdot c \cdot \Delta T \tag{5.1}$$

Where:

- Q: heat energy (in Jules)
- m: mass of the liquid (in kilograms)
- c: specific heat capacity of the liquid (in J/kg·ºC)
- ΔT: temperature change (in ºC or K)

Considering that there are two people living in the house, that the water has a density of 1 kg/l and a specific heat capacity of 4.186 kJ/kg·ºC and assuming that the water enters the heater at 10 ºC and is supposed to leave at 55 ºC:

$$Q = 60 \cdot 2 \cdot 4.186 \cdot (55 - 10) = 22604.4\ kJ/day$$

Applying a conversion factor:

$$E = \frac{22604.4}{3600} = 6.279\ kWh/day$$

The results are gathered in *Table 8*, where it is also approximately indicated the number of days that the solar thermal system would be expected to provide hot water depending on the month, which from now on the electric heater will have to cover.

Hot water electric heater	
Hot water consumption	60 l/person·day
People living in house	2 people
Total volume of water	120 litres
Energy required	6.279 kWh/day
To add in January (2 days)	12.558 kWh
To add in February (5 days)	31.395 kWh
To add in March (10 days)	62.79 kWh
To add in April (30 days)	188.37 kWh
To add in May (31 days)	194.649 kWh
To add in June (30 days)	188.37 kWh
To add in July (31 days)	194.649 kWh
To add in September (30 days)	188.37 kWh
To add in October (10 days)	62.79 kWh
To add in November (5 days)	31.395 kWh
To add in December (2 days)	12.558 kWh

Table 8: Consumption increase by hot water electric heater

Adding the increases in energy consumption of each of the three electric appliances for each month, the Scenario 1 future consumption is presented in *Table 9*.

Consumption Scenario 1 (kWh)	
January	418.501
February	358.48
March	388.082
April	488.37
May	454.649
June	791.286
July	1046.995
August	1090.037
September	892
October	474.578
November	392.56
December	401.102

Table 9: Future energy consumption Scenario 1

5.2.4. FUTURE CONSUMPTION: SCENARIO 2

The Scenario 2 represents the same situation as Scenario 1, with the surely increase in consumption by the means of swimming pool water pump, hot water electric heater and air conditioning systems, but it also considers the possibility of changing an old diesel car with an electric car that will be charged at home.

According to the owner, the car is approximately driven 250 km during weekdays and 50 km during weekends, which means a total distance of 1200 kilometres per month. The new electric model has yet to be decided, but it was stated that the brand-new electric Renault 5 could be a possibility. This car has an electricity consumption of around 0.16 kWh per km. Thus, the amount of 192 kWh must be added to the household consumption for each month of the year, as shown in *Table 10*.

Consumption Scenario 2 (kWh)	
January	610.501
February	550.48
March	580.082
April	680.37
May	646.649
June	983.286
July	1238.995
August	1282.037
September	1084
October	666.578
November	584.56
December	593.102

Table 10: Future energy consumption Scenario 2

5.2.5. FUTURE CONSUMPTION: SCENARIO 3

The Scenario 3 takes the consumption increase studied in the two previous scenarios and introduces the possibility of purchasing another electric vehicle meant for professional purposes. The owner's idea would be to buy an EV van to transport the material needed between different locations around the Autonomous Community of Andalusia. It was indicated that during the peak season, May to September, the van will be driven 800 kilometres per month and 400 kilometres per month the rest of the year. A van of such characteristics has an average consumption of 0.22 kWh/km. Thus, an increase of 176 kWh per month during the peak season and 88 kWh per month during the low season will have to be considered. The results of such calculations are shown in *Table 11*.

Consumption Scenario 3 (kWh)	
January	698.501
February	638.48
March	668.082
April	768.37
May	822.649
June	1159.286
July	1414.995
August	1458.037
September	1260
October	754.578
November	672.56
December	681.102

Table 11: Future energy consumption Scenario 3

5.3. SOLAR RADIATION DATABASE SELECTION

5.3.1. INTRODUCTION

Accurate solar radiation data is critical for the design, simulation, and performance evaluation of photovoltaic systems. Solar radiation databases provide information on global horizontal irradiance, direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI), typically on an hourly or daily basis. These data are derived from ground-based measurements, satellite observations, or a combination of both, and are processed using validated models to ensure consistency and reliability. The data are obtained from reliable sources, such as national meteorological agencies or satellite-based platforms, and are used to simulate the energy yield of the system under site-specific climatic conditions. The quality and resolution of this data significantly influence the reliability of the performance predictions and the overall design of the photovoltaic installation.

Among the most widely used solar radiation databases are PVGIS (Photovoltaic Geographical Information System), Meteonorm, and NASA-SSE (NASA's Surface Meteorology and Solar Energy dataset). These sources offer long-term averaged data for various locations and are fundamental tools for estimating the energy yield of PV systems under local climatic conditions.

In this section a comparison between them and a selection of one database will take place before running the energy yield simulations. This will be accomplished by comparing their typical meteorological years (TMY), which represents a statistically typical year of solar radiation and meteorological conditions, constructed from historical time series by selecting the most representative months. It is particularly useful for long-term performance simulations of photovoltaic systems, as it reflects average climate conditions without the extremes of specific years.

5.3.2. METEONORM

Meteonorm is a global solar radiation database that enables the simulation of solar irradiance at virtually any location worldwide. The system combines interpolated data from nearby ground-based meteorological stations with satellite-derived measurements to generate highly accurate estimates of solar radiation.

This hybrid approach improves the reliability of the data by leveraging both local measurements and broader atmospheric observations. As a result, Meteonorm serves as a valuable tool for the design, simulation, and performance analysis of photovoltaic systems, ensuring realistic and site-specific solar resource assessments.

The Meteonorm 8.2 version covers the period between 2001 and 2020 and its typical meteorological year for the household's location is shown in *Table 12*.

Month	GHI (kWh/m²)	DHI (kWh/m²)	Temperature (°C)	Wind Velocity (m/s)
January	86.2	29.2	10.6	3.29
February	99.8	35.3	11.7	3.3
March	144.5	57.8	14.4	3.1
April	173.1	72	16.9	2.8
May	218.2	78.4	20.3	2.6
June	235.3	68.5	23.8	2.6
July	238.8	67.2	26.4	2.5
August	210.4	68.8	26.6	2.29
September	161.5	54	22.8	2.2
October	123.7	48.5	19.1	2.09
November	86.2	30.4	14.2	2.8
December	75.9	24.9	11.5	3.09
Year	1853.4	635	18.2	2.72

Table 12: TMY Meteonorm

5.3.3. NASA-SSE

The NASA-SSE database is a widely used resource that provides free access to a comprehensive set of meteorological and solar radiation data. Developed by NASA's Langley Research Centre, this database supports renewable energy applications, environmental studies, and climate research by offering consistent and validated datasets over extended time periods.

The NASA-SSE platform includes 22 years of data, covering the period from July 1, 1983, to June 30, 2005. It offers a spatial resolution of 1°×1° in latitude and longitude, which corresponds to a grid of approximately 100×100 km. The database benefits from an improved algorithm that enhances the estimation accuracy of surface solar radiation, making it particularly valuable for solar resource assessment.

However, due to its spatial resolution, it is important to consider that local topographic variations may lead to significant differences in solar radiation values even between nearby locations. This aspect must be taken into account when applying the data to specific sites, especially in regions with complex terrain.

Table 13 shows its typical meteorological year for the household's location.

Month	GHI (kWh/m^2)	DHI (kWh/m^2)	Temperature (°C)
January	71.9	27.9	11.3
February	89.6	32.2	11.9
March	139.8	46.2	13.9
April	167.7	56.4	15.6
May	198.4	66.3	18.5
June	226.2	58.8	22.4
July	241.8	53	25
August	214.2	49	25.1
September	158.1	45	22.5
October	108.8	39.4	18.8
November	74.1	29.4	15.1
December	61.1	25.7	12.6
Year	1751.7	529.3	17.7

Table 13: TMY NASA-SSE

5.3.4. PVGIS

The Photovoltaic Geographical Information System (PVGIS) is a publicly accessible platform developed by the European Commission's Joint Research Centre (JRC) that provides high-resolution solar radiation and photovoltaic performance data. It is widely used for solar resource assessment and energy yield estimation, particularly across Europe, Africa, and Southeast Asia.

PVGIS integrates data from multiple sources, including 182 ground-based meteorological stations from the ESRA (European Solar Radiation Atlas) and several satellite-derived datasets, such as:

- CMSAF (2007-2016)
- SARAH (2005-2016)
- NSRDB – NREL (2005-2015)
- COSMO & ERA5

These datasets enhance the spatial and temporal reliability of the radiation estimates, making PVGIS a robust tool for energy system analysis and planning.

The typical meteorological year for the project's location is exposed in *Table 14*.

Month	GHI (kWh/m²)	DHI (kWh/m²)	Temperature (°C)	Wind Velocity (m/s)
January	92.5	26.8	11.1	3.47
February	104.4	32.7	10	3.59
March	155.8	52.5	13.9	3.76
April	179.9	58.4	14.6	4.11
May	226.3	67.7	17.8	3.66
June	241.2	61.9	20.7	3.13
July	241.1	64.8	25	2.98
August	222.5	56.9	24.4	2.49
September	167.7	51.3	22.4	2.56
October	136.5	44	19.5	3.5
November	95.3	32	16.1	3.09
December	86	27.2	13.7	3.11
Year	1949.3	576.2	17.4	3.29

Table 14: TMY PVGIS

5.3.5. COMPARISON AND SELECTION

By plotting the different GHI values of the three databases throughout the year in *Figure 36*, it can be seen at first sight that the GHI values of PVGIS are higher than average as well as that the NASA-SEE ones are lower, being Meteonorm between them through the whole year.

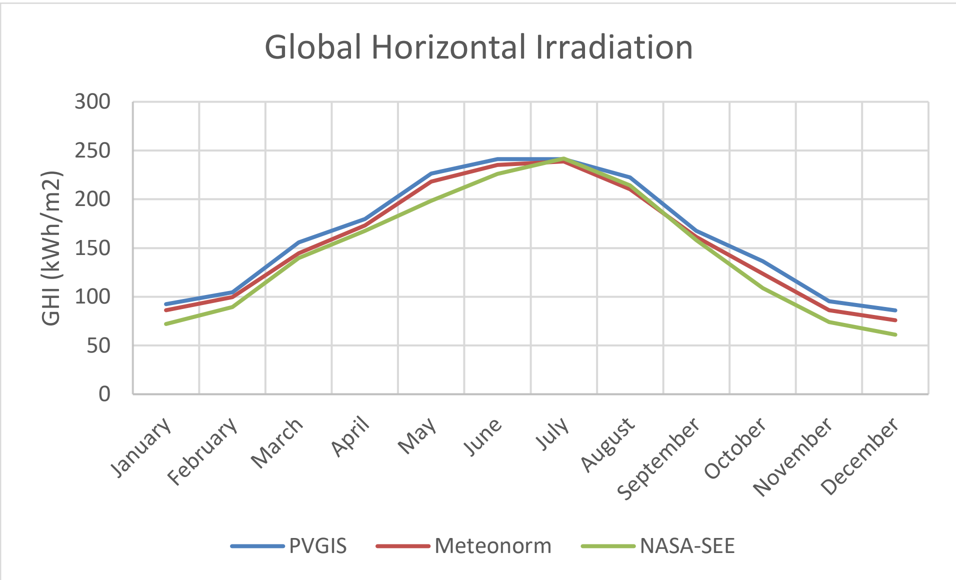


Figure 36: GHI values comparison of the three databases

Computing their average GHI percentage deviation, it can be seen in *Figure 37* that Meteonorm would be the solar radiation database to choose for the simulations, as it is the one with the lower percentage deviation.

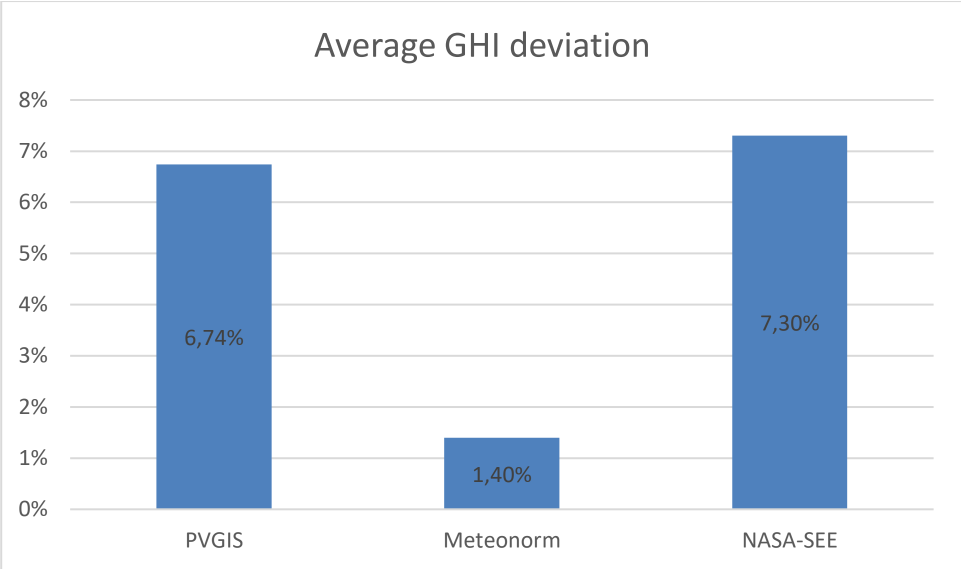


Figure 37: GHI percentage deviation of each database

On the other hand, in *Figure 38* their DHI values are plotted. Here, their differences are clearly more noticeable. While NASA-SSE is still offering lower values, Meteonorm has extremely higher ones, especially in the second and third quarters of the year. In this case PVGIS is the database which offers values nearer to the average.

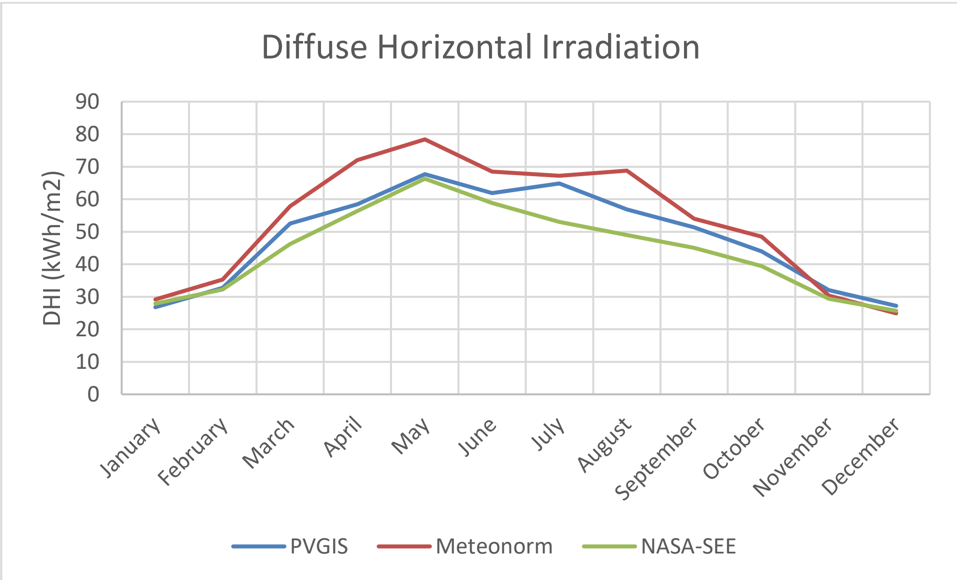


Figure 38: DHI values comparison of the three databases

Again, *Figure 39* shows the average DHI percentage deviation. As it was noticed in *Figure 38,* Meteonorm has the highest percentage deviation, followed by NASA-SEE. Taking this result into account, PVGIS would be the database to choose just by considering the DHI values analysis.

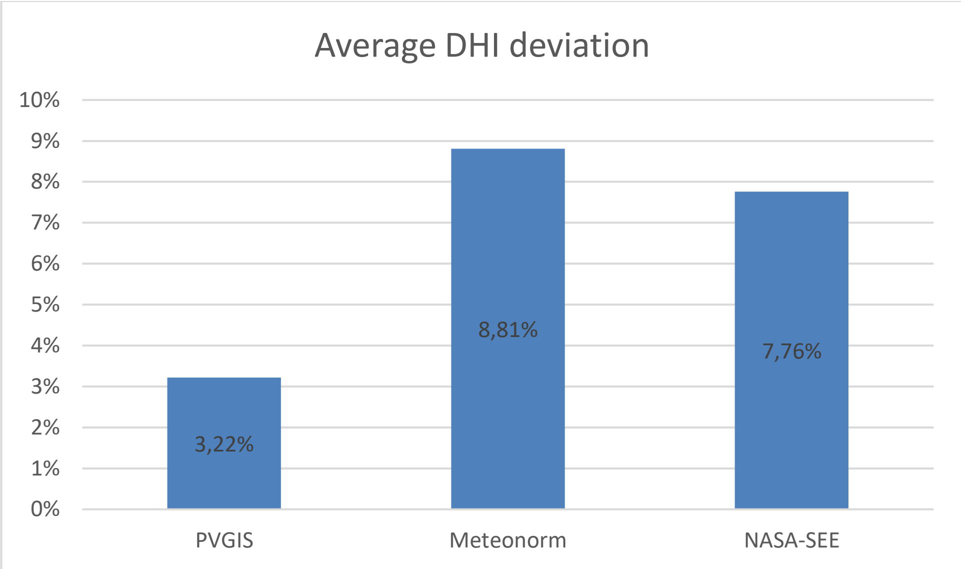


Figure 39: DHI percentage deviation of each database

Due to having different databases to be chosen depending on the GHI and DHI analysis, and in order to choose one among the three of them, an overall average deviation of each database has been calculated in *Figure 40*, considering both GHI and DHI parameters.

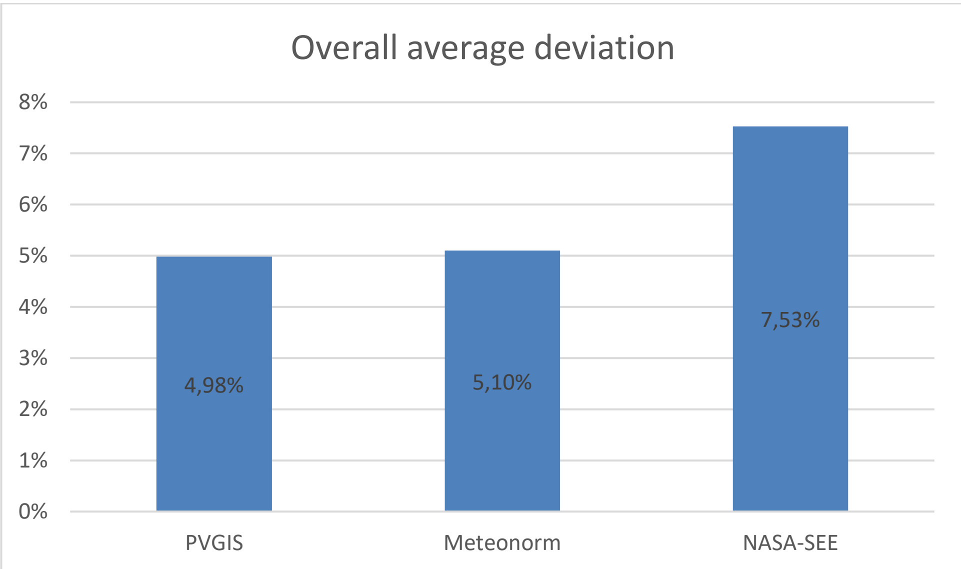


Figure 40: Overall percentage deviation of each database

Consequently, the solar radiation database chosen to run the simulations with is the PVGIS database, due to having the lowest percentage deviation from average between the three databases analysed.

5.4. RULES AND REGULATIONS

Royal Decree 244/2019, of 5 April, regulating the administrative, technical, and economic conditions for the self-consumption of electric energy.

Royal Decree 1699/2011, of 18 November, regulating the grid connection of small-scale electricity production facilities.

Royal Decree 1955/2000, regulating the activities of transmission, distribution, marketing, supply, and the authorisation procedures for electricity installations.

Royal Decree 842/2002, approving the Low Voltage Electrotechnical Regulation.

Royal Decree 314/2006, approving the Technical Building Code.

Royal Decree 413/2014, of 6 June, regulating the activity of electricity production from renewable energy sources, cogeneration, and waste.

Royal Decree 1627/1997, of 24 October, establishing the minimum health and safety provisions for construction works.

Royal Decree 485/1997, of 14 April, on minimum provisions regarding workplace health and safety signage.

Royal Decree 773/1997, of 30 May, on minimum health and safety provisions regarding the use of personal protective equipment by workers.

Royal Decree 1215/1997, of 18 July, establishing health and safety provisions for the use of work equipment by workers.

Royal Legislative Decree 1/2016, of 16 December, approving the consolidated text of the Law on Integrated Pollution Prevention and Control.

Royal Decree 1110/2007, of 24 August, approving the Unified Regulation of Measurement Points in the Electricity System.

Royal Decree-Law 7/2006, of 23 June, adopting urgent measures in the energy sector.

Law 54/1997, of 27 November, on the Electricity Sector.

Law 15/2012, of 27 December, on fiscal measures for energy sustainability.

Law 31/1995, of 8 November, on the prevention of occupational risks.

Law 34/2007, of 15 November, on air quality and atmospheric protection.

Law 82/1980, of 30 December, on energy conservation.

Law 24/2013, of 26 December, on the Electricity Sector.

Order of 5 September 1985, establishing administrative and technical rules for the operation and connection to the electricity grids of hydroelectric power plants up to 5,000 KVA and self-generation electricity plants.

Law 7/2022, of 8 April, on waste and contaminated soils for a circular economy.

Specific regulations of the distribution company for Medium and Low Voltage Installations.

Applicable UNE Standards:

- **UNE-EN 61194:1997**, Characteristic parameters of photovoltaic systems.
- **UNE-EN 61725:1998**, Analytical expression for daily solar profiles.
- **UNE-EN 61277:2000**, Terrestrial photovoltaic power-generating systems – Generalities and guide.
- **UNE-EN 61724:2000**, Monitoring of photovoltaic systems – Guidelines for measurement, data exchange, and analysis.
- **UNE-EN ISO 9488:2001**, Solar energy – Vocabulary.

5.5. PRINCIPAL COMPONENTS OF THE INSTALLATION

5.5.1. SOLAR PANELS

In order to select which solar panels will be installed, it is important to choose a reliable manufacturer with experience and offering long-term warranties.

In the solar industry, the classification “Tier 1” is commonly used to refer to solar panel manufacturers that are considered financially stable and bankable. This designation does not evaluate the technical quality of the solar panels themselves but rather reflects the manufacturer's financial strength, reliability, and proven track record in large-scale photovoltaic projects. The classification is most notably defined by Bloomberg New Energy Finance (BNEF), which uses it primarily as a measure of a company's bankability in the context of project financing.

According to BNEF, a Tier 1 manufacturer is one that has supplied its own branded, self-produced products to at least six different projects, each larger than 1.5 MW, that have been financed by non-recourse loans from six different banks within the past two years. This criterion implies that banks and financial institutions trust the long-term viability of the manufacturer and are willing to support projects using its products without requiring additional guarantees.

Tier 1 manufacturers are typically vertically integrated, meaning they control the entire production process from silicon purification to module assembly. They also invest heavily in research and development, maintain strong quality control standards, and offer long-term warranties, often up to 25 years. These companies are frequently involved in utility-scale projects and have a global commercial presence. Prominent Tier 1 manufacturers (as of recent rankings) include LONGi Solar, JA Solar, JinkoSolar, Trina Solar, Canadian Solar, Q CELLS, REC Group, First Solar, SunPower/Maxeon, and Risen Energy.

The model chosen is LONGi Solar LR5-72HPH-550M.

LONGi Solar is widely recognised as one of the leading manufacturers of high-performance solar modules. The company has established a strong global reputation for quality, reliability, and innovation, and consistently ranks among the top photovoltaic manufacturers in terms of market share and bankability [41].

LONGi specialises in high-efficiency monocrystalline silicon technologies such as PERC (Passivated Emitter and Rear Cell) and has recently introduced more advanced cell architectures like TOPCon and HPBC, which enable higher module efficiencies and improved energy yields [42].

As a vertically integrated manufacturer, LONGi controls the entire production chain from silicon wafers to finished modules, ensuring strict quality control and traceability. Moreover, the company places a strong emphasis on sustainability, having committed to 100% renewable electricity use in its operations under the RE100 initiative [43].

LONGi panels typically include product warranties of 12-15 years and performance guarantees of 25-30 years, which align with industry-leading standards [44]. These factors make LONGi a reliable choice for both residential and utility-scale solar projects.

The system will require the installation of 10 modules, whose characteristics under Standard Testing Conditions (STC) are shown in *Table 15*.

SOLAR PANEL CHARACTERISTICS	
MANUFACTURER	LONGi Solar
MODULE TYPE	LR5-72HPH-550M
MAXIMUM POWER	550 W
OPEN CIRCUIT VOLTAGE	49.8 V
SHORT CIRCUIT CURRENT	13.98 A
VOLTAGE AT MAXIMUM POWER	41.95 V
CURRENT AT MAXIMUM POWER	13.12 A
MODULE EFFICIENCY	21.3%

Table 15: Electrical characteristics of the selected module [44]

5.5.2. INVERTER

The inverter is the equipment in charge of transforming the generated energy and regulating it for its consumption in the household and for the injection of the surplus energy into the grid.

The inverter chosen is Huawei SUN2000-5KTL-M1. Huawei is one of the leading global manufacturers of solar inverters, combining extensive experience in digital technologies with advanced power electronics to offer high-efficiency and reliable solutions. As a long-established leader in the ICT (Information and Communication Technology) sector, Huawei brings strong expertise in AI, data analytics, and connectivity to the renewable energy industry, making its inverters among the most intelligent on the market [45].

The company's *FusionSolar* portfolio includes both residential and commercial/utility-scale inverters that incorporate features such as integrated arc-fault detection, smart string monitoring, and AI-based fault diagnosis [46].

Huawei inverters are known for their high efficiency, with some models achieving conversion efficiencies of over 98.6%, as well as for their modular, fan-less design, which improves durability and reduces maintenance [47]. Furthermore, the integration of battery storage systems and optimisation algorithms enables enhanced energy management, making them well-suited for self-consumption and smart grid applications.

Huawei has received multiple recognitions from global institutions such as TÜV Rheinland and has consistently ranked among the top inverter suppliers in terms of global shipments and bankability [48]. These qualities make Huawei a highly attractive option for solar installations prioritising digital integration, high efficiency, and system intelligence.

The system will require the installation of 1 inverter, whose electrical characteristics are exposed in *Table 16*.

INVERTER CHARACTERISTICS	
MANUFACTURER	Huawei
TECHNICAL SPECIFICATION	SUN2000-5KTL-M1
MAXIMUM EFFICIENCY	98.4%
RECOMMENDED MAX. PV POWER	7500 Wp
MAX. INPUT VOLTAGE	1100 V
OPERATING VOLTAGE RANGE	140 V – 980 V
START-UP VOLTAGE	200 V
MAX. INPUT CURRENT PER MPPT	13.5 A
NUMBER OF MPP TRACKERS	2
GRID CONNECTION	Three-phase
RATED OUTPUT POWER	5000 W

Table 16: Electrical characteristics of the selected inverter [9]

Out of its 2 MPP trackers, just one will be used as shown in the Single-line DC diagram of the technical drawings from ***Annex IV*** since the minimum MPP voltage of just 5 solar panels connected in series (190.3 V) is below the inverter's start-up voltage. Hence, just one string of all 10 solar panels connected in series will be formed.

5.5.3. SOLAR PANELS MOUNTING STRUCTURE

5.5.3.1. Structure description

A static structure is proposed to allow the installation of module rows on the roof, as it has been verified that this type of mounting can reduce installation costs. This structure will be directly fixed to the concrete block in accordance with applicable regulations, ensuring high resistance to meteorological loads.

The system has been specifically designed for solar installations where quick and simple assembly are key requirements. It is characterised by its versatility, reliability, and ease of installation.

The structure's fastening elements will be made of galvanised or stainless steel to prevent and avoid corrosion. However, the fasteners securing the modules will be made of stainless steel. The fastening system will ensure the necessary thermal expansions without transferring loads that could affect the integrity of the modules. Metallic plates/clamps will be used as connecting elements between modules.

Attachment to the roof will be carried out following the manufacturer's established recommendations. The structure must withstand the forces derived from:

- Wind loads in any direction
- The self-weight of the structure and supported modules
- Snow loads on the surface of the modules
- Seismic loads according to regulations

The metallic support structure of the photovoltaic modules will be connected to the constructed grounding system.

5.5.3.2. Selection of Structure Type, Tilt Angle and Azimuth Angle

In section ***2.3.4. Solar Resource Optimisation***, two different structures were mentioned: fixed-tilt structures and East-West structures. In addition, *Figure 24* compared their energy yield, drawing as a conclusion that while E-W structures have a flatter and more uniform curve, they normally yield less energy than fixed-tilt structures.

To analyse which type of structure is the optimal one to install in this project, a simulation has been carried out with the solar radiation database chosen in section ***5.3.5.*** and the current consumption of the household presented in *Table 5*.

The goal in this case is to analyse whether it is worth installing an E-W structure which yields less energy throughout the day but offers higher rates of self-consumption or if the better use of the energy generated by its direct consumption does not really pay off the deficit in the overall energy generation. Therefore, these simulations will not determine the size of the PV system and are just useful to decide the type of structure with which future simulations will be carried out.

Since the current consumption of the household is quite low, a PV system with 2.2 kWp will be enough to compare both structures and make a decision.

Regarding the fixed-tilt structure, it was previously mentioned in section ***2.3.4.2. Fixed-tilt structures: azimuth and tilt angles*** that for a household located in the Northern Hemisphere, an azimuth angle of 180º (i.e., facing South) is the optimal one to maximise the generation. Additionally, it was also stated that for low latitudes, a tilt angle near the latitude angle was also near to the optimum. In this case, the location has a latitude angle of around 36º. Nonetheless, as it can be seen in *Figure 41*, the PVsyst software indicates that to optimise the annual yield in this location, a tilt angle of 35º is to be selected.

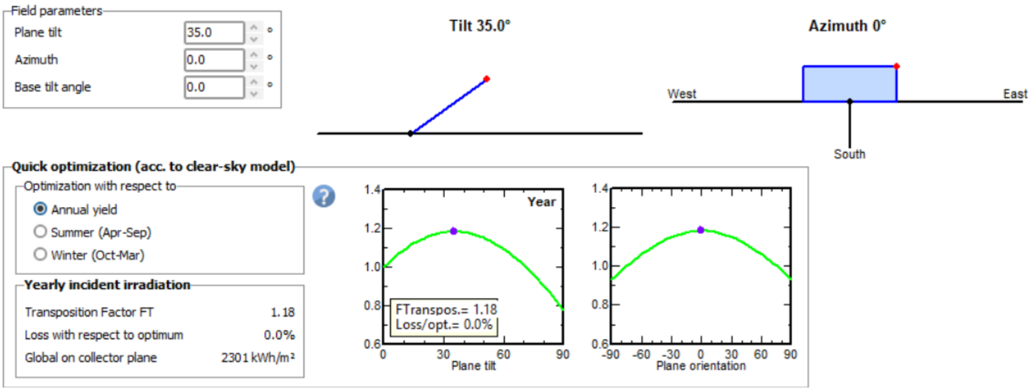


Figure 41: Optimal tilt and azimuth angles for a fixed-tilt structure according to PVsyst

Consequently, the solar panels will be placed with a layout such as the one shown in *Figure 42*, where all solar panels are facing South with a tilt angle of 35º.

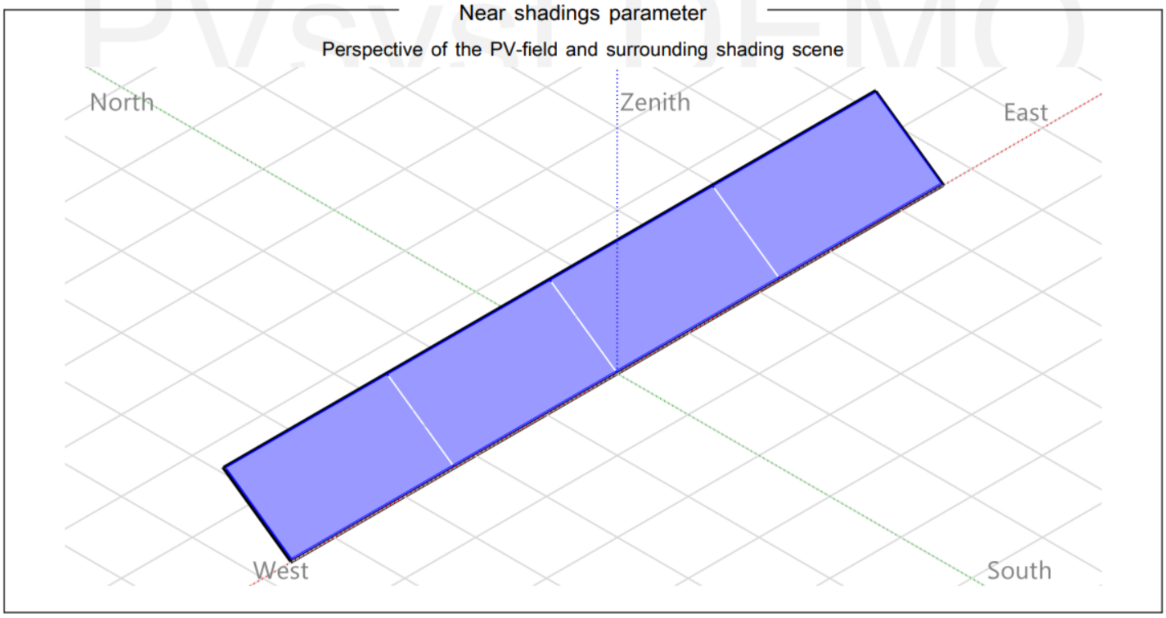


Figure 42: Fixed-tilt 35º South structure for a 2.2 kWp installation

After running the simulation, the results in *Table 17* have been obtained. The interesting aspects to be analysed are the effective energy at the output of the array (EArray) and the energy that the user consumes directly from the installation (E_Solar), which in this case are around 4200 kWh of energy generated and 1550 kWh of self-consumption. As it can be seen, despite being a low power installation, the self-consumption rate would not even reach 40% due to being the household's consumption very low. Hence, the different scenarios developed in section ***5.2. Consumption Analysis*** will be used in further analysis to achieve more realistic results.

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_User kWh	E_Solar kWh	E_Grid kWh	EFrGrid kWh
January	92.5	26.79	11.07	159.8	144.2	295.8	405.9	125.1	157.9	280.8
February	104.4	32.72	9.96	155.2	140.7	288.5	327.1	105.9	170.3	221.2
March	155.8	52.55	13.89	193.2	179.9	363.6	325.3	125.0	223.3	200.2
April	179.9	58.36	14.61	191.3	178.2	359.4	300.0	123.4	220.5	176.6
May	226.3	67.68	17.83	213.9	198.9	396.9	260.0	119.2	260.9	140.8
June	241.2	61.87	20.70	216.8	201.7	398.8	262.4	122.2	259.6	140.2
July	241.1	64.79	25.00	222.6	207.2	402.3	309.8	139.6	245.5	170.3
August	222.5	56.94	24.38	227.9	213.1	414.2	352.9	154.2	242.8	198.7
September	167.7	51.31	22.43	196.9	183.9	360.4	363.1	144.2	201.1	218.9
October	136.5	44.01	19.49	189.6	175.9	349.8	411.8	152.0	183.3	259.8
November	95.3	32.03	16.15	153.5	139.7	281.6	361.2	114.1	155.3	247.0
December	86.0	27.20	13.72	156.2	139.3	284.3	388.5	122.5	149.5	266.0
Year	1949.3	576.24	17.49	2276.9	2102.8	4195.6	4068.1	1547.5	2470.2	2520.6

Table 17: Energy management annual results with a 35º tilted structure

Keeping in mind the three quantities mentioned, a simulation of a 2.2 kWp configuration was run but with an east-west structure instead of the previous fixed-tilt one. In this configuration, illustrated in *Figure 43*, half of the panels are placed with an azimuth angle of 90º (facing East) and the other half with an azimuth angle of 270º (facing West), both with tilt angles of 10º.

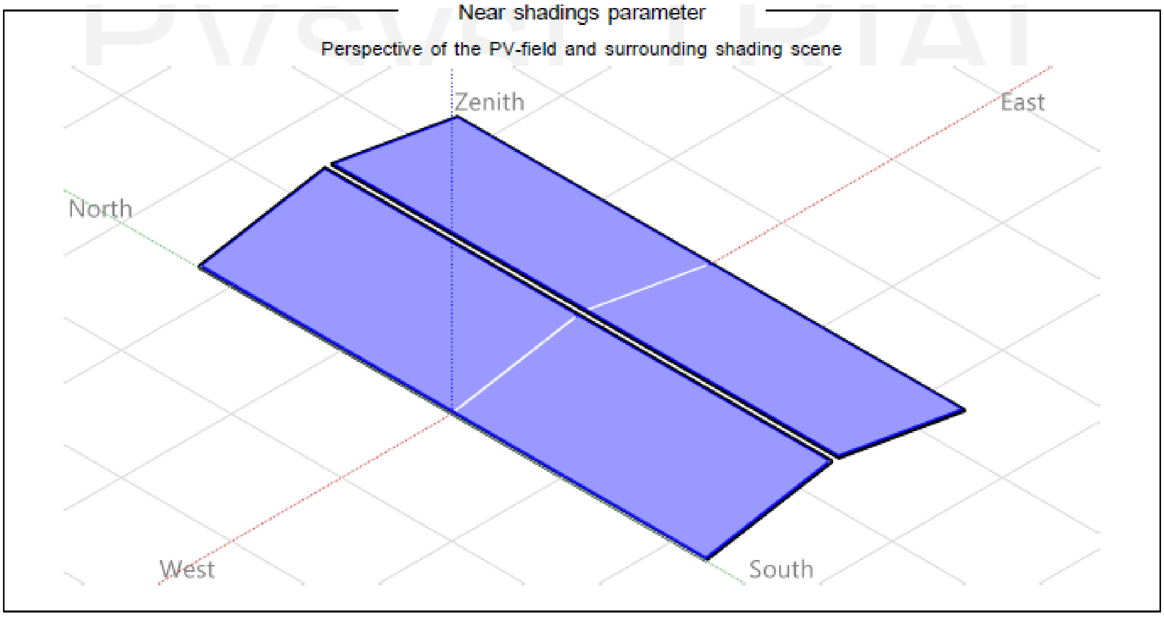


Figure 43: East-West structure for a 2.2 kWp PV installation

Again, after running the simulation, the results shown in *Table 18* are obtained.

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_User kWh	E_Solar kWh	E_Grid kWh	EFrGrid kWh
January	92.5	26.79	11.07	92.4	81.8	174.2	406.0	115.1	54.3	290.9
February	104.4	32.72	9.96	104.0	94.1	200.4	327.1	104.3	90.8	222.8
March	155.8	52.55	13.89	155.2	145.2	303.1	325.3	126.8	168.3	198.5
April	179.9	58.36	14.61	178.9	168.7	349.5	300.0	130.4	210.0	169.6
May	226.3	67.68	17.83	224.7	212.9	434.1	260.0	129.3	293.6	130.7
June	241.2	61.87	20.70	239.7	227.7	458.8	262.4	136.3	310.7	126.1
July	241.1	64.79	25.00	239.8	227.7	451.1	309.8	154.6	284.9	155.3
August	222.5	56.94	24.38	221.4	209.7	417.9	352.9	164.3	242.8	188.6
September	167.7	51.31	22.43	166.7	156.9	316.9	363.1	147.3	161.4	215.9
October	136.5	44.01	19.49	136.1	125.9	259.2	411.8	147.2	105.1	264.6
November	95.3	32.03	16.15	94.9	85.3	178.2	361.2	109.2	64.1	252.0
December	86.0	27.20	13.72	85.8	75.0	158.4	388.5	110.7	43.4	277.9
Year	1949.3	576.24	17.49	1939.7	1811.0	3701.7	4068.2	1575.4	2029.5	2492.8

Table 18: Energy management annual results with an East-West structure

Retrieving the same data as before, the effective energy at the output of the array is approximately 3700 kWh, around 12% less than the first configuration analysed. Despite the expected lower energy yield, the self-consumption is just of 1575 kWh. It has barely increased by less than 2% in comparison with the previous configuration.

It can be concluded that the very low increase in the amount of energy that is self-consumed with an East-West structure does not compensate the loss of generated energy one would obtain with a South fixed-tilt structure. Therefore, for the remaining of the project, the simulations will be run with a fixed-tilt structure with an azimuth angle of 180º (facing South) and a tilt angle of 35º.

5.5.3.3. Security and structural stability justification

Regarding the building's structural safety, where the installation is to be carried out, it should be noted that no action will be taken that affects the integrity of the load-bearing structural elements of the building, nor have any new structural elements been introduced. The additional weight on the roof in the new configuration will be covered by the overload usage hypothesis. Building regulations require a minimum overload value for roofs, which, depending on the building's year of construction, are as follows:

- Buildings constructed between 1963 and 1988: *Table 19*

Element Use	**Overload (kg/m²)**
A. Roof terraces	
Accessible only for maintenance	100
Accessible only privately	150
Accessible to the public	According to its use

Table 19: Overloads for roof terraces as specified in the M.V. Standard 101/1962

- Buildings constructed between 1988 and 2006: *Table 20*

Element Use	**Overload (kg/m²)**
A. Roof terraces	
Accessible only for maintenance	100
Accessible only privately	150
Accessible to the public	According to its use

Table 20: Overloads for roof terraces as specified in the NBE-AE-88 Standard

- Buildings constructed from 2006 onwards: *Table 21*

Use category	**Use subcategory**	**Uniform load (kN/m²)**	**Concentrated load (kN)**
F. Walkable roofs accessible only privately		1	2
G. Roofs accessible only for maintenance	**G1.1** Roofs with slope less than 20º	1	2
	G1.2 Roofs with lightweight purlins (no slab)	0.4	1
	G2. Roofs with slope greater than 40º	0	2

Table 21: Overloads for roof terraces as specified in the CTE DBSE-AE Standard

According to the age of the existing building where the current photovoltaic solar installation is to be carried out, it was designed in 2008. Therefore, the case at hand is classified as a roof accessible only for maintenance purposes with a slope lower than 20º. According to *Table 21*, a maximum overload of 1 kN/m² would be within the limits. The load of the intended installation is of 0.2 kN/m², including the fastening elements and the system's own supporting structure, as explained in the calculations included in ***Annex I***. Therefore, it is determined that the building structure is fully capable of withstanding the load in the new configuration.

As for the system's own structure, composed of metal profiles, metal clamps, and specific fastening elements (such as screws, nuts, pins, etc.), it is assumed that the one chosen will have been designed by a specialised company and efficiently supports the panels in their installed position.

5.6. SIMULATIONS

5.6.1. SCENARIO 1

Considering the estimated annual energy consumption of *Table 9* and starting with an initial peak power of 2.2 kWp and nominal power of 2 kWn, the results in *Table 22* are obtained. One can see that the system is clearly undersized since it generates only around 60% of the total energy the household consumes, out of which just 35% would be provided by the photovoltaic installation. Therefore, an increase in the installed powered must be considered to decrease the dependency on the energy bought from the grid.

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_User kWh	E_Solar kWh	E_Grid kWh	EFrGrid kWh
January	92.5	26.79	11.07	159.8	144.2	295.8	418.5	128.2	154.8	290.3
February	104.4	32.72	9.96	155.2	140.7	288.5	358.5	114.7	161.5	243.8
March	155.8	52.55	13.89	193.2	179.9	363.6	388.1	145.6	202.7	242.5
April	179.9	58.36	14.61	191.3	178.2	359.4	488.4	182.9	161.0	305.5
May	226.3	67.68	17.83	213.9	198.9	396.9	454.6	189.4	190.7	265.2
June	241.2	61.87	20.70	216.8	201.7	398.8	791.3	299.0	82.8	492.3
July	241.1	64.79	25.00	222.6	207.2	402.3	1047.0	355.9	29.3	691.1
August	222.5	56.94	24.38	227.9	213.1	414.2	1090.4	368.4	28.7	722.0
September	167.7	51.31	22.43	196.9	183.9	360.4	892.0	290.8	54.5	601.2
October	136.5	44.01	19.49	189.6	175.9	349.8	474.6	172.0	163.3	302.6
November	95.3	32.03	16.15	153.5	139.7	281.6	392.6	122.9	146.5	269.6
December	86.0	27.20	13.72	156.2	139.3	284.3	401.1	125.9	146.1	275.2
Year	1949.3	576.24	17.49	2276.9	2102.8	4195.6	7197.0	2495.8	1521.9	4701.2

Table 22: Results for 2.2 kWp (2 kWn) in Scenario 1

By doubling the power up to 4.4 kWp and 4 kWn respectively, the results in *Table 23* are obtained. In this case, the energy generated by the installation has practically doubled, as expected, but, surprisingly, the simulation indicates that most of that increase in energy will be injected into the grid instead of self-consumed by the household. As one can analyse, the self-consumption has only increase by almost 400 kWh while the energy injected into the grid as excess generation has increased by around 3000 kWh. Moreover, the results suggest that the amount of energy purchased from the grid has only decreased by almost 8% after doubling the power of the installation. Nevertheless, 36% of the energy generated by the photovoltaic installation will be directly consumed by the household, which is not a high rate but neither low.

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_User kWh	E_Solar kWh	E_Grid kWh	EFrGrid kWh
January	92.5	26.79	11.07	159.8	144.2	592.4	418.5	141.7	414.4	276.8
February	104.4	32.72	9.96	155.2	140.7	578.1	358.5	125.7	417.3	232.8
March	155.8	52.55	13.89	193.2	179.9	728.3	388.1	159.1	525.4	229.0
April	179.9	58.36	14.61	191.3	178.2	720.0	488.4	206.8	469.2	281.6
May	226.3	67.68	17.83	213.9	198.9	795.1	454.6	210.4	536.8	244.2
June	241.2	61.87	20.70	216.8	201.7	798.9	791.0	345.4	405.4	445.6
July	241.1	64.79	25.00	222.6	207.2	805.9	1047.0	434.1	323.2	612.9
August	222.5	56.94	24.38	227.9	213.1	829.6	1090.0	445.9	334.7	644.2
September	167.7	51.31	22.43	196.9	183.9	721.8	892.0	342.8	335.9	549.2
October	136.5	44.01	19.49	189.6	175.9	700.8	474.6	185.7	473.3	288.9
November	95.3	32.03	16.15	153.5	139.7	564.1	392.6	132.7	396.8	259.9
December	86.0	27.20	13.72	156.2	139.3	569.4	401.1	134.0	400.6	267.1
Year	1949.3	576.24	17.49	2276.9	2102.8	8404.3	7196.4	2864.1	5033.1	4332.2

Table 23: Results for 4.4 kWp (4 kWn) in Scenario 1

It is worth mentioning that there are other important aspects to consider in the sizing apart from the simulation results, which just give an approximate insight. The electricity consumption has been given to the software by monthly values instead of hourly ones due to the specific situation this project has regarding the consumption patterns, which increases the uncertainty of the results. Additionally, it is interesting to mention that with the adoption of an intelligent strategy prioritising load connection during sunny hours and with the possibility of experiencing electricity consumption increases in the future being quite high, a PV system with 4.4 kWp and 4 kWn seems to be an appropriate configuration for Scenario 1.

5.6.2. SCENARIO 2

Considering the estimated annual energy consumption of *Table 10* and starting with an initial peak power of 4.4 kWp and nominal power of 4 kWn, the results in *Table 24* are obtained. With the increase in electricity consumption due to the electric car while maintaining the same installed power as in Scenario 1, the self-consumption degree has increased by 10% up until 46%. In this case, being the solar energy self-consumed just around 38% of the total energy consumption, it is worth increasing the power of the installation and compare the results with the ones obtained in *Table 24*.

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_User kWh	E_Solar kWh	E_Grid kWh	EFrGrid kWh
January	92.5	26.79	11.07	159.8	144.2	592.4	610.5	197.8	358.4	412.7
February	104.4	32.72	9.96	155.2	140.7	578.1	550.5	182.3	360.7	368.2
March	155.8	52.55	13.89	193.2	179.9	728.3	580.1	226.2	458.4	353.9
April	179.9	58.36	14.61	191.3	178.2	720.0	680.4	273.6	402.4	406.8
May	226.3	67.68	17.83	213.9	198.9	795.1	646.4	287.0	460.3	359.4
June	241.2	61.87	20.70	216.8	201.7	798.9	983.3	414.0	336.8	569.3
July	241.1	64.79	25.00	222.6	207.2	805.9	1239.0	495.2	262.0	743.8
August	222.5	56.94	24.38	227.9	213.1	829.6	1282.0	507.5	273.0	774.5
September	167.7	51.31	22.43	196.9	183.9	721.8	1084.0	404.2	274.5	679.8
October	136.5	44.01	19.49	189.6	175.9	700.8	666.6	251.5	407.5	415.1
November	95.3	32.03	16.15	153.5	139.7	564.1	584.6	189.1	340.4	395.5
December	86.0	27.20	13.72	156.2	139.3	569.4	593.1	192.8	341.8	400.3
Year	1949.3	576.24	17.49	2276.9	2102.8	8404.3	9500.4	3621.0	4276.2	5879.4

Table 24: Results for 4.4 kWp (4 kWn) in Scenario 2

Now, a configuration with 5.5 kWp and 5 kWn is considered and *Table 25* gathers the results after running the simulation in the PVsyst software. The self-consumption degree has expectedly dropped by 8% to 38%, which is more than acceptable. The solar energy covers almost 40% of the household's demand and the rest of the energy will have to be purchased from the grid, which could be partly compensated with the injection of excess energy to the grid. All in all, this configuration is a good trade-off between solar energy coverage and self-consumption degree.

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_User kWh	E_Solar kWh	E_Grid kWh	EFrGrid kWh
January	92.5	26.79	11.07	159.8	143.3	736	611	204	492	407
February	104.4	32.72	9.96	155.2	140.3	721	550	188	493	362
March	155.8	52.55	13.89	193.2	179.7	909	580	233	627	347
April	179.9	58.36	14.61	191.3	178.1	899	680	285	566	396
May	226.3	67.68	17.83	213.9	198.7	993	646	297	643	349
June	241.2	61.87	20.70	216.8	201.6	998	983	431	513	552
July	241.1	64.79	25.00	222.6	207.1	1007	1239	520	432	719
August	222.5	56.94	24.38	227.9	213.0	1036	1282	531	450	751
September	167.7	51.31	22.43	196.9	183.7	901	1084	419	434	665
October	136.5	44.01	19.49	189.6	175.4	873	667	258	569	409
November	95.3	32.03	16.15	153.5	139.1	702	585	194	469	390
December	86.0	27.20	13.72	156.2	138.5	707	593	196	472	397
Year	1949.3	576.24	17.49	2276.9	2098.6	10484	9500	3757	6161	5743

Table 25: Results for 5.5 kWp (5 kWn) in Scenario 2

There is no point on trying to increase the power of the installation even further as the solar energy coverage will definitely not increase much more since there has only been an increase by 2% between the results presented in *Table 24* and the ones in *Table 25*. This means that the load is already near the point of consuming as much solar energy as possible and that most of the further increase in energy generation will be fed into the grid, which is not the objective of such an installation for self-consumption of electricity. Moreover, it will increase the investment costs unnecessarily without bringing much benefit to the owner. Therefore, an installation with 5.5 kWp and 5 kWn would be a good fit in Scenario 2.

5.6.3. SCENARIO 3

Considering the estimated annual energy consumption of *Table 11* and starting with an initial peak power of 5.5 kWp and nominal power of 5 kWn, the results in *Table 26* are obtained. With the increase in electricity consumption due to the electric van while maintaining the same installed power as in Scenario 2, the self-consumption degree has increased by 5% up until 43%. In this case, being the solar energy coverage around 39% of the total energy consumption, it is worth increasing the power of the installation and compare the results with the ones obtained in *Table 26*.

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_User kWh	E_Solar kWh	E_Grid kWh	EFrGrid kWh
January	92.5	26.79	11.07	159.8	143.3	736	699	229	467	470
February	104.4	32.72	9.96	155.2	140.3	721	638	214	468	425
March	155.8	52.55	13.89	193.2	179.7	909	668	264	596	404
April	179.9	58.36	14.61	191.3	178.1	899	768	315	535	453
May	226.3	67.68	17.83	213.9	198.7	993	823	365	574	457
June	241.2	61.87	20.70	216.8	201.6	998	1159	494	450	665
July	241.1	64.79	25.00	222.6	207.1	1007	1415	579	374	836
August	222.5	56.94	24.38	227.9	213.0	1036	1458	590	392	868
September	167.7	51.31	22.43	196.9	183.7	901	1260	477	376	783
October	136.5	44.01	19.49	189.6	175.4	873	755	288	539	467
November	95.3	32.03	16.15	153.5	139.1	702	673	220	444	453
December	86.0	27.20	13.72	156.2	138.5	707	681	223	446	458
Year	1949.3	576.24	17.49	2276.9	2098.6	10484	10996	4258	5661	6738

Table 26: Results for 5.5 kWp (5 kWn) in Scenario 3

The power of the installation has been increased to 6.6 kWp and 6 kWn, obtaining the results presented in *Table 27*. The self-consumption ratio has decreased from 43% to 37% as a consequence of increasing the solar energy coverage up until almost 40%. In this case, the very small increase in solar energy coverage does not justify an increase of the installed power. The household is consuming as much as it can from the photovoltaic installation and the whole increased generated energy is practically being injected into the grid. Therefore, for Scenario 3 the optimal configuration would be the same one as for Scenario 2, i.e., 5 kWp and 5 kWn of installed photovoltaic and inverter power, respectively.

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_User kWh	E_Solar kWh	E_Grid kWh	EFrGrid kWh
January	92.5	26.79	11.07	159.8	136.8	845	699	234	569	465
February	104.4	32.72	9.96	155.2	136.2	841	638	219	580	419
March	155.8	52.55	13.89	193.2	178.0	1081	668	270	758	398
April	179.9	58.36	14.61	191.3	177.3	1075	768	324	697	444
May	226.3	67.68	17.83	213.9	197.9	1187	823	376	753	447
June	241.2	61.87	20.70	216.8	200.9	1193	1159	510	625	649
July	241.1	64.79	25.00	222.6	206.3	1204	1415	599	546	816
August	222.5	56.94	24.38	227.9	212.3	1240	1458	609	571	849
September	167.7	51.31	22.43	196.9	182.7	1076	1260	490	534	770
October	136.5	44.01	19.49	189.6	171.9	1028	755	293	685	461
November	95.3	32.03	16.15	153.5	133.5	810	673	224	546	449
December	86.0	27.20	13.72	156.2	131.3	807	681	226	541	455
Year	1949.3	576.24	17.49	2276.9	2065.2	12388	10996	4375	7405	6621

Table 27: Results for 6.6 kWp (6 kWn) in Scenario 3

5.6.4. CONCLUSION

Since an installation of 5.5 kWp and 5 kWn is the best fit for Scenarios 2 and 3 and given the fact that the Scenario 2 is quite a probable one, this is the configuration that will be developed in the project. It is true that Scenario 1 is the most certain one and the one which will happen first. Nevertheless, the possibility of changing the old diesel car with an electric car is also there and it will happen sooner or later. It is more economically efficient to cover this scenario right from the beginning rather than carrying out an installation of 4.4 kWp (4 kWn), the one most suitable for Scenario 1, and waiting until Scenario 2 takes place to carry out an expansion of the solar PV system.

The full PVsyst simulation report can be found in ***Annex III***, corresponding to a photovoltaic system of 5.5 kWp and 5 kWn considering the estimated annual electricity consumption of Scenario 2. It offers a comprehensive and detailed analysis of the expected performance of the photovoltaic system. Among its most valuable outputs is the estimation of the annual energy yield, which is the table that has been continuously used earlier to compare and select between structures or amount of power installed. This estimation is provided on both annual and monthly scales, offering a clear picture of how much energy the system is expected to produce throughout the year. Such data is essential not only for assessing technical feasibility but also for evaluating the economic viability of the project.

Another important metric presented in the report is the performance ratio (PR), which in this case it has been calculated at 0.792. This parameter reflects the overall efficiency of the system by considering various losses that occur between the solar radiation input and the usable AC output. These losses may include temperature-related effects, shading, soiling, inverter inefficiencies, and potential system downtime. A high PR value indicates a well-designed and efficient system. As such, the PR serves as a benchmark for comparing different PV system configurations or evaluating system performance over time.

The report also includes a detailed loss diagram, which visually and numerically represents each source of energy loss within the system. This breakdown allows to identify the most significant inefficiencies and target them for improvement. Losses due to module mismatch, wiring, shading, thermal effects, and other factors are all accounted for in this section. By analysing the loss diagram, one can prioritise interventions that may yield the greatest performance improvements.

Furthermore, the PVsyst report documents the detailed configuration of the system, including the type and arrangement of PV modules, inverters, and the overall system layout. It highlights design choices such as the number of modules in series and parallel, the sizing ratio between the array and the inverter, and the expected operating voltage ranges. This information is essential for ensuring that the simulation is transparent and reproducible, and it also supports technical validation of the system's design.

5.7. ELECTRICAL CALCULATIONS

In the following sections, the electrical calculations will be explained. The formulas used and their corresponding explanations as well as significant results obtained will be given. Nevertheless, the tables containing the full calculations are included in ***Annex II***.

5.7.1. COMPATIBILITY BETWEEN MODULES AND INVERTER

The compatibility of the photovoltaic array with the inverters to be used must be verified through voltages and currents, meeting the following conditions.

The compatibility of the inverter with the photovoltaic array in terms of voltage is verified using the following expression:

$$V_{\max inverter} > n_{mod\ series} \cdot V_{OC \max STC} \tag{5.2}$$

At the same time, the following condition must be met simultaneously:

$$V_{\min inverter} \leq n_{mod\ series} \cdot V_{mp \min STC} \tag{5.3}$$

Where:

- $V_{\max inverter}$ and $V_{\min inverter}$: data obtained from the inverter datasheet in volts
- $n_{mod\ series}$: number of modules in series
- $V_{OC \max STC}$: maximum open-circuit voltage in STC conditions in volts
- $V_{mp \min STC}$: minimum operating voltage at maximum power in STC conditions in volts

The last two parameters will need to be evaluated using the following equation:

$$V_T = V_{STC} + \alpha \cdot V_{STC} \cdot (T - 25) \tag{5.4}$$

Where:

- V_{STC}: voltage under standard conditions (STC) in volts
- α: voltage variation coefficient depending on the temperature in %/ºC, obtained from the solar panel datasheet
- T: temperature in Celsius degrees

The compatibility of the inverter with the photovoltaic array in terms of current is verified using the following expression:

$$I_{\max sc\, MPPT} > n_{strings\, MPPT} \cdot I_{\max sc\, module} \tag{5.5}$$

Where:

- $I_{\max sc\, MPPT}$: maximum permissible short-circuit current per MPPT in amperes
- $n_{strings\, MPPT}$: number of strings connected per MPPT
- $I_{\max sc\, module}$: maximum short-circuit current of the module in standard conditions in amperes

As with the voltage, this last parameter will need to be evaluated using the following equation:

$$I_{sc\, T} = I_{sc\, STC} + \alpha \cdot I_{sc\, STC} \cdot (T - 25) \tag{5.6}$$

Where:

- $I_{sc\, STC}$: short-circuit current under STC conditions in amperes
- α: voltage variation coefficient depending on the temperature in %/ºC, obtained from the solar panel datasheet
- T: temperature in Celsius degrees

Finally, considering the characteristics indicated by the manufacturers of the photovoltaic module and the inverters in their respective technical specifications, the maximum voltage is evaluated at -10°C and the maximum intensity at 60°C.

The results obtained are presented in *Table 28*. As can be analysed, in a string of 10 modules connected in series, every calculated parameter is within the limits of the inverter. Considering the minimum voltage at maximum power at 60ºC and multiplying it by the number of modules in series, a minimum voltage of 380.06 V is obtained, higher than the minimum operating voltage of the inverter. Similarly, considering the maximum voltage at an open circuit with -10ºC and summing across the modules in series, a voltage of 544.2 V is obtained, far from the maximum voltage allowed by the inverter. In addition, the maximum currents at 60ºC in maximum power and short-circuit situations are both lower than the limits stated in the inverter datasheet for such parameters.

V_{MP} (-10ºC)	V_{MP} (60 ºC)	V_{OC} (-10ºC)	I_{SC} (60ºC)	I_{MP} (60ºC)
45.84 V	38.06 V	54.42 V	14.22 A	13.35 A

Table 28: Results on operating voltages and currents at different temperatures

5.7.2. NOMINAL VOLTAGE AND MAXIMUM PERMISSIBLE VOLTAGE DROP

The nominal operating voltage shall be 400 V between phases and 230 V between phase and neutral. Voltage drops shall be less than 1.5% in the DC section and 1.5% in the AC section. The cross-sectional areas of the cables needed to maintain voltage drops within limits shall be calculated in accordance with the formulas included in section ***5.7.3***.

5.7.3. CONDUCTORS CROSS SECTION

The calculations are divided into the DC section and the AC section. For the DC section, the circuit current is considered to be the short-circuit current of each photovoltaic module subarray, and the maximum operating voltage is the voltage at maximum power for each module group. In the AC section, calculations are based on the maximum current that the inverter can deliver to each line.

The conductor cross-sections have been calculated in accordance with the Low Voltage Electrotechnical Regulation based on the following criteria for both the DC and AC sections:

- Compatibility between photovoltaic modules and inverters
- Maximum permissible current
- Minimum voltage drop
- Selection of overcurrent protection devices

The cabling design complies with the provisions set out in ITC-BT-40 and follows the specifications of Table 52-B2 from the UNE 20460-5-523 standard.

5.7.3.1. Maximum admissible current in AC and DC

The following condition must be respected for both DC and AC conductors:

$$I_b \leq F \cdot I_Z \tag{5.7}$$

Where:

- I_b: current drawn by the circuit in amperes, increased by 125% of the nominal current as specified in ITC-BT-40, section 5. This value depends on the nature of the circuit and is defined as follows:
    - Direct current: in this case, the short-circuit current (I_{SC} STC) specified in the module's technical datasheet, multiplied by 1.25 as indicated
    - Alternating current: in this case, the maximum output current (I_{MAX}) of the inverter as specified in its technical datasheet, multiplied by 1.25 as indicated

- F: correction factor for conductor grouping, as specified in Table B.52.17 of the standard UNE-HD 60364-5-52:2022
- I_Z: maximum permissible current of the cable, as defined in Table B.52.5 of the standard UNE-HD 60364-5-52:2022

As it can be seen in the electrical calculations included in ***Annex II***, the selected cross-sectional areas for the cables in both AC and DC sections are capable of conducting more than double the maximum expected currents.

5.7.3.2. Maximum voltage drop in DC

For the direct current installation, as specified in ITC-BT-40, section 5, the maximum voltage drop for an energy-generating element is limited to 1.5% of its nominal voltage, from the point of generation to its connection to the grid. In this case, for the DC installation, the boundary point will be designated as the connection to the DC inputs of the inverter in question.

The voltage drop calculation in volts is determined by the following expression:

$$\Delta v = \frac{2 \cdot I \cdot L}{\gamma \cdot S} \tag{5.8}$$

Where:

- I: maximum current in amperes, in this case the current at maximum power
- L: circuit length in metres
- γ: conductor conductivity, which at 90ºC is 44 m/Ωmm^2 for copper and 28 m/Ωmm^2 for aluminium
- S: conductor cross-sectional area in mm^2

Having determined that the DC circuit length will approximately be of 40 metres, the calculations show that a cross-sectional area of 4 mm^2 would lead to a voltage drop higher than 1.655%, which exceeds the limit of 1.5%. Hence, a cross-sectional area of 6 mm^2 has been selected, which results in a voltage drop of 1.103%.

5.7.3.3. Maximum voltage drop in AC

Likewise, the maximum voltage drop will be limited to 1.5% of the nominal voltage, from the output of the inverter to the connection with the grid.

The voltage drop calculation in volts for a three-phase system is determined by the following equation:

$$\Delta v = \frac{\sqrt{3} \cdot I \cdot L \cdot \cos\varphi}{\gamma \cdot S} \tag{5.9}$$

Where:

- I: nominal current at the output of the inverter in amperes
- L: circuit length in metres
- $\cos\varphi$: power factor
- γ: conductor conductivity, which at 90ºC is 44 m/Ωmm^2 for copper and 28 m/Ωmm^2 for aluminium
- S: conductor cross-sectional area in mm^2

Approximately, the inverter and the PV protection board will be no more than 5 metres apart, and the same maximum distance between the latter and the existing AC protection board is also assumed. For such a short length, the voltage drop will not be a problem in the AC circuit of the installation. In this case, a 2.5 mm^2 conductor would be compliant with both maximum current and voltage drop limits. However, in practice that section is considered to be quite small for an electricity generation system and it is preferred to rather install conductors with 4 mm^2 cross-sectional areas to increase the mechanical robustness of the system and to reduce their thermal heating. The resulting total voltage drop with such cables is of 0.178%.

5.7.3.4. DC Cabling

All cables used in the system are made of copper. A cross-sectional area of 6 mm^2 has been selected to ensure that the voltage drop between the photovoltaic modules, and the inverter remains below 1.5%, thereby limiting power losses due to cabling to less than 1.5%. The interconnection between modules is made using the cables integrated into the modules themselves, while the wiring between the terminal modules and the inverter is carried out using H1Z2Z2-K copper cables.

The cables comply with current regulations regarding insulation and protection levels. Specifically, they feature insulation rated above 1500 V and are classified as double-insulated (Class II).

Cables used for interconnecting photovoltaic modules are protected against weather-induced degradation, including solar radiation, UV exposure, and high-temperature environmental conditions.

All cabling is properly labelled in accordance with the electrical schematics.

Electrical connections between circuit lines are made using MC-4 connectors, which feature a minimum protection rating of IP65 and are housed in impact-resistant polyamide enclosures.

The single-line DC diagram, included in ***Annex IV***, illustrates the cross-sectional areas and protection elements of all DC lines.

5.7.3.5. AC Cabling

The cable running from the inverter output to the low-voltage (LV) distribution board is of type RZ1-K, consisting of copper conductors with polyolefin insulation.

Similarly, the AC cabling used to connect the inverters to the main distribution board of the photovoltaic installation is also RZ1-K.

All cables are made of copper. Their cross-sectional area, which is of 4 mm^2, has been dimensioned to ensure that the voltage drop between the inverter and the grid connection point remains below 1.5%.

The single-line AC diagram, included in ***Annex IV***, illustrates the cross-sectional areas and protection elements of all AC lines.

5.8. PROTECTIONS

The protective elements of the installation are sized in accordance with the Spanish Low Voltage Electrotechnical Regulation. A main protection board will be installed at the output of the photovoltaic system, and the installation will include protection measures against short circuits, DC faults, overvoltages, undervoltages, overfrequencies, underfrequencies, as well as protection against direct and indirect contact. Grounding will be implemented in compliance with the applicable regulations: Royal Decree 842/2002 of August 2 and Royal Decree 337/2014 of May 9, which govern the low and high voltage electrotechnical regulations, respectively.

All calculated protection devices are shown in the single-line DC and AC diagrams included in ***Annex IV***.

5.8.1. MAIN PROTECTION BOARD AT THE OUTPUT OF THE GENERATION SYSTEM

A main protection board will be installed for the 5 kWn system. The main board will be installed according to the instructions provided in the technical drawings from ***Annex IV***.

5.8.2. PROTECTIONS AGAINST SHORT-CIRCUITS AND DC FAULTS

The inverter is equipped with an insulation monitoring device for the connected photovoltaic system. In the event of an insulation failure, the inverter will disconnect the generator connection.

5.8.3. PROTECTIONS AGAINST OVERVOLTAGES AND UNDERVOLTAGES

The inverter is equipped with over- and undervoltage protection for the grid, as required by regulations. In the event of a fault of such characteristics, the inverter will disconnect the photovoltaic generator from the grid until the conditions return to normal.

The inverter must comply with the UNE-EN 61000-4-5:2015 standard for over- and undervoltage protection.

The inverter's voltage protection system will disconnect the installation from the grid as specified in ITC-BT-40, section 7, as follows:

- The undervoltage relay will disconnect the system in less than 0.5 seconds once the voltage reaches 85% of its nominal value.
- The overvoltage relay will disconnect the system in less than 0.5 seconds once the voltage reaches 110% of its nominal value.

Since no lightning rods, Faraday cages, or other direct lightning strike protection devices will be installed, the surge protection will be of type 2.

Additionally, the inverter will disconnect the generator installation from the grid in the event of a power failure.

5.8.4. PROTECTIONS AGAINST OVERFREQUENCIES AND UNDERFREQUENCIES

The inverter will be equipped with protection against underfrequencies and overfrequencies, as required by regulations. In the event of a frequency deviation, the inverter will disconnect the photovoltaic generator from the grid until the conditions return to normal.

The inverter's frequency protection system will disconnect the installation from the grid as specified in ITC-BT-40, section 7, as follows:

- The frequency relay will activate when the frequency is below 49 Hz or above 51 Hz for more than 5 cycles.

5.8.5. PROTECTIONS AGAINST DIRECT AND INDIRECT CONTACTS

The following measures have been considered to protect against direct contact throughout the installation, both for direct current and alternating current:

- Protection by insulation of active parts
- Protection by barriers and enclosures
- Protection by means of obstacles
- Protection by distancing

As complementary measures, 30 mA sensitivity differential switches will be used in the AC circuits. In the DC circuits, the primary protection is the insulation of active parts, along with continuous monitoring. In the event of insulation failure, the affected circuit will be disconnected, and the responsible personnel will be notified.

5.8.6. SELECTION OF OVERCURRENT PROTECTION ELEMENTS IN DC

According to the standard UNE-HD 60364-7-712, Low Voltage Electrical Installations – Part 7-712: Requirements for Special Installations or Locations – Solar Photovoltaic Power Supply Systems, section 712.432.102, for the protection of photovoltaic strings using gPV fuses, the following condition must be met:

$$1.1 \cdot I_{SC\,\max string} \leq I_n \leq I_{mod\,\max OCPR} \quad (5.10)$$

Where:

- $I_{SC\,\max string}$: maximum calculated current for the string in amperes, with a value of 1.25·$I_{SC\ STC}$, known from the solar panel datasheet
- I_n: nominal current of the protective device in amperes (gPV fuse)
- $I_{mod\,\max OCPR}$: maximum operating current of the photovoltaic module in amperes, known value from the solar panel datasheet as the Max Fuse Rating

Additionally, the following condition regarding the operating voltages of the elements must also be met:

$$U_{OC\,max} \leq U_e \quad (5.11)$$

Where:

- $U_{OC\,max}$: maximum operating voltage of the photovoltaic string in volts
- U_e: nominal voltage in volts of the protective element

Being 19.5 A the maximum calculated current for the string and 46 A the conductor’s maximum admissible current, a fuse rating of 25 A has been selected with the objective to protect the installation in case of overcurrent, making sure at the same time that the protection does not trigger during normal and safe operation.

5.8.7. SELECTION OF OVERCURRENT PROTECTION ELEMENTS IN AC

The overload protection of a line by a protective device is achieved when the following expression is satisfied:

$$I_b \leq I_n \leq I_z \quad (5.12)$$

Where:

- I_b: current drawn by the circuit in amperes, in this case, the nominal output current of the inverter, found in its datasheet
- I_n: nominal current of the protective device in amperes
- I_z: maximum permissible current of the conductor, obtained using Table B.52.5 of the standard UNE-HD 60364-5-52:2022

Regarding the AC section, the maximum current at the output of the inverter is of 8.5 A. On the other hand, the conductor chosen admits a maximum current of 32 A. Hence, a rating of 16 A has been selected to protect the AC circuit from overcurrent while making sure the protection does not trigger during normal operation.

5.9. GROUNDING

The grounding system will be constructed according to VDE and DIN standards, using components that comply with DIN 48801 to 48852 standards. It will be completed and ready for service.

In addition to these protective measures, all necessary steps will be taken to ensure that the installation is inherently safe against harm to both people and equipment. The photovoltaic inverters will include protections for grid connection, and the manufacturers of these devices will comply with the applicable European regulations.

The metal parts of the structures, the inverter enclosures, and all metallic elements that could come into contact with active parts of the installation will be connected to the grounding system.

A bare copper cable with a cross-sectional area of 6 mm^2 in the DC section and of 4 mm^2 in the AC section, in accordance with the Low Voltage Electrotechnical Regulations ITC-BT-18, will run through the installation and connect to the grounding system. At various points, using insulated cable of the same specifications, the supporting structures of the modules and all metal elements that could potentially come into contact with active parts of the installation will be connected.

5.10. METERING SYSTEM

Subjects under any form of self-consumption will have the necessary metering equipment for the correct billing of prices, tariffs, charges, access fees, and other system costs and services that apply to them. The meter reader will apply, where applicable, the corresponding loss coefficients established by the regulations.

In general, consumers under any form of self-consumption must have a bidirectional metering device at the point of connection or, if necessary, a metering device at each of the connection points.

Additionally, generation installations must have metering equipment to record net generation in the following cases:

- Collective Self-Consumption
- Installations connected to the grid
- Non-renewable technology, cogeneration, or waste

- If there is more than one supply contract for auxiliary services in C2.Ex/NC Installations
- If the nominal apparent power is equal to or greater than 12 MVA

The auxiliary production services, as defined in Article 3 of the Unified Regulation of Measurement Points of the Electrical System, approved by Royal Decree 1110/2007 of August 24, which approves the Unified Regulation of Measurement Points of the Electrical System, will be considered negligible. Therefore, no separate supply contract for the consumption of auxiliary production services will be required, provided the following conditions are met:

- When they are installations close to the internal network
- When they are renewable energy generation installations intended to supply one or more consumers under any form of self-consumption and their installed capacity is less than 100 kW
- On an annual basis, the energy consumed by such auxiliary production services is less than 1% of the net energy generated by the installation

For measuring auxiliary services, a standardised meter provided by the utility company will be used, complying with current regulations.

5.11. MONITORING SYSTEM

The control and monitoring system of the installation must display and store a set of data related to the installation's status at any given time. It is divided into three main subsystems:

- Acquisition system: it consists of the components that receive the values of each variable to be measured and convert them into voltage signals (in the mV range) or current signals (in the mA range)
- Transmission subsystem: it consists of the connection elements between the acquisition subsystem and the device where the acquired data will be processed. This connection can be either local (via RS-485 or power line communication) or remote (via modem)
- Information processing subsystem: it consists of the PC that receives the data from the acquisition subsystem, either locally or remotely.

5.12. PV INSTALLATION DESCRIPTION

The solar photovoltaic installation is composed of solar panels LONGi Solar LR5-72HPH-550M, which produce DC electricity, and the latter is transformed in AC by 1 inverter Huawei SUN2000-5KTL-M1, with a total nominal power of 5 kWn. The system has a peak power of 5.5 kWp and *Table 29* shows the principal characteristics of the installation.

INSTALLATION CHARACTERISTICS	
PEAK POWER	5.5 kWp
NUMBER OF SOLAR PANELS	10
SOLAR PANELS	LONGi LR5-72HPH-550M
NOMINAL POWER	5 kWn
NUMBER OF INVERTERS	1
INVERTER	Huawei SUN2000-5KTL-M1

Table 29; Solar photovoltaic installation characteristics

5.13. ENVIRONMENTAL IMPACT ASSESSMENT

5.13.1. INTRODUCTION

Photovoltaic modules are a means of energy production, as they generate significantly more energy than they consume, using an inexhaustible and non-polluting source: the Sun. The main energy consumption occurs during the manufacturing of the modules and the mounting structure. However, their overall energy balance is positive, with an energy payback period currently ranging between 1 and 4 years according to the National Renewable Energy Laboratory (NREL), a figure that is expected to decrease significantly in the future.

For grid-connected systems, the key component is the inverter, which must be adequate to ensure it does not cause issues in the grid. Therefore, it must meet a series of technical requirements to avoid malfunctions and to ensure its operation does not compromise the safety or stability of the electrical grid beyond acceptable limits.

5.13.2. ENVIRONMENTAL ASPECTS

Solar photovoltaic energy, as a renewable source, represents a significantly more environmentally friendly energy solution compared to conventional energy sources, as it relies on inexhaustible, human-scale resources to meet energy needs. A specific advantage of solar photovoltaic energy is that its application typically takes place at a local level, eliminating the need for extensive energy transportation infrastructure from production points to consumption areas.

The main environmental impacts occur during the extraction of raw materials, although most photovoltaic cells manufactured today are made from silicon, a material derived from sand which is abundant and requires minimal quantities, as well as in the industrial process of manufacturing the cells, modules, and mounting structures.

During the usage phase, the environmental impact is negligible, with no toxic emissions, as it only involves light manual cleaning and supervision tasks. The module disposal phase is the least studied, as these systems are relatively recent and no clear removal pathways have been established. Generally, when a module is damaged, it is returned to the manufacturer for repair, reuse, or disposal. Glass and aluminium could be reused or at least incorporated into recycling channels, as well as cadmium, although there are no systematic processes for this yet.

In the physical environment, there are no effects on air quality or soil, as there is no noise or impact on the existing hydrology. However, special attention must be given to the potential impacts resulting from improper management of photovoltaic modules once they reach the end of their useful life, by implementing recycling and reuse strategies for the materials that make up the photovoltaic module.

The main impact on the physical environment is the visual effect on the landscape, which can generally be minimised or masked in most installations. Therefore, efforts should be made to ensure integration that respects the environment and buildings. Regarding the biological environment, there are no significant effects on flora and fauna.

5.13.3. ASSESSMENT OF CO_2 EMISSIONS AVOIDED BY THE PV INSTALLATION

The growing concern about the environmental, social, and economic consequences of climate change, reflected in the commitments made in the Kyoto agreements, along with the fact that energy production and consumption are the primary contributors to greenhouse gas emissions, place the energy sector as key to achieving the objectives. Energy efficiency and the development of renewable energies are the main tools to achieve these goals.

Of the six greenhouse gases or groups of gases considered in the Kyoto Protocol, CO_2 alone represents three-quarters of the total, with more than 90% of it being energy-related. This highlights the great importance of policies aimed at limiting CO_2 emissions for any strategy to limit greenhouse gases and the key role played by the development of renewable energies, as is also the case with other important environmental protection goals. In the case of CO_2, swift action becomes even more crucial due to the long time it takes for measures to effectively impact emissions.

For many environmental problems, there are relatively quick end-of-process treatments, or they can be addressed through modifications in current technology, such as the reduction of SO_2 emissions or the removal of lead from gasoline. However, this is not the case with CO_2 emissions, which, being inherent in the use of fossil fuels, currently have no viable technology capable of absorbing them.

Therefore, the only current way to limit CO_2 emissions is through modifications to structures, processes, equipment, and behaviours related to energy use. The long lifespan of investments in the energy sector means that CO_2-related strategies have much longer implementation timelines compared to those applied to other environmental problems. This is where long-term planning for the development of renewable energies, and consequently photovoltaic installations, plays a decisive role.

According to the PVsyst simulations carried out in section ***5.6.2.***, the annual electricity generated by the 5 kWn installation is of 10484 kWh. The average emissions intensity of fossil-based electricity is estimated at 450 grams of CO_2 per kWh [49]. Using these figures, and assuming a project lifespan of 25 years with constant energy generation, the avoided CO_2 emissions can be calculated as follows:

$$Total\ electricity\ generated = 10484\ kWh/year \times 25\ years = 262{,}100\ kWh$$

Multiplying by the emissions intensity:

$$262{,}100\ kWh \times 450\ g\ CO_2/kWh \equiv 117{,}945\ kg\ CO_2$$

Thus, approximately 18 tonnes of CO_2 emissions will be avoided thanks to this project due to electricity generation from solar photovoltaic energy.

Chapter 6. ECONOMIC ANALYSIS

6.1. TERMS IN ELECTRICITY BILL

6.1.1. POWER TERM

Consumers pay a fixed price for having access to electricity depending on the contracted power. For residential households in Spain with low voltage supply and a contracted power equal or less than 15 kW, being the case of the one where this project is carried out, the 2.0TD access tariff applies, which includes 2 power terms: one for peak periods and another one for mid-peak and off-peak periods. These periods have been established depending on the expected national demand at a determined hour of the week, with no seasonal variation for the 2.0TD tariff, as it can be seen in *Table 30*.

Period	Time (Weekdays)	Weekends and holidays	Description
Off-peak	00:00 – 08:00	All day	Lowest prices, encourages night-time use
Mid-peak	08:00 – 10:00 14:00 – 18:00 22:00 – 00:00	-	Intermediate prices, moderate demand
Peak	10:00 – 14:00 18:00 – 22:00	-	Highest prices, periods of highest demand

Table 30: Time-of-use periods in the 2.0TD Tariff (Spain)

The two power terms, which have the unit of €/kW·day, represent a fixed cost on the monthly electricity bill, being usually the peak period power more expensive. Although not dependent on the consumption pattern of the household nor the generation pattern of the PV installation, the power term will be considered in section ***6.2. Future Electricity Tariff*** for a proper comparison between available tariffs in the market, as it could be a decisive factor in case of similar results regarding the energy term of those tariffs.

6.1.2. ENERGY TERM

The energy term is the most relevant aspect to take into account when analysing the economic viability of the project. It is a variable term that is based on the amount of electricity the consumer has required from the grid and the amount that has been fed into the grid as surplus energy generated by the PV installation.

Regarding the consumption of energy from the grid and depending on the tariff chosen, there could be three different electricity prices for each of the periods shown in *Table 30* as well as just a fixed price per kWh independently from at which time it has been consumed. There are plenty of different offers from electricity suppliers, each one with its own advantages and disadvantages. The price the consumers pay per kWh is the sum of the energy cost and the transport and distribution tolls for financing the grid's operation and maintenance. As an alternative for the free market, the PVPC (Precio Voluntario al Pequeño Consumidor) regulated tariff is offered in Spain. However, it is not attractive at all for this specific case due to its very low surplus energy prices for PV system owners as well as its high price variation throughout the day.

As for surplus energy prices, they are mostly offered in the free market as a fixed price per kWh fed into the grid. Usually ranged between 0.04-0.08 €/kWh, the surplus energy is normally always bought at a lower price by the electricity supplier than the price the client pays when consuming energy from the grid. It is also worth noting that this surplus energy compensation mechanism, established by the Royal Decree 244/2019, has been designed with the intention of compensating the surplus fed into the grid just with a reduction in the electricity bill and discarding completely the possibility of the owners gaining a profit. Hence, the fixed terms of the contract such as the whole contracted power term, the grid access tolls in the energy term and other costs such as the metering system renting are always to be paid.

The amount of money to be reduced in the energy term by means of surplus energy injected into the grid cannot exceed the amount of money paid by the consumer for the cost of energy imported from the grid. Therefore, at maximum just the energy cost is compensated, but the client would still have to pay both the fixed cost of the power term and the variable cost of the grid access tolls depending on the amount of electricity consumed in the energy term.

Nevertheless, there are alternatives offered by the electricity suppliers with which the limitation mentioned above could be avoided, as is the case of the so-called virtual batteries. They allow to store the cash generated by the injection of surplus energy and use it to reduce the electricity bill whenever one wants, not necessarily in the same month when the generation of surplus energy took place. With such alternative, there exists the possibility of bringing the electricity bill down to 0, when enough cash in the virtual battery is available.

6.2. FUTURE ELECTRICITY TARIFF

6.2.1. CURRENT AND POSSIBLE FUTURE TARIFFS

The household owner current electricity contract is summarised in *Table 31*. The energy term is divided into the energy cost and the access tolls. This tariff, offered by Iberdrola and named as Stable Plan, has a fixed electricity price and is therefore not split up into the three periods presented in Table 30. The household has a contracted power of 6.928 kW both at peak and off-peak periods, with which the cost of the power term will be calculated.

Current tariff	
Energy term (€/kWh)	
Energy cost	0.0958
Access tolls	0.0432
Total energy cost	0.139
Power term (€/kW·day)	
Peak	0.120713
Off-peak	0.037057

Table 31: Current electricity prices

This tariff, as it is not meant to be for clients with PV systems, will have to be changed by another one which compensates for the surplus energy injected to the grid, either by direct compensation or by means of a virtual battery.

Repsol offers an attractive virtual battery tariff, in which the electricity price is quite high but so is the surplus feed-in tariff, one of the highest in the market, as it can be seen in *Table 32*. Both prices are fixed, as well as the contracted power prices. Thus, no distinction between consumption periods is made. Also, an additional cost derived from the virtual battery will have to be considered when analysing this tariff.

Repsol virtual battery tariff	
Energy term (€/kWh)	
Energy cost	0.1067
Tolls	0.0432
Total energy cost	0.1499
Surplus energy	0.08
Power term (€/kW·day)	
Peak	0.068219
Off-peak	0.068219
Virtual battery (€/month)	
Cost	1.99

Table 32: Electricity prices: Repsol

The second alternative which will be considered, also with a virtual battery, is the tariff shown in *Table 33* and offered by Endesa. It has a slightly lower electricity price, also fixed and independent of the consumption period. As a trade-off, the supplier buys the surplus energy at a lower price. In this case, the power term is divided into peak and off-peak periods, being the latter the cheaper one. As before, there is an extra cost that corresponds to the virtual battery.

<table>
<tr><td colspan="2">Endesa virtual battery tariff</td></tr>
<tr><td colspan="2">Energy term (€/kWh)</td></tr>
<tr><td>Energy cost</td><td>0.09909</td></tr>
<tr><td>Tolls</td><td>0.0432</td></tr>
<tr><td>Total energy cost</td><td>0.14229</td></tr>
<tr><td>Surplus energy</td><td>0.06</td></tr>
<tr><td colspan="2">Power term (€/kW·day)</td></tr>
<tr><td>Peak</td><td>0.11214</td></tr>
<tr><td>Off-peak</td><td>0.040267</td></tr>
<tr><td colspan="2">Virtual battery (€/month)</td></tr>
<tr><td>Cost</td><td>2</td></tr>
</table>

Table 33: Electricity prices: Endesa

Finally, a last tariff will also be analysed, in this case not with virtual battery but with direct compensation. The chosen one is offered by Naturgy and is presented in *Table 34*. Although shown as fixed price, this solar tariff divides the energy prices as 0.19 €/kWh, 0.12€/kWh and 0.08 €/kWh for peak, mid-peak and off-peak periods, respectively, incentivising the shift of demand to times of low load at national level. However, due to the special characteristic of this household, that not only future scenarios have been needed to be developed with the objective of obtaining a better picture of what the future consumption will look like but also that the household hourly consumption of a whole year is not available, a weighted average of the three electricity prices has been computed to carry out the analysis with monthly values. As in Endesa's tariff, the power term is also split into peak and off-peak periods.

<table>
<tr><td colspan="2">Naturgy solar tariff</td></tr>
<tr><td colspan="2">Energy term (€/kWh)</td></tr>
<tr><td>Energy cost</td><td>0.0718</td></tr>
<tr><td>Tolls</td><td>0.0432</td></tr>
<tr><td>Total energy cost</td><td>0.115</td></tr>
<tr><td>Surplus energy</td><td>0.07</td></tr>
<tr><td colspan="2">Power term (€/kW·day)</td></tr>
<tr><td>Peak</td><td>0.108163</td></tr>
<tr><td>Off-peak</td><td>0.033392</td></tr>
</table>

Table 34: Electricity prices: Naturgy

6.2.2. RESULTS, COMPARISON AND SELECTION

The economic analysis will be carried out taking the consumptions developed in section ***5.2.4. Future Consumption: Scenario 2*** into consideration, which were exposed in *Table 10.* Additionally, the results shown in *Table 25* of the PVsyst simulation with Scenario 2 consumptions and the chosen 5.5 kWp configuration will be required to analyse the surplus energy injected to the grid and the imported energy from the grid for each month. The following results have been calculated considering only the power term, the energy term and the cost of the virtual battery in case there is one. They do not contain other fixed costs such as the metering system renting, among others, since they have to be paid in all cases and are equal in every tariff. Therefore, the results are useful for comparison between different tariffs, but they must not be considered as final electricity costs to be paid by the client. In each case, the taxes have been added considering the current ones as of May 2025, which are the electricity tax of 5.11% applicable to both power and energy term and the value added tax (VAT) of 21% applicable to the total cost of electricity including other services such as the virtual battery.

Initially, *Table 35* presents the results of the monthly costs of electricity for the household in case of Scenario 2 consumptions and without installing a solar PV installation. They have been calculated considering the contracted power and energy prices of the current tariff.

Without PV	
January	151.11 €
February	136.16 €
March	145.63 €
April	161.92 €
May	157.30 €
June	215.48 €
July	262.13 €
August	269.73 €
September	233.34 €
October	131.01 €
November	145.12 €
December	147.93 €

Table 35: Annual electricity costs without PV

Following, the results obtained with the PV installation and Repsol's virtual battery tariff are shown in *Table 36*. It is worth mentioning that with the virtual battery, the cash generated by the surplus energy injected into the grid can be saved and used whenever the client wants. In this case, it has been assumed that the available balance in the virtual battery is directly used the same month it has been generated. The net energy term to be paid derives from extracting the cash generated by the surplus injection to the total cost of energy consumed from the grid. Then, the total amount results from adding the contracted power costs to the energy costs, applying a 5.11% tax and then adding the virtual battery cost to finally apply the 21% VAT to the total cost.

Repsol virtual battery with PV				
Month	Imports	Exports	Net	Total
January	61.01 €	39.36 €	21.65 €	67.21 €
February	54.26 €	39.44 €	14.82 €	54.92 €
March	52.02 €	50.16 €	1.86 €	42.04 €
April	59.36 €	45.28 €	14.08 €	56.38 €
May	52.32 €	51.44 €	0.88 €	40.79 €
June	82.74 €	41.04 €	41.70 €	91.52 €
July	107.78 €	34.56 €	73.22 €	132.80 €
August	112.57 €	36.00 €	76.57 €	137.07 €
September	99.68 €	34.72 €	64.96 €	121.10 €
October	61.31 €	45.52 €	15.79 €	59.76€
November	58.46 €	37.52 €	20.94 €	65.11 €
December	59.51 €	37.76 €	21.75 €	67.34 €

Table 36: Annual electricity costs with PV and Repsol's tariff

With the exact same procedure, the results gathered in *Table 37* from Endesa's virtual battery tariff and with the PV installation have been obtained.

Endesa virtual battery with PV				
Month	Imports	Exports	Net	Total
January	57.91 €	29.52 €	28.39 €	80.16 €
February	51.51 €	29.58 €	21.93 €	65.49 €
March	49.37 €	37.62 €	11.75 €	56.58 €
April	56.35 €	33.96 €	22.39 €	68.76 €
May	49.66 €	38.58 €	11.08 €	55.72 €
June	78.54 €	30.78 €	47.76 €	101.03 €
July	102.31 €	25.92 €	76.39 €	138.78 €
August	106.86 €	27.00 €	79.86 €	143.20 €
September	94.62 €	26.04 €	68.58 €	127.51 €
October	58.20 €	34.14 €	24.06 €	72.23 €
November	55.49 €	28.14 €	27.35 €	75.08 €
December	56.49 €	28.32 €	28.17 €	77.46 €

Table 37: Annual electricity costs with PV and Endesa's tariff

When analysing the final case, with PV installation and Naturgy's solar tariff with direct compensation, a different procedure is to be taken. Firstly, the cost of importing energy from the grid must be divided in energy cost and grid access tolls since, as explained in section ***6.1.2. Energy Term***, the compensation of surplus energy cannot exceed the energy cost of the same month, as the amount paid for access tolls is not to be compensated. Then, the theoretical amount to be compensated is compared with the imported energy cost. If the value of the injected surplus energy is higher than the imported energy cost, then just the entire energy cost is compensated, and the rest is wasted and not saved to use in following months. Otherwise, the value of the injected surplus energy is compensated to reduce the higher value of the imported energy cost. Finally, the total result of each month is calculated by adding the contracted power cost to the price to be paid in terms of tolls and the difference between energy cost and surplus energy compensation. Again, to this total cost the electricity tax and VAT have been added. *Table 38* shows the results obtained in this analysis.

Naturgy solar tariff with PV					
Month	Imports		Exports		Total
	Energy cost	Tolls	Theoretical	To compensate	
January	29.22 €	17.58 €	34.44 €	29.22 €	61.03 €
February	25.99 €	15.64 €	34.51 €	25.99 €	54.81 €
March	24.91 €	14.99 €	43.89 €	24.91 €	57.73 €
April	28.43 €	17.11 €	39.62 €	28.43 €	59.18 €
May	25.06 €	15.08 €	45.01 €	25.06 €	57.84 €
June	39.63 €	23.85 €	35.91 €	35.91 €	72.48 €
July	51.62 €	31.06 €	30.24 €	30.24 €	105.37 €
August	53.92 €	32.44 €	31.50 €	31.50 €	108.44 €
September	47.75 €	28.73 €	30.38 €	30.38 €	96.04 €
October	29.37 €	17.67 €	39.83 €	29.37 €	61.14 €
November	28.00 €	16.85 €	32.83 €	28.00 €	58.85 €
December	28.50 €	17.15 €	33.04 €	28.50 €	60.48 €

Table 38: Annual electricity costs with PV and Naturgy's tariff

To obtain a visual insight, Figure 44 compares the power and energy term costs of the different tariffs presented before. As it can be seen at first glance, installing a PV system automatically translates in a notable reduction in the monthly electricity costs of the household. Focusing on the three possible future tariffs, it looks like Naturgy's solar tariff, although not offering the virtual battery and hence not allowing to compensate all the surplus energy injected into the grid during the whole year, is still the most competitive one due to its lower energy price. Between the two virtual battery tariffs, they seem to be quite similar to each other, being Repsol's tariff slightly cheaper throughout the year.

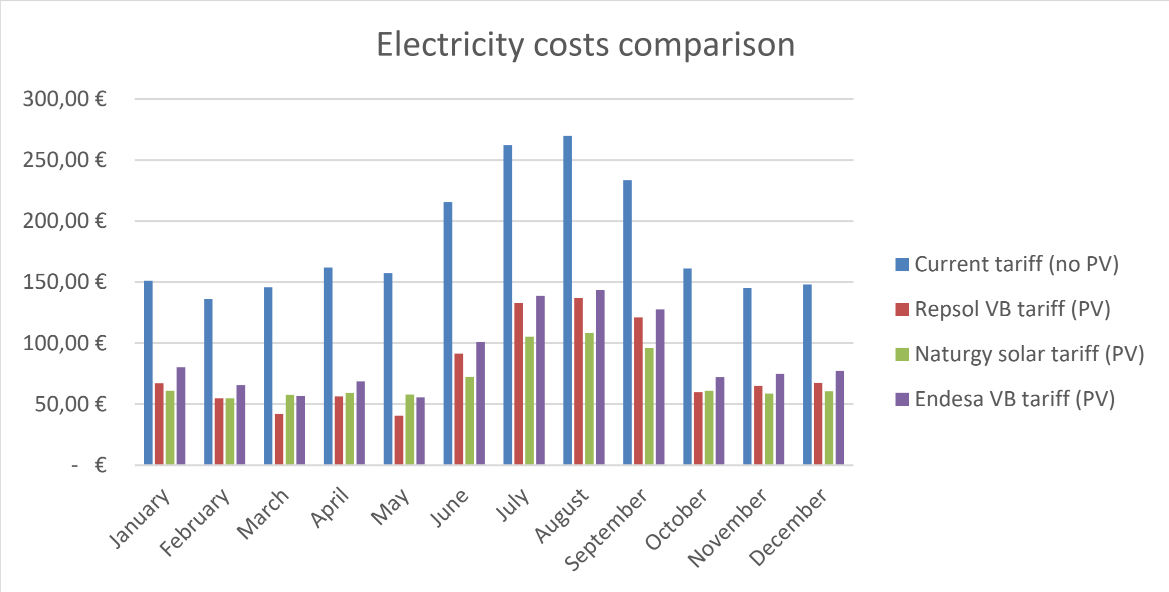


Figure 44: Costs comparison between tariffs

In *Figure 45* the monthly savings that could be potentially achieved by installing a PV system are plotted. By analysing it, one can see that months such as March or May, having Repsol's tariff with a PV system would mean around a 70% reduction in comparison with the current tariff without PV system. Alternatively, by choosing Naturgy's solar tariff one would obtain regularly monthly savings in the electricity bill of around 50-60% all year round.

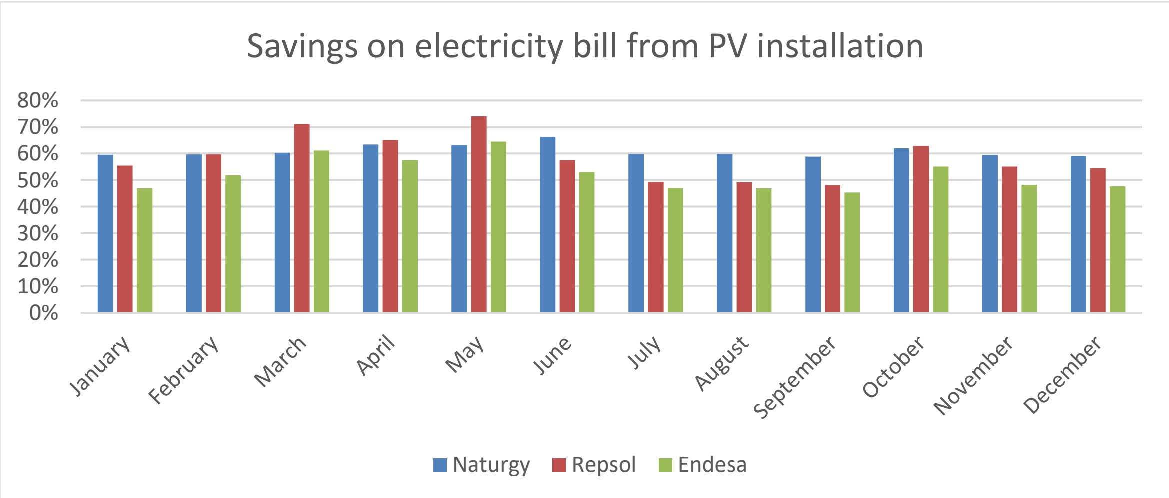


Figure 45: Monthly savings on electricity bill with PV system

Adding up the tariff-dependent annual electricity costs of the three tariffs and comparing them with the electricity costs derived from the current tariff in the case where no PV system is installed, the results on annual savings, presented in *Table 39*, are obtained. As previously suspected in *Figure 44*, Naturgy's solar tariff would be the one to choose in order to maximise the annual savings obtained from installing a PV system.

Annual savings	
Repsol	1250.84 €
Naturgy	1333.47 €
Endesa	1124.86 €

Table 39: Annual savings from PV system

6.3. *FINAL ECONOMIC RESULTS*

6.3.1. *TOTAL INSTALLATION COST ESTIMATION*

The cost estimation is derived from a comprehensive review of pricing data from photovoltaic installation companies operating in Málaga, specifically those servicing Mijas. The sources include detailed quotations from local providers, industry reports, and market analyses for 2024-2025. Key providers considered include Málaga Solar, Ubora Solar, SolarChain, Cambio Energético, and Quantica Renovables, all of which have established operations in the region. The estimation accounts for the full scope of a grid-connected, turnkey PV system, including solar panels, a 5 kW inverter, mounting structures, cabling, electrical protections, monitoring systems, and administrative procedures for legalization.

The cost of a 5.5 kWp PV installation in Spain typically ranges from 1300€ to 1800€ per kWp, based on market data for turnkey systems without batteries. For a 5.5 kWp system, this translates to a baseline cost range of 7150€ to 9900€. To refine this estimate, specific quotations from Málaga-based companies were analyzed:

- Málaga Solar offers a 5 kWp installation for 6263€ (VAT included), including 10 JASolar panels, a 5 kW Huawei inverter, aluminum mounting structures, monitoring systems, cabling, electrical protections, and legalization procedures. Scaling to 5.5 kWp (an additional 0.5 kWp), the estimated cost is approximately 6800€ to 7000€, based on a per-kWp cost of 1250€.
- Ubora Solar provides turnkey installations in Mijas, with costs aligned to the market range of 1300€-1800€ per kWp. For 5.5 kWp, the estimated cost is 7150€ to 9900€.
- Iberdrola offers a 5.52 kWp installation for 6940€, leading to a per-kW cost of 1257.25€.
- Cambio Energético quotes 5 kWp systems at 5000€ to 6000€. For 5.5 kWp, the adjusted cost is approximately 5500€ to 6600€, though this is lower than the market average, suggesting potential variability in component quality or scope.
- Quantica Renovables reports costs for 5 kWp systems between 3500€ and 9000€, depending on configuration. For 5.5 kWp, the estimated range is 6000€ to 9900€.
- Octopus offers a 5.3 kWp installation for 6900€. Scaling up to 5.5 kWp and considering 1300€/kWp, a cost of 7150€ would be obtained.

To ensure a rigorous and conservative estimate, the analysis prioritizes data from Málaga Solar due to its detailed quotation and local expertise. The adjusted cost for a 5.5 kWp system, based on Málaga Solar's pricing, is approximately 6800€ to 7000€. However, to account for potential variations in component quality, installation complexity, and market fluctuations, a slightly broader range is adopted, aligning with the upper end of the market average. Thus, the estimated cost for a 5.5 kWp PV installation in Mijas, Málaga, is of 7000€-7500 €.

This range includes:

- Solar panels
- Inverter
- Mounting structure
- Electrical components
- Monitoring system
- Installation and legalization

For the reminder economic calculations in the following sections, a total cost of 7250€ will be assumed.

6.3.2. POSSIBLE SUBSIDIES AND INCENTIVES

In Spain, homeowners who install solar photovoltaic systems for self-consumption can benefit from several financial incentives and subsidies that enhance the economic viability of such projects. One of the most significant incentives available is the reduction in the Property Tax, known as Impuesto sobre Bienes Inmuebles (IBI). However, Mijas does not grant any special IBI discount for solar installations [51].

Additionally, several cities in Spain offer a notable incentive through a reduction in the Tax on Constructions, Installations, and Works, referred to as Impuesto sobre Construcciones, Instalaciones, y Obras (ICIO). This tax, which is a one-time payment applied to construction or installation work requiring a permit, can be reduced by up to 95% for photovoltaic installations [52]. Once again, Mijas does not offer any ICIO rebate for residential PV installations either [51].

Furthermore, the European Next Generation funds, which previously provided subsidies of 600€ per kWp for installations like the 5.5 kWp system (potentially 3300 € in total) and 490€ per kWh for battery storage, ended on December 31, 2023 [53]. The Spanish government has requested continued funding until 2026, but as of May 2025, no confirmation has been received.

As a national incentive, homeowners can deduct 20–60% of eligible PV installation costs on their annual income tax also known as Impuesto sobre la Renta de Personas Físicas (IRPF). A 20% deduction with a maximum base per year of 5000€ applies if the PV system yields at least a 7% primary-energy consumption reduction, which must be measured by certified energy ratings [55]. A 40% deduction with a maximum base per year of 7500€ is available for larger savings, higher or equal to 30% reduction and resulting energy rating A/B, and a 60% deduction with a maximum base per year of 5000€ applies for the same high savings when the work is done by a community of owners [54]. To qualify, the taxpayer must own or rent the dwelling, and it must be their main residence or a rented dwelling, to be let before end 2025. An official energy-efficiency certificate is required before and after the works, showing the demanded savings (e.g. ≥7% savings or 2-class rating improvement) [56]. The work must be completed by December 2025 and the post-work certificate issued by the 1st of January 2026, being the homeowners able to claim the deduction in their regular tax return as no separate application is needed.

As calculated in section ***5.6.2. Scenario 2***, the PV system will reduce the household energy consumption by 38%, thus qualifying for a 40% IRPF reduction. Considering the installation cost of 7250€ and assuming a budget of 250€ for the two required energy performance certificates (CEEs) needed to claim the deduction, the total possible IRPF reduction would be of 2650€.

6.3.3. FINANCIAL METRICS

6.3.3.1. Preliminary assumptions and input data

The initial investment will be of 7250€, as estimated in section ***6.3.1***, and the expected lifespan of the project is of 25 years, although, if maintained properly, it can continue to produce electricity even beyond 30 years, but with lower efficiency. The annual savings in the electricity bill have been calculated to be in *Table 39* of around 1333.47€ in Year 1 when installing a 5.5 kWp PV system and choosing Naturgy as electricity supplier with its offered solar tariff. With the following considerations mentioned, some financial metrics such as the net present value (NPV), the payback period and the internal rate of return (IRR) of the project will be calculated. Additionally, the same calculations will be performed but considering also the possible IRPF deduction the owner would be qualifiable for.

The solar panels typically degrade about 0.5%-1% per year, meaning that annual energy production, and thus savings, will slightly decrease each year. Therefore, considering a PV degradation factor of 0.5% and assuming that the energy demand (9500 kWh), the self-consumption ratio (35.84%) and the grid injection ratio (58.77%) remain constant during the lifetime of the project, the energy balance from Year 1 to Year 25 has been calculated and is presented in *Table 40*. It shows how the energy generated is progressively reduced year by year, which, consequently, lowers the amount of energy self-consumed and exported, ultimately making the imports of energy from the grid to rise.

Year	Generated (kWh)	Self-consumed (kWh)	Imported (kWh)	Exported (kWh)
1	10484	3757	5743	6161
2	10432	3738	5762	6130
3	10379	3720	5780	6100
4	10328	3701	5799	6069
5	10276	3682	5818	6039
6	10225	3664	5836	6009
7	10173	3646	5854	5978
8	10123	3627	5873	5949
9	10072	3609	5891	5919
10	10022	3591	5909	5889
11	9971	3573	5927	5860
12	9922	3555	5945	5830
13	9872	3538	5962	5801
14	9823	3520	5980	5772
15	9774	3502	5998	5743
16	9725	3485	6015	5715
17	9676	3467	6033	5686
18	9628	3450	6050	5658
19	9579	3433	6067	5629
20	9532	3416	6084	5601
21	9484	3399	6101	5573
22	9437	3382	6118	5545
23	9389	3365	6135	5518
24	9342	3348	6152	5490
25	9296	3331	6169	5463

Table 40: Future energy balance estimation

As for the electricity price forecast in the next 25 years, a 2% annual increase in Spain's residential electricity prices over the next 25 years will be assumed, grounded in historical trends and projections. From 2003 to 2023, Spain's electricity prices rose by approximately 3% annually, driven by reliance on natural gas (26% of the energy mix) and grid modernization costs [57]. For 2025, the National Commission on Markets and Competition (CNMC) projects a 1.3% rise in electricity consumption, with price increases expected due to the reinstatement of a 21% VAT (from 10% in 2024) and volatile natural gas prices. Key drivers supporting a 2% annual increase include:

- Growing demand: electrification of transport, heating and data centers will increase electricity consumption, with CNMC forecasting 1.3-3.5% growth in 2025.
- Natural gas volatility: combined-cycle plants, reliant on natural gas, remain a marginal price-setting source, with global gas market fluctuations impacting costs.
- Renewable integration: while renewable expansion may mitigate price spikes, grid investments and policy shifts (e.g. carbon pricing) will maintain upward pressure.

Thus, a 2% annual increase is conservative, below the historical 3% average, making it a reasonable assumption for long-term forecasting in Spain's energy market.

With the objective of evaluating the impact of the energy price increase and the solar panels degradation on the annual savings, Years 7, 14 and 21 will be further analysed to obtain the trend annual savings follow. Once identified, the annual savings of the remaining years will be deduced and used for the economic calculations.

Considering the 0.5% degradation factor and both self-consumption and grid injection ratios for each month of the year obtained from the PVsyst results in *Table 25*, the monthly energy balance of Year 7 has been calculated in *Table 41*.

Month	Generation (kWh)	Demand (kWh)	Self-consumption (kWh)	Exports (kWh)	Imports (kWh)
January	714	611	198	477	413
February	700	550	182	478	368
March	882	580	226	608	354
April	872	680	277	549	403
May	964	646	288	624	358
June	968	983	418	498	565
July	977	1239	505	419	734
August	1005	1282	515	437	767
September	874	1084	407	421	677
October	847	667	250	552	417
November	681	585	188	455	397
December	686	593	190	458	403

Table 41: Energy balance Year 7

Applying the 2% annual increase on energy costs, the houseowner's current electricity tariff would look in Year 7 like the one shown in *Table 42*.

Current tariff	
Energy term (€/kWh)	
Energy cost	0.1079
Access tolls	0.0487
Total energy cost	0.1565
Power term (€/kW·day)	
Peak	0.1359
Off-peak	0.0417

Table 42: Current electricity tariff Year 7

Table 43 shows the monthly electricity costs the houseowner would face in Year 7 in case of not installing a PV system. They express the result of multiplying the energy demand of each month with the total energy cost, adding the power term costs and taking also the electricity tax (5.11%) and VAT (21%) into account.

Without PV	
Month	Cost
January	170.17 €
February	153.33 €
March	164.00 €
April	182.35 €
May	177.14 €
June	242.67 €
July	295.20 €
August	303.76 €
September	262.78 €
October	181.32 €
November	163.43 €
December	166.59 €

Table 43: Electricity costs in Year 7 without PV

Again, applying the 2% annual increase on energy costs, the Naturgy solar electricity tariff would look in Year 7 like the one shown in *Table 44*.

Naturgy solar tariff	
Energy term (€/kWh)	
Energy cost	0.0809
Tolls	0.0487
Total energy cost	0.1295
Surplus energy	0.0788
Power term (€/kW·day)	
Peak	0.1218
Off-peak	0.0376

Table 44: Naturgy solar tariff Year 7

Proceeding in the same way as in section ***6.2.2. Results, Comparison and Selection***, where the functioning of the surplus energy compensation was explained, the monthly electricity costs in Year 7 with the PV system would be the ones calculated in *Table 45*.

Naturgy solar tariff with PV Year 7					
Month	Imports		Exports		Total
	Energy cost	Tolls	Theoretical	To compensate	
January	33.40 €	20.09 €	37.64 €	33.40 €	69.10 €
February	29.72 €	17.88 €	37.71 €	29.72 €	62.07 €
March	28.62 €	17.22 €	47.96 €	28.62 €	65.44 €
April	32.62 €	19.63 €	43.30 €	32.62 €	67.10 €
May	28.93 €	17.41 €	49.19 €	28.93 €	65.68 €
June	45.67 €	27.48 €	39.24 €	39.24 €	85.25 €
July	59.38 €	35.73 €	33.05 €	33.05 €	122.48 €
August	62.00 €	37.30 €	34.42 €	34.42 €	126.05 €
September	54.77 €	32.96 €	33.20 €	33.20 €	111.49 €
October	33.69 €	20.27 €	43.53 €	33.69 €	69.32 €
November	32.08 €	19.30 €	35.88 €	32.08 €	66.69 €
December	32.57 €	19.60 €	36.11 €	32.57 €	68.47 €

Table 45: Electricity costs with Naturgy's solar tariff in Year 7

Therefore, summing up the monthly costs of both situations, with and without PV installation, in a context of 0.5% annual degradation of the solar panels and 2% increase in energy price, 1483.59€ have been obtained as annual savings in Year 7.

With exactly the same procedure as explained in the annual savings calculations of Year 7, the annual savings of Year 14 and Year 21 are to be obtained. Considering the 0.5% degradation factor and both self-consumption and grid injection ratios for each month of the year obtained from the PVsyst results in *Table 25*, the monthly energy balance of Year 14 has been calculated in *Table 46*.

Month	Generation (kWh)	Demand (kWh)	Self-consumption (kWh)	Exports (kWh)	Imports (kWh)
January	690	611	191	461	420
February	676	550	176	462	374
March	852	580	218	587	362
April	842	680	267	530	413
May	930	646	278	602	368
June	935	983	404	481	579
July	943	1239	487	405	752
August	971	1282	498	422	784
September	844	1084	393	407	691
October	818	667	242	533	425
November	658	585	182	439	403
December	662	593	184	442	409

Table 46: Energy balance Year 14

Applying the 2% annual increase on energy costs, the houseowner's current electricity tariff would look in Year 14 like the one shown in *Table 47*.

Current tariff	
Energy term (€/kWh)	
Energy cost	0.1239
Access tolls	0.0559
Total energy cost	0.1798
Power term (€/kW·day)	
Peak	0.1562
Off-peak	0.0479

Table 47: Current electricity tariff Year 14

Table 48 shows the monthly electricity costs the houseowner would face in Year 14 in case of not installing a PV system. They express the result of multiplying the energy demand of each month with the total energy cost, adding the power term costs and taking also the electricity tax (5.11%) and VAT (21%) into account.

Without PV	
Month	Cost
January	195.48 €
February	176.13 €
March	188.39 €
April	209.46 €
May	203.48 €
June	278.75 €
July	339.09 €
August	348.93 €
September	301.85 €
October	208.28 €
November	187.73 €
December	191.36 €

Table 48: Electricity costs in Year 14 without PV

Again, applying the 2% annual increase on energy costs, the Naturgy solar electricity tariff would look in Year 14 like the one shown in *Table 49*.

Naturgy solar tariff	
Energy term (€/kWh)	
Energy cost	0.0929
Tolls	0.0559
Total energy cost	0.1488
Surplus energy	0.0906
Power term (€/kW·day)	
Peak	0.1399
Off-peak	0.0432

Table 49: Naturgy's solar tariff Year 14

Proceeding in the same way as explained in section ***6.2.2. Results, Comparison and Selection***, where the functioning of the surplus energy compensation was explained, the monthly electricity costs with the PV system in Year 14 would be the ones calculated in *Table 50*.

Naturgy solar tariff with PV Year 14					
Month	Imports		Exports		Total
	Energy cost	Tolls	Theoretical	To compensate	
January	39.00 €	23.46 €	41.74 €	39.00 €	79.86 €
February	34.72 €	20.89 €	41.83 €	34.72 €	71.75 €
March	33.59 €	20.21 €	53.19 €	33.59 €	75.73 €
April	38.36 €	23.08 €	48.02 €	38.36 €	77.76 €
May	34.16 €	20.55 €	54.55 €	34.16 €	76.15 €
June	53.80 €	32.37 €	43.52 €	43.52 €	102.64 €
July	69.83 €	42.01 €	36.65 €	36.65 €	145.65 €
August	72.86 €	43.84 €	38.18 €	38.18 €	149.89 €
September	64.22 €	38.64 €	36.82 €	36.82 €	132.40 €
October	39.50 €	23.77 €	48.27 €	39.50 €	80.24 €
November	37.45 €	22.53 €	39.79 €	37.45 €	77.06 €
December	38.02 €	22.88 €	40.04 €	38.02 €	79.11 €

Table 50: Electricity costs with Naturgy's solar tariff in Year 14

Therefore, summing up the monthly costs of both situations, with and without PV installation, in a context of 0.5% annual degradation of the solar panels and 2% increase in energy price, 1680.69€ have been obtained as annual savings in Year 14.

Finally, repeating the same procedure, the annual savings of year 21 will be obtained. Considering the 0.5% degradation factor and both self-consumption and grid injection ratios for each month of the year obtained from the PVsyst results in *Table 25*, the monthly energy balance of Year 21 has been calculated in *Table 51*.

Month	Generation (kWh)	Demand (kWh)	Self-consumption (kWh)	Exports (kWh)	Imports (kWh)
January	666	611	185	445	426
February	652	550	170	446	380
March	822	580	211	567	369
April	813	680	258	512	422
May	898	646	269	582	377
June	903	983	390	464	593
July	911	1239	470	391	769
August	937	1282	480	407	802
September	815	1084	379	393	705
October	790	667	233	515	434
November	635	585	175	424	410
December	640	593	177	427	416

Table 51: Energy balance Year 21

Applying the 2% annual increase on energy costs, the houseowner's current electricity tariff would look in Year 21 like the one shown in *Table 52*.

Current tariff	
Energy term (€/kWh)	
Energy cost	0.1424
Access tolls	0.0642
Total energy cost	0.2065
Power term (€/kW·day)	
Peak	0.1794
Off-peak	0.0551

Table 52: Current electricity tariff Year 21

Table 53 shows the monthly electricity costs the houseowner would face in Year 21 in case of not installing a PV system. They express the result of multiplying the energy demand of each month with the total energy cost, adding the power term costs and taking also the electricity tax (5.11%) and VAT (21%) into account.

Without PV	
Month	Cost
January	224.54 €
February	202.32 €
March	216.40 €
April	240.60 €
May	233.74 €
June	320.20 €
July	389.51 €
August	400.81 €
September	346.73 €
October	239.25 €
November	215.65 €
December	219.81 €

Table 53: Electricity costs in Year 21 without PV

Again, applying the 2% annual increase on energy costs, the Naturgy solar electricity tariff would look in Year 21 like the one shown in *Table 54*.

Naturgy solar tariff	
Energy term (€/kWh)	
Energy cost	0.1067
Tolls	0.0642
Total energy cost	0.1709
Surplus energy	0.1040
Power term (€/kW·day)	
Peak	0.1607
Off-peak	0.0496

Table 54: Naturgy's solar tariff Year 21

Proceeding in the same way as explained in section ***6.2.2. Results, Comparison and Selection***, where the functioning of the surplus energy compensation was explained, the monthly electricity costs in Year 21 would be the ones calculated in *Table 55*.

Naturgy solar tariff with PV Year 21					
Month	Imports		Exports		Total
	Energy cost	Tolls	Theoretical	To compensate	
January	45.50 €	27.38 €	46.29 €	45.50 €	92.27 €
February	40.54 €	24.39 €	46.39 €	40.54 €	82.91 €
March	39.39 €	23.70 €	59.00 €	39.39 €	87.60 €
April	45.04 €	27.10 €	53.26 €	45.04 €	90.07 €
May	40.26 €	24.22 €	60.50 €	40.26 €	88.26 €
June	63.28 €	38.07 €	48.27 €	48.27 €	123.11 €
July	82.00 €	49.34 €	40.65 €	40.65 €	172.80 €
August	85.53 €	51.46 €	42.34 €	42.34 €	177.83 €
September	75.21 €	45.25 €	40.84 €	40.84 €	156.88 €
October	46.26 €	27.83 €	53.54 €	46.26 €	92.86 €
November	43.69 €	26.29 €	44.13 €	43.69 €	89.03 €
December	44.35 €	26.68 €	44.41 €	44.35 €	91.39 €

Table 55: Electricity costs with Naturgy's solar tariff in Year 21

Therefore, summing up the monthly costs of both situations, with and without PV installation, in a context of 0.5% annual degradation of the solar panels and 2% increase in energy price, 1904.53€ have been obtained as annual savings in Year 21.

To sum up, *Table 56* gathers the expected annual savings that have been calculated until this point.

Year	Savings
1	1.333,47 €
7	1.483,59 €
14	1.680,69 €
21	1.904,53 €

Table 56: Calculated annual savings

By plotting them in *Figure 46*, the slightly exponential curve of the annual savings tendency throughout the years is obtained, together with the equation which describes such trend.

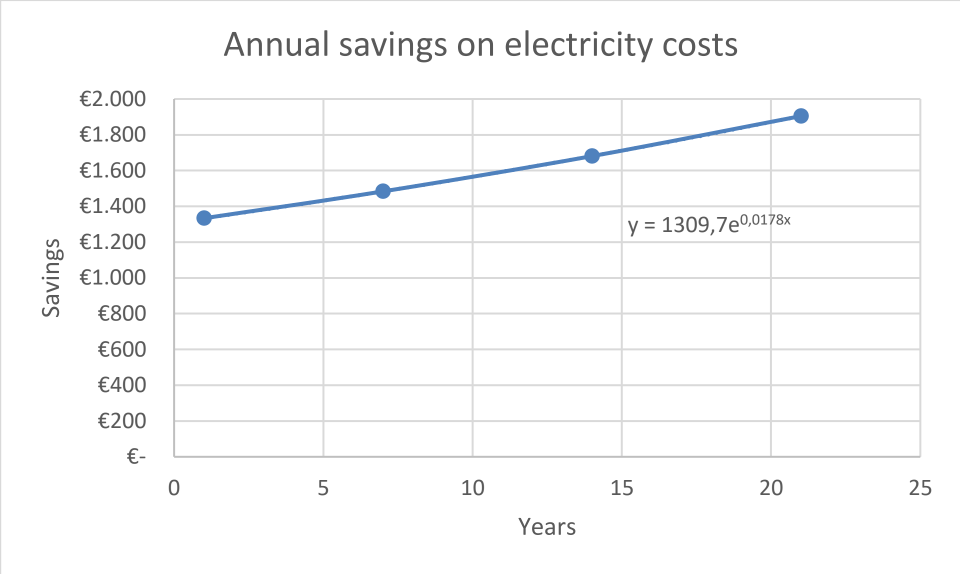


Figure 46: Tendency of annual savings on electricity costs

Making use of the equation and particularising it to each year of the project, the estimated annual savings derived from the PV installation are shown in *Table 57*.

Year	Savings
1	1.333.22 €
2	1.357.17 €
3	1.381.54 €
4	1.406.35 €
5	1.431.61 €
6	1.457.32 €
7	1.483.49 €
8	1.510.13 €
9	1.537.25 €
10	1.564.86 €
11	1.592.97 €
12	1.621.58 €
13	1.650.70 €
14	1.680.34 €
15	1.710.52 €
16	1.741.24 €
17	1.772.51 €
18	1.804.35 €
19	1.836.75 €
20	1.869.74 €
21	1.903.32 €
22	1.937.50 €
23	1.972.30 €
24	2.007.72 €
25	2.043.77 €

Table 57: Annual savings estimation from trend

Regarding maintenance costs, inverters typically last for 10-15 years. Hence, an inverter replacement will be considered in the middle of the project's lifespan with a negative cashflow of 700€ in Year 13. Furthermore, although rooftop solar PV installations require very low maintenance, possible minor maintenance costs such as electrical inspections, occasional repairs or possible monitoring system subscriptions will be modelled as an annual reserve of 50€.

A discount rate of 5% will be used in this analysis to reflect the opportunity cost of capital for a single-family household investing in a rooftop PV system. This rate represents the return the household forgoes by not investing the same amount in low-risk alternatives such as savings accounts or diversified investment funds. A 5% rate is a balanced assumption that accounts for moderate risk, reduced liquidity, and long-term investment horizons typical of residential PV installations. It also provides a conservative estimate in light of the fact that electricity prices in Spain have historically risen faster than general inflation.

6.3.3.2. Financial results without subsidies or incentives

Table 58 contains all considerations that have just been introduced in section ***6.3.3.1.*** and that will be taken into account when estimating future cash flows. The calculations will be carried out employing the Excel software.

Year	**Cash flow description**	**Value**
0	Initial investment	-7250€
1	Annual savings	1333.22€
2-25	Annual savings Year n	$1309.7e^{0.0178n}$ €
1-24	Maintenance reserve	-50€
13	Inverter replacement	-700€

Table 58: Structure of cash flow calculation without subsidies

Considering the cash flows in Table 58 and a 5% discount rate, a net present value of 14,124.42€ is obtained. The positive NPV value suggests that the project should be undertaken, as it would increase the investor's wealth.

By taking the net cash flow of the first years into account, the results show that the estimated payback period is between Years 5 and 6 of the project. This means that the initial investment is already recovered even before the first quarter of the project has been reached, without any kind of incentives or subsidies.

Finally, this project delivers an internal rate of return of 19%, much higher than the opportunity cost of approximately 5% obtained when investing the same amount of money in alternatives with similar risk such as savings accounts or government funds.

6.3.3.3. Financial results considering possible subsidies and incentives

Alternatively, the IRPF deduction will be taken into consideration, which can be modelled as a negative cash flow in Year 0 of 250€ for the acquisition of the energy certificates and a positive cash flow in Year 1 of 40% the initial investment as the IRPF deduction, i.e., 2900€. *Table 59* contains all considerations that have just been introduced in section ***6.3.3.1.*** and that will be taken into account when estimating future cash flows. The calculations will be carried out employing the Excel software.

Year	Cash flow description	Value
0	Initial investment	-7250€
0	Cost of energy certificates	-250€
1	Annual savings	1333.22€
1	IRPF deduction	2900€
2-25	Annual savings Year n	$1309.7e^{0.0178n}$ €
1-25	Maintenance reserve	-50€
13	Inverter replacement	-700€

Table 59: Structure of cash flow calculation with subsidies

This results in an even higher NPV of the project (16,636.33€), an exceptional IRR of 26.25% and a shorter payback period between Years 3 and 4.

All in all, carrying out such a project seems to be an excellent investment for the household owner from an economic viewpoint since it will provide an outstanding return on the investment for a very low risk.

Chapter 7. CONCLUSIONS

This project has had the objective of designing a solar photovoltaic installation for self-consumption of electricity in the residential sector, specifically in a single-family household located in the South of Spain in Mijas, Málaga.

The first chapters have been developed to serve as an introduction to the technology used in this project and to explain important concepts to understand the content of the following chapters as well as to give an insight into the current state of development of PV systems. Then, the objectives and methodology to be used to achieve them were introduced before going on to analysing both technical and economical sides of the project.

The first challenge to be tackled was the household consumption. Since the hourly consumption Excel sheets were not available and the consumption would be highly increased in the future, three different scenarios were developed. Each of them had different assumptions regarding the consumption behaviour of high-demanding loads and it was decided that Scenario 2 would be the one to focus on.

After comparing and selecting the solar radiation database that would be used in the PVsyst simulations, the system's configuration was decided. Based on the simulations results, it was determined that a 35º fixed-tilt structure was the optimal one to install in this location. Then, different simulations varying the peak and nominal power of the system were run so as to decide how much energy generation would the household require, finding a compromise between the energy coverage by the installation from the total household demand and the self-consumption rate. As a result, a system with 5.5 kWp and 5 kWn was obtained.

Following, the electrical calculations took place. Knowing that 10 panels of 550 W were required, the sum of their lowest MPP voltage suggested that forming 2 strings of 5 modules each would lead to insufficient voltage values for the inverter to work. Thus, just one string with the 10 solar panels connected in series was considered. Then, taking the metres of conductors needed and the currents expected to flow through those conductors into account, the sizing of both cross-sectional areas of cables and ratings of protection devices was carried out. It was a straightforward calculation since the limits are clearly specified in the Spanish Low Voltage Electrotechnical Regulations, which were considered during the whole technical viability analysis.

Having determined that the project was viable from a technical viewpoint and knowing the annual energy flows that would take place, i.e., how much energy would the household consume from the PV installation, how much would be fed into the grid and how much would be required to be imported from the grid, the economic viability of the project was ready to be analysed. First, it was important to estimate what the total cost of the installation would be based on the current market prices and the budgets offered by companies with activity near the household's location. This choice was preferred rather than elaborating an own budget in this project for various reasons. In this project, just the technical side was going to be designed and, consequently, there were other aspects when considering the project as a whole that would have to be approximately estimated. It was of big importance to have a very accurate cost estimation since it is decisive for the homeowner to carry on the investment or not. Therefore, it was decided that searching and asking for budgets to companies was the best way to achieve this accuracy, rather than making up material costs, costs from the electronic side of the project, construction works costs and other costs derived from bureaucratic procedures.

Then, different electricity tariffs from electricity suppliers for solar PV system owners were analysed and compared against the situation of not installing the PV system. In such comparisons, just the power and energy term were considered since taking small, fixed costs such as the metering system renting into account would not make a difference as it is to be paid in the same amount in all cases.

Afterwards, probably the most relevant calculations for the household owner were tackled, such as the annual savings and with them, the net present value, the payback period and the internal rate of return of the project. For the calculation of such economic indices, the future cash flows had to be estimated. Hence, some influencing factors such as PV degradation, energy price increases and possible maintenance and replacement costs were considered. As a result, an IRR of around 26% and a payback period of 3-4 years was obtained (19% and 5-6 years without considering IRPF deduction), meaning that the return on investment of this project is much higher than other investments with similar risk.

All in all, the project has successfully demonstrated both technical and economic viabilities, meaning that it will definitely bring economic benefits to the household owner while, at the same time, reducing the greenhouse gas emissions and dependence on fossil fuels by generating energy from a renewable energy source, the Sun.

Chapter 8. BIBLIOGRAPHY

[1] G2V Optics. (n.d.). *Theory of solar cells*. https://g2voptics.com/photovoltaics-solar-cells/theory-of-solar-cells/

[2] DevXplained. (2020, November 16). *P-N junction*. DevXplained. https://devxplained.eu/en/blog/p-n-junction

[3] Maysun Solar. (2022, August 31). *Solar cells: Size, process and technology explained*. https://www.maysunsolar.com/solar-cells-size-process-and-technology-explained/

[4] Peacock, F. (2025, May 19). *Polycrystalline vs monocrystalline solar panels*. SolarQuotes. https://www.solarquotes.com.au/panels/photovoltaic/monocrystalline-vs-polycrystalline/

[5] Fraunhofer Institute for Solar Energy Systems ISE, & PSE Projects GmbH. (2024). *Photovoltaics report*. https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

[6] Masmoudi, F., Ben Salem, F., & Derbel, N. (2014). *Equivalent circuit of an ideal photovoltaic cell with single-diode*. ResearchGate. https://www.researchgate.net/figure/Equivalent-circuit-of-an-ideal-photovoltaic-cell-with-single-diode-The-current-I_fig1_287751798

[7] Honsberg, C., & Bowden, S. (n.d.). *IV curve*. PVEducation. https://www.pveducation.org/pvcdrom/solar-cell-operation/iv-curve

[8] Seaward Electronic Ltd. (n.d.). *Curve tracing FAQ's*. Seaward. https://www.seaward.com/gb/support/solar/faqs/29495-curve-tracing-faq-s/

[9] Huawei Technologies Co., Ltd. (n.d.). *Smart Energy Controller SUN2000-3-10KTL-M1 (High Current Version) technical specification* [Datasheet].

[10] MPPT Eltawil, M. A., & Zhao, Z. (2013). MPPT techniques for photovoltaic applications. *Renewable and Sustainable Energy Reviews, 25*, 793–813. https://doi.org/10.1016/j.rser.2013.05.022

[11] Sakthi Suriya Raj, J. S., Periyasamy, P., Winston, D. P., Ramaraj, R., & Christabel, S. C. (2015). *Intelligent MPPT control technique for solar PV system*. ResearchGate. https://www.researchgate.net/publication/283228341_Intelligent_MPPT_control_technique_for_solar_PV_system

[12] Singh, V. K., Bhoi, A. K., Saxena, A., Zobaa, A. F., & Biswal, S. (Eds.). (2021). *Renewable energy and future power systems*. Springer Nature Singapore. https://doi.org/10.1007/978-981-33-6753-1

[13] ScienceDirect. (n.d.). *Microinverters*. https://www.sciencedirect.com/topics/engineering/microinverters

[14] Lozanova, S. (2025, April 29). *Guide to a solar energy diagram: Uses and applications*. GreenLancer. https://www.greenlancer.com/post/solar-energy-diagram

[15] Shukir, S. S. (2021). Solar system inverters types. *Journal of Advances in Electrical Devices, 6*(3), 24–31. Retrieved from: http://www.matjournals.com

[16] Zhang, Y., Wijeratne, L., Talebi, S., & Lary, D. J. (2021). *Schematic depicting the solar zenith angle, solar altitude angle, and solar azimuth angle*. Sensors. https://www.researchgate.net/figure/Schematic-depicting-the-solar-zenith-angle-solar-altitude-angle-and-solar-azimuth-angle_fig2_354755033

[17] ScienceDirect. (n.d.). *Global horizontal irradiance*. https://www.sciencedirect.com/topics/engineering/global-horizontal-irradiance

[18] Solar resource map © 2021 Solargis https://solargis.com

[19] Kuga Electrical. (n.d.). *Optimum solar panel angle: A guide*. https://www.13kuga.com.au/solar-panel-orientation-vs-production/

[20] M. El-Kassaby, Monthly and daily optimum tilt angle for south facing solar collectors; theoretical model, experimental and empirical correlations, Sol. Wind Technol. vol. 5 (6) (1988) 589–596.

[21] I.H. Rowlands, B.P. Kemery, I. Beausoleil-Morrison, Optimal solar-PV tilt angle and azimuth: An Ontario (Canada) case-study, Energy Policy vol. 39 (3) (2011) 1397–1409.

[22] Open Electrical. (n.d.). *Solar production: Which location is best for solar panels in your home?* https://www.openelectrical.com.au/solar-production-which-location-is-best-for-solar-panels-in-your-home/

[23] Liu, K. (2024, May 13). *How to find the best orientation and angle of solar panels?* Renogy. https://www.renogy.com/learning-center/how-to-find-the-best-orientation-and-angle-of-solar-panels

[24] Z. R. Dogaheh and V. Puig, "Tilt Angle Optimization of Photovoltaic Panels," *2019 6th International Conference on Control, Decision and Information Technologies (CoDIT)*, Paris, France, 2019, pp. 1847-1852

[25] Arbi Gharakhani Siraki, Pragasen Pillay, Study of optimum tilt angles for solar panels in different latitudes for urban applications, Solar Energy, Volume 86, Issue 6, 2012, Pages 1920-1928. https://www.sciencedirect.com/science/article/pii/S0038092X12000953

[26] Rufy Roof Engineering. (n.d.). *Photovoltaic structures – RRE PV – EAST WEST*. https://photovoltaic-structures.com/photovoltaic-structures-rre-pv-east-west/

[27] Sheffield Solar's Microgen Database. http://www.microgen-database.org.uk/

[28] Eoghan McKenna, Jacquelyn Pless, Sarah J. Darby, Solar photovoltaic self-consumption in the UK residential sector: New estimates from a smart grid demonstration project, Energy Policy, Volume 118, 2018, Pages 482-491. https://www.sciencedirect.com/science/article/pii/S0301421518302222

[29] ACCIONA Energía. (2023, January 31). *The pros of having your own rooftop solar panels*. https://www.acciona.com.au/updates/stories/the-pros-of-having-your-own-rooftop-solar-panels

[30] Solar Electric Supply. (n.d.). *Sloped roof Sharp solar panel system with tilt-up kit – Wisconsin*. https://www.solarelectricsupply.com/sloped-roof-tilt-up-comp-shingle-wisconsin-solar-system

[31] Gobierno de España. (2019). *Real Decreto 244/2019, de 5 de abril, por el que se regulan las condiciones administrativas, técnicas y económicas del autoconsumo de energía eléctrica.* Boletín Oficial del Estado, nº 83. https://www.boe.es/eli/es/rd/2019/04/05/244

[32] Gobierno de España. (2020). *Real Decreto 1183/2020, de 29 de diciembre, de acceso y conexión a las redes de transporte y distribución de energía eléctrica.* Boletín Oficial del Estado, nº 340. https://www.boe.es/eli/es/rd/2020/12/29/1183

[33] Asociación Española de Normalización (UNE). (2019). *UNE-EN 50549-1:2019: Requisitos para la conexión de generadores al sistema de distribución de baja tensión. Parte 1: Generadores hasta e incluyendo 16 A por fase.*

[34] Agencia Andaluza de la Energía. (2021). *Plan Integral de Fomento para el Autoconsumo Energético en Andalucía 2021-2030.* Junta de Andalucía. https://www.agenciaandaluzadelaenergia.es/actualidad/plan-integral-autoconsumo-andalucia

[35] Gobierno de España. (2021). *Ley 7/2021, de 20 de mayo, de cambio climático y transición energética.* Boletín Oficial del Estado, nº 121. https://www.boe.es/eli/es/l/2021/05/20/7
[36] European Commission. (n.d.). *GrowSmarter Project – Smart solutions for a sustainable future.* https://grow-smarter.eu
[37] International Energy Agency. (2023). *Renewables 2023: Analysis and forecast to 2028.* Paris: IEA. https://www.iea.org/reports/renewables-2023
[38] Unión Española Fotovoltaica (UNEF). (2023). *Informe Anual: El sector fotovoltaico español.* UNEF. https://unef.es
[39] European Commission. (2022). *Energy Communities: Unlocking the potential of citizens in the energy transition.* https://energy.ec.europa.eu/topics/markets-and-consumers/energy-communities_en
[40] International Renewable Energy Agency (IRENA). (2023). *Solar Energy: A key pillar of the global energy transition.* IRENA. https://www.irena.org/publications
[41] BloombergNEF, *PV Module Bankability Report 2023*. https://about.bnef.com
[42] LONGi, *Product Portfolio and Technology Overview*, 2023. https://www.longi.com/en
[43] The Climate Group, *RE100 Members*, 2023. https://www.there100.org
[44] LONGi, *Warranty and Certifications*, 2023. https://www.longi.com/en/download/
[45] Huawei, *About FusionSolar Smart PV*, 2023. https://solar.huawei.com
[46] Huawei, *Smart PV Solutions for Residential and C&I Applications*, 2023. https://solar.huawei.com/eu
[47] TÜV Rheinland, *Efficiency and Reliability Certifications for Huawei Inverters*, 2022. https://www.tuv.com
[48] HIS Markit, *Global PV Inverter Market Tracker*, 2023. https://ihsmarkit.com
[49] International Energy Agency (IEA). (2024). *Renewable Energy Market Update: 2024*. https://www.iea.org/reports/renewable-energy-market-update-2024
[50] International Renewable Energy Agency. (n.d.). *Solar energy*. https://www.irena.org/Energy-Transition/Technology/Solar-energy
[51] Fundación Renovables. (n.d.). *Bonificaciones fiscales en Mijas, Málaga, Andalucía*. https://fundacionrenovables.org/autoconsumo/ibi-icio-iae/bonificaciones-ibi-icio-iae-mijas-malaga-andalucia.html
[52] Ayuntamiento de Málaga. (n.d.). *ICIO: Bonificación por obras de especial interés para instalación de sistemas de aprovechamiento de energía solar*. https://sede.malaga.eu/es/tramitacion/detalle-del-tramite/index.html?id=9999&tipoVO=5
[53] Fimax Asesores. (n.d.). *Subvenciones para instalar placas solares en empresas 2024*. https://www.fimax.es/en/subvenciones-instalar-placas-solares-empresas/

[54] Iberdrola. (n.d.). Deducción del IRPF por instalar placas solares. http://iberdrola.es/eu/blog/autoconsumo/deduccion-irpf-placas-solares
[55] Agencia Estatal de Administración Tributaria. (n.d.). ¿En qué periodo impositivo puedes aplicar la deducción? https://sede.agenciatributaria.gob.es/Sede/vivienda-otros-inmuebles/deducciones-obras-mejora-eficiencia-energetica-viviendas/deduccion-obras-rehabilitacion-energetica/que-periodo-impositivo-puedes-aplicar-deduccion.html
[56] Agencia Estatal de Administración Tributaria. (n.d.). Deduction for works to reduce heating and cooling demand. Retrieved May 21, 2025, from https://sede.agenciatributaria.gob.es/Sede/irpf/campana-renta/deducciones-eficiencia-energetica/deduccion-obras-reduccion-demanda-calefaccion-refrigeracion.html

[57] Eurostat (2024). Electricity prices for household consumers - bi-annual data (from 2007 onwards) [Data set]. https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_204/default/table?lang=en

[58] United Nations. (n.d.). *Teaching the Sustainable Development Goals*. https://www.un.org/es/teach/SDGs

[59] UNEF. (2022, January 31). *Photovoltaic self-consumption installed in Spain grew by more than 100% in 2021*. https://www.unef.es/en/comunicacion/comunicacion-post/photovoltaic-self-consumption-installed-in-spain-grew-by-more-than-100-in-2021

[60] Global Solar Council. (2023, March 1). *Photovoltaic self-consumption installed in Spain grew by 108% compared to 2021*. https://www.globalsolarcouncil.org/news/photovoltaic-self-consumption-installed-in-spain-grew-by-108-compared-to-2021/

[61] Renewables Now. (2024, February 20). *Spain's solar self-consumption growth slows to 1.9 GW in 2023*. https://renewablesnow.com/news/spains-solar-self-consumption-growth-slows-to-19-gw-in-2023-846380/

[62] PV Magazine. (2025, January 24). *Spain's rooftop PV installations hit 1.18 GW in 2024*. https://www.pv-magazine.com/2025/01/24/spains-rooftop-pv-installations-hit-1-18-gw-in-2024/

[63] Reuters. (2024, May 28). *Rooftop solar outlook dims in Spain amid lower energy prices*. https://www.reuters.com/sustainability/climate-energy/rooftop-solar-outlook-dims-spain-amid-lower-energy-prices-2024-05-28/

[64] PV Know How. (2024, January 25). *Spain's self-consumption PV expands by 1.4GW*. https://www.pvknowhow.com/news/spains-self-consumption-pv-expands-by-1-4gw/

[65] PV Tech. (2024, January 26). *Spain adds 1.4GW of self-consumption PV in 2024*. https://www.pv-tech.org/spain-adds-1-4gw-of-self-consumption-pv-in-2024/

ANNEX I. STRUCTURAL OVERLOAD JUSTIFICATION

Occupied surface:

$$Number\ of\ modules = 10$$

$$Occupied\ surface\ per\ module = 2.278 \cdot 1.134 \cdot \cos 35 = 2.12\ m^2$$

$$Total\ occupied\ surface = 2.12 \cdot 10 = 21.2\ m^2$$

Total weight:

$$Weight\ of\ module = 27.5\ kg$$

$$Weight\ of\ structure \approx 3\ kg/panel \approx 30\ kg$$

$$Weight\ of\ foundation \approx 225\ kg$$

$$Total\ weight = 27.5 \cdot 10 + 30 + 225 = 530\ kg = 5199.3\ N$$

Overload:

$$L_{uniform} = \frac{Force}{Surface} = \frac{5199.3}{21.2} = 245.25\ N/m^2$$

In this case, being 2008 the construction year of the house, the maximum allowed overload is of 1 kN/m^2, according to the CTE DBSE-AE Standard shown in *Table 21*. The load of the structure that is meant to be placed in the household's roof is of 0.2 kN/m^2. Therefore, it is determined that the building structure is fully capable of withstanding the load in the new configuration.

ANNEX II. ELECTRICAL CALCULATIONS

SOLAR PANEL DATA														
MODEL	Nominal power (W)	Isc (A)	Voc (V)	Impp (A)	Vmpp (V)	Temperature coefficient of Isc	Temperature coefficient of Voc	Max Fuse Rating (A)	Vmp (-10ºC) (V)	Vmp (60ºC) (V)	Voc (-10ºC) (V)	Isc (60ºC) (A)	Impp (60ºC) (A)
LONGI LR5-72HPH-550M	550	13,98	49,8	13,12	41,95	0,050	-0,265	25	45,84	38,06	54,42	14,22	13,35

INVERTER DATA													
MODEL	Input Data								Output Data				
	Max. input voltage (V)	Max. input current per MPPT (A)	Max. short-circuit current (A)	Start-up voltage (V)	Max. input voltage per MPPT (V)	Number of MPPT	Strings per MPPT	Number of strings	Rated output power (W)	Max. apparent power (VA)	Voltage (V)	Nominal current (A)	Max. current (A)
HUAWEI SUN2000-5KTL-M1	1100	13,5	19,5	200	980	2	1	2	5000	5500	400	7,25	8,5

VOLTAGE DROP CALCULATIONS AND MAXIMUM ADMISSIBLE CURRENT COMPROBATION

DC CALCULATIONS																											
String lenths						Voltage results						Current results							Cross-section areas of conductors, protections and voltage drops								
MPPT	String	Modules (n)	Lenght (m)	Drop (m)	Total lenght (m)	Voltage (Voc) (V)	Max. voltage input (V)	Min. MPP voltage (V)	Start-up voltage (V)	Max. MPP voltage (V)	Max. adm. MPP voltage (V)	Current (A)	I cal (A) 1,1·1,25·Isc STC	MPP current (A)	Max. MPP current (A)	Short-circuit current (A)	S-C MPP current (A)	Max. S-C MPP current (A)	Conductor	S (mm²)	Type	Installation method	I max (A)	Protection	Rating (A)	Conductivity (m/Ωmm2)	Drop (V)	Drop (%)
MPPT 01	STRING 1.01	10	30,00	10,00	40,00	544,19	1.100,00	380,59	200,00	458,41	980,00	13,35	19,22	13,35	13,50	14,22	14,22	19,50	CU	6,00	DC	B1	46,00	FUSIBLE gPV	25,00	44,00	5,06	1,103 %
MPPT 02	STRING 1.02				-	-	1.100,00	-	200,00	-	980,00			-	13,50		-	19,50										

AC CALCULATIONS																						
Section	Lenght (m)	Voltage (V)	Type	Installation method	Power (W)	Nominal current (A)	Max. Current (A)	I cal (A) 1,25*I	*Conductor*	*Phase conductors*	*Neutral conductors*	*S phase (mm2)*	*S neutral (mm2)*	*I max (A)*	*Parallel circ. corr. factor*	*I max corrected (A)*	*Protection*	*Rating (A)*	*Max. rating (R.E.B.T) (A)*	*Conductivity (m/Ωmm2)*	Drop (V)	Drop (%)	Total drop (%)
Inverter - PV PB	5,00	400	THREE-PHASE	B1	5.000,00	7,25	8,50	10,63	CU	1	1	4,00	4,00	32,00	1,00	32,00	AUT MODULAR	16,00	32,00	44,00	0,36	0,089%	0,178%
PV PB - AC PB	5,00	400	THREE-PHASE	B1	5.000,00	7,25	8,50	10,63	CU	1	1	4,00	4,00	32,00	1,00	32,00	AUT MODULAR	16,00	32,00	44,00	0,36	0,089%	

ANNEX III. PVSYST SIMULATION REPORT

PVsyst - Simulation report

Grid-Connected System

Project: ISFV Mijas TFG

Variant: 5,5 kWp 5 kWn 35 South Scenario 2

Sheds on ground

System power: 5.50 kWp

Mijas_ISF_TFG - Spain

Author

PVsyst V8.0.7
VCM, Simulation date:
25/03/25 13:20
with V8.0.7

Project summary

Geographical Site	Situation		Project settings	
Mijas_ISF_TFG	Latitude	36.54 °N	Albedo	0.20
Spain	Longitude	-4.71 °W		
	Altitude	102 m		
	Time zone	UTC		

Weather data
Mijas_ISF_TFG
PVGIS api TMY

System summary

Grid-Connected System
Simulation for year no 1

Sheds on ground

Orientation #1
Fixed plane
Tilt/Azimuth 35 / 0 °

Near Shadings
Linear shadings : Fast (table)

User's needs
Monthly values

System information

PV Array		Inverters	
Nb. of modules	10 units	Nb. of units	1 unit
Pnom total	5.50 kWp	Pnom total	5.00 kWac
		Pnom ratio	1.100

Results summary

Produced Energy	9918.5 kWh/year	Specific production	1803 kWh/kWp/year	Perf. Ratio PR	79.20 %
Used Energy	9500.4 kWh/year			Solar Fraction SF	39.55 %

Table of contents

General parameters

Grid-Connected System — Sheds on ground

Orientation #1

Fixed plane		Sheds configuration		Sizes	
Tilt/Azimuth	35 / 0 °	Nb. of sheds	2 units	Sheds spacing	0.00 m
		Set of tables		Collector width	2.29 m
		Shading limit angle		Average GCR	%
		Limit profile angle	°	Top inactive band	0.02 m
				Bottom inactive band	0.02 m

Models used		Horizon		Near Shadings
Transposition	Perez	Average Height	5.9 °	Linear shadings : Fast (table)
Diffuse	Imported			
Circumsolar	separate			

User's needs
Monthly values

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year	
0.61	0.55	0.58	0.68	0.65	0.98	1.24	1.28	1.08	0.67	0.58	0.59	9.50	MWh/mth

PV Array Characteristics

PV module		Inverter	
Manufacturer	Generic	Manufacturer	Generic
Model	LR5-72HPH-550M G2	Model	SUN2000-5KTL-M1-400V
(Original PVsyst database)		(Original PVsyst database)	
Unit Nom. Power	550 Wp	Unit Nom. Power	5.00 kWac
Number of PV modules	10 units	Number of inverters	2 * MPPT 50% 1 unit
Nominal (STC)	5.50 kWp	Total power	5.0 kWac
Modules	2 string x 5 In series	Operating voltage	140-980 V
At operating cond. (50°C)		Max. power (=>50°C)	5.50 kWac
Pmpp	5.04 kWp	Pnom ratio (DC:AC)	1.10
U mpp	189 V	No power sharing between MPPTs	
I mpp	27 A		

Total PV power		Total inverter power	
Nominal (STC)	6 kWp	Total power	5 kWac
Total	10 modules	Number of inverters	1 unit
Module area	25.8 m²	Pnom ratio	1.10
Cell area	24.0 m²		

Array losses

Array Soiling Losses		Thermal Loss factor		DC wiring losses	
Loss Fraction	3.0 %	Module temperature according to irradiance		Global array res.	117 mΩ
		Uc (const)	29.0 W/m²K	Loss Fraction	1.5 % at STC
		Uv (wind)	0.0 W/m²K/m/s		

LID - Light Induced Degradation		Module Quality Loss		Module mismatch losses	
Loss Fraction	1.5 %	Loss Fraction	-0.3 %	Loss Fraction	2.0 % at MPP

Array losses

Module average degradation

Year no 1
Loss factor 0.46 %/year
Imp / Vmp contributions 80% / 20%

Mismatch due to degradation

Imp RMS dispersion 0 %/year
Vmp RMS dispersion 0 %/year

IAM loss factor

Incidence effect (IAM): User defined profile

0°	25°	45°	60°	65°	70°	75°	80°	90°
1.000	1.000	0.995	0.962	0.936	0.903	0.851	0.754	0.000

System losses

Auxiliaries loss

Proportional to Power 3.0 W/kW
0.0 kW from Power thresh.

AC wiring losses

Inv. output line up to injection point

Inverter voltage 400 Vac tri
Loss Fraction 0.00 % at STC
Inverter: SUN2000-5KTL-M1-400V
Wire section (1 Inv.) Alu 1 x 3 x 3 mm²
Wires length 0 m

Horizon definition

Horizon from PVGIS website API, Lat=36°32'17", Long=-4°42'51", Alt=102m

Average Height	5.9 °	Albedo Factor	0.52
Diffuse Factor	0.92	Albedo Fraction	100 %

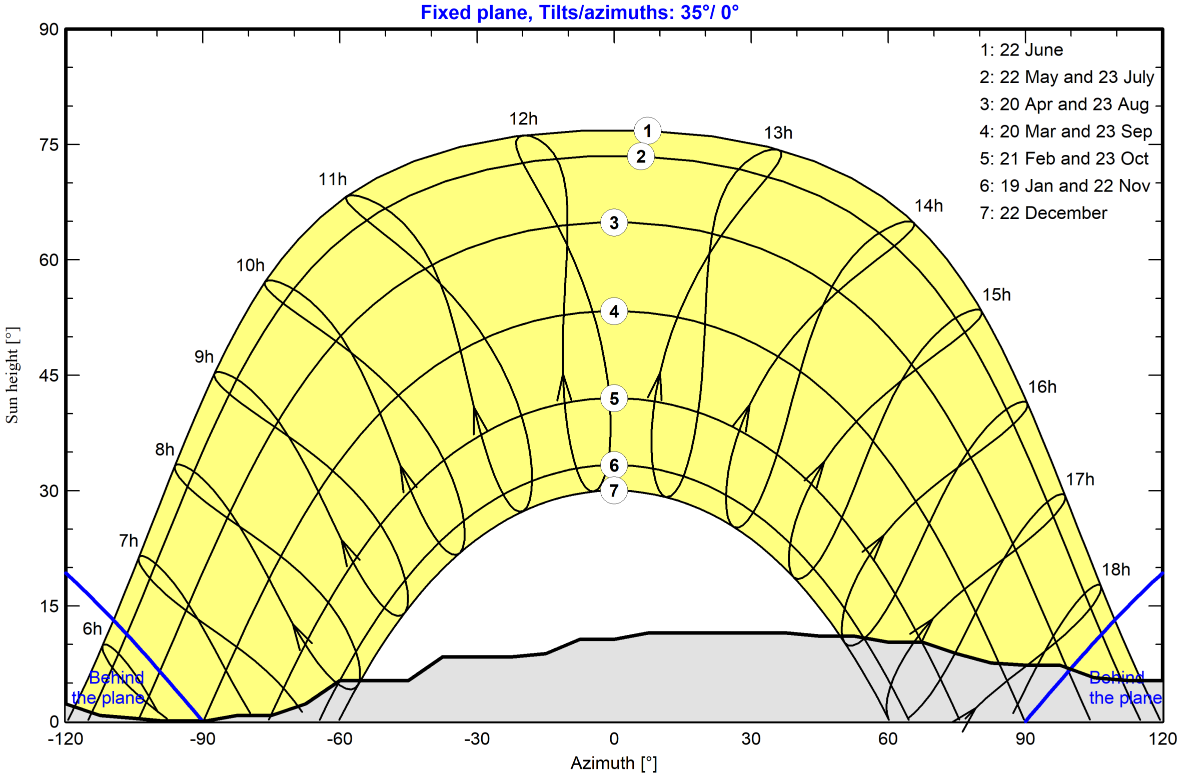
Horizon profile

Azimuth [°]	-180	-173	-165	-158	-150	-143	-135	-128	-120	-113	-105	-98	-90	-83
Height [°]	1.5	2.3	4.2	6.1	6.1	5.3	3.4	3.4	2.3	0.8	0.4	0.0	0.0	0.8
Azimuth [°]	-75	-68	-60	-45	-38	-23	-15	-8	0	8	38	45	53	60
Height [°]	0.8	2.3	5.3	5.3	8.4	8.4	8.8	10.7	10.7	11.5	11.5	11.1	11.1	10.3
Azimuth [°]	68	75	83	90	98	105	113	135	143	150	158	165	173	180
Height [°]	10.3	8.8	7.6	7.3	7.3	5.7	5.3	5.3	5.7	3.8	3.1	2.3	1.5	1.5

Sun Paths (Height / Azimuth diagram)

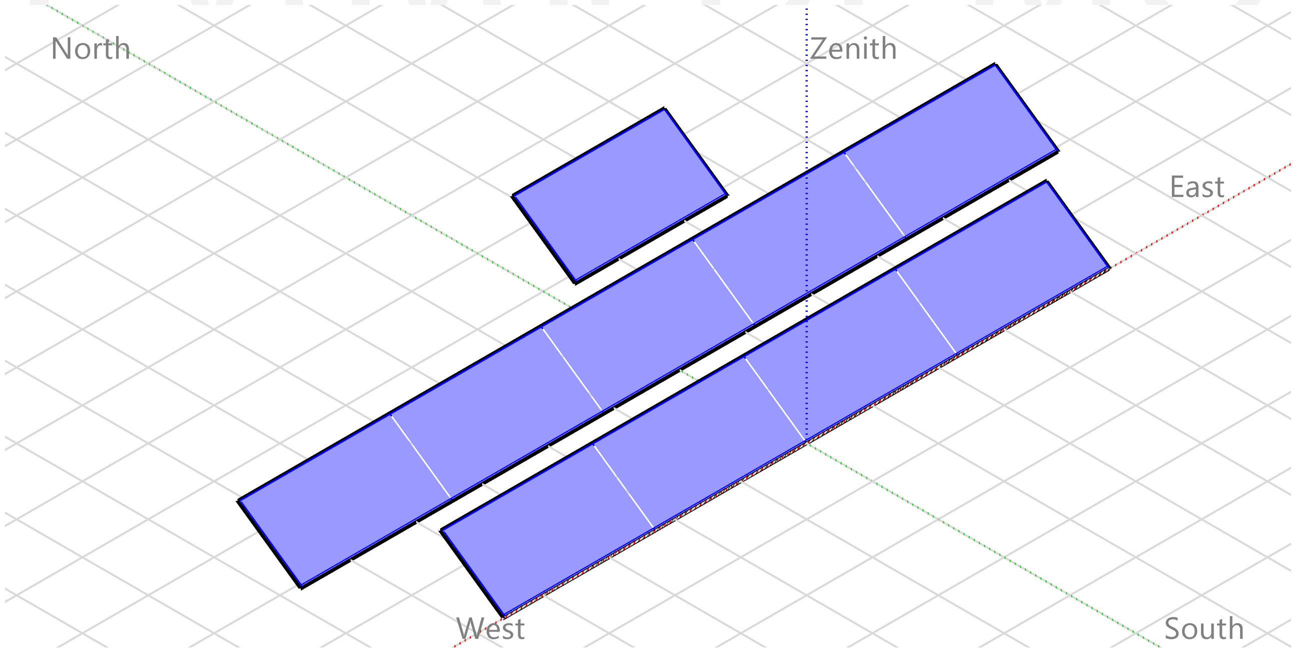
Orientation #1

Fixed plane, Tilts/azimuths: 35°/ 0°



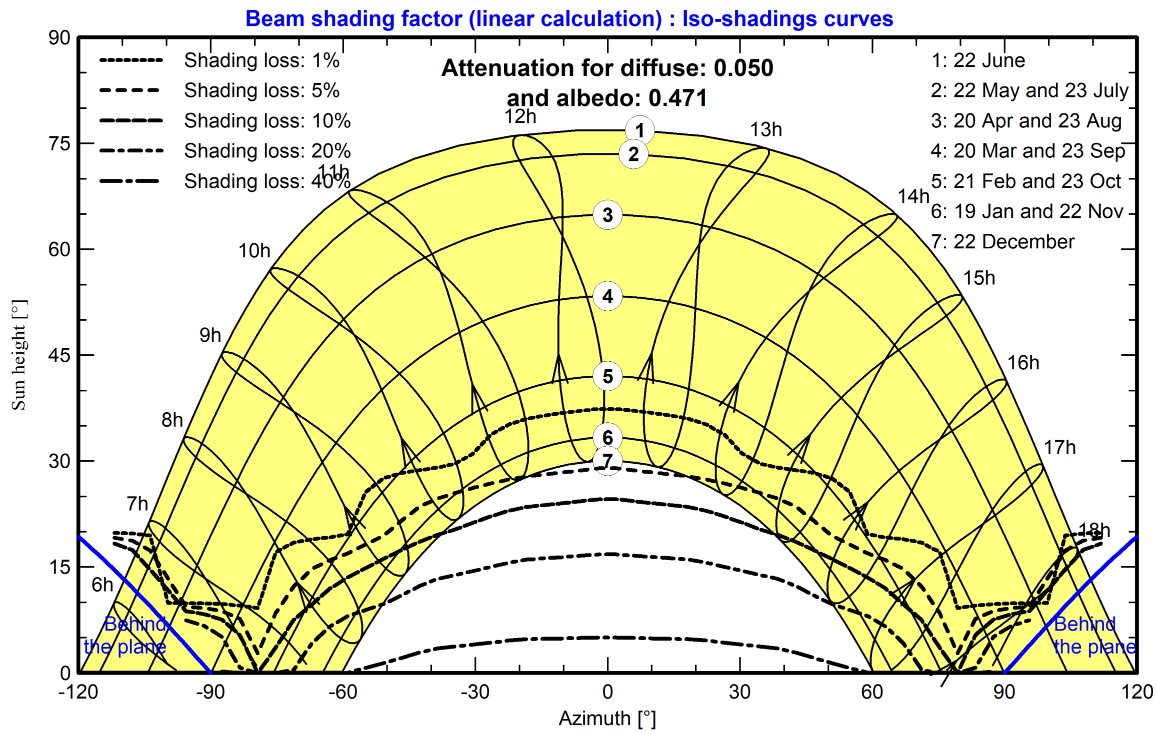
Near shadings parameter

Perspective of the PV-field and surrounding shading scene



Iso-shadings diagram

Orientation #1 - Fixed plane, Tilts/azimuths: 35°/ 0°

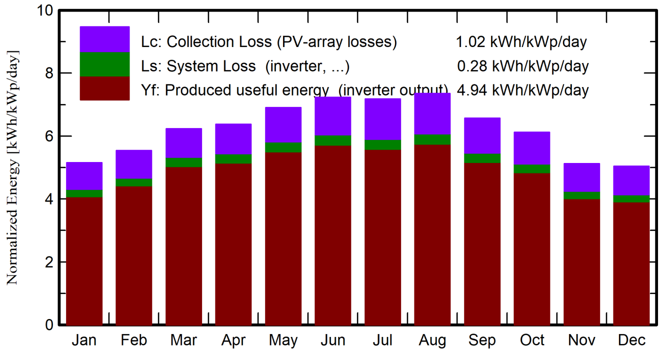


Main results

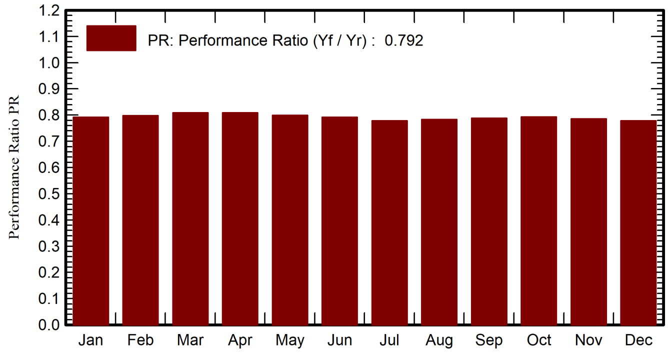
System Production

Produced Energy	9918.5 kWh/year	Specific production	1803 kWh/kWp/year
Used Energy	9500.4 kWh/year	Perf. Ratio PR	79.20 %
		Solar Fraction SF	39.55 %

Normalized productions (per installed kWp)



Performance Ratio PR



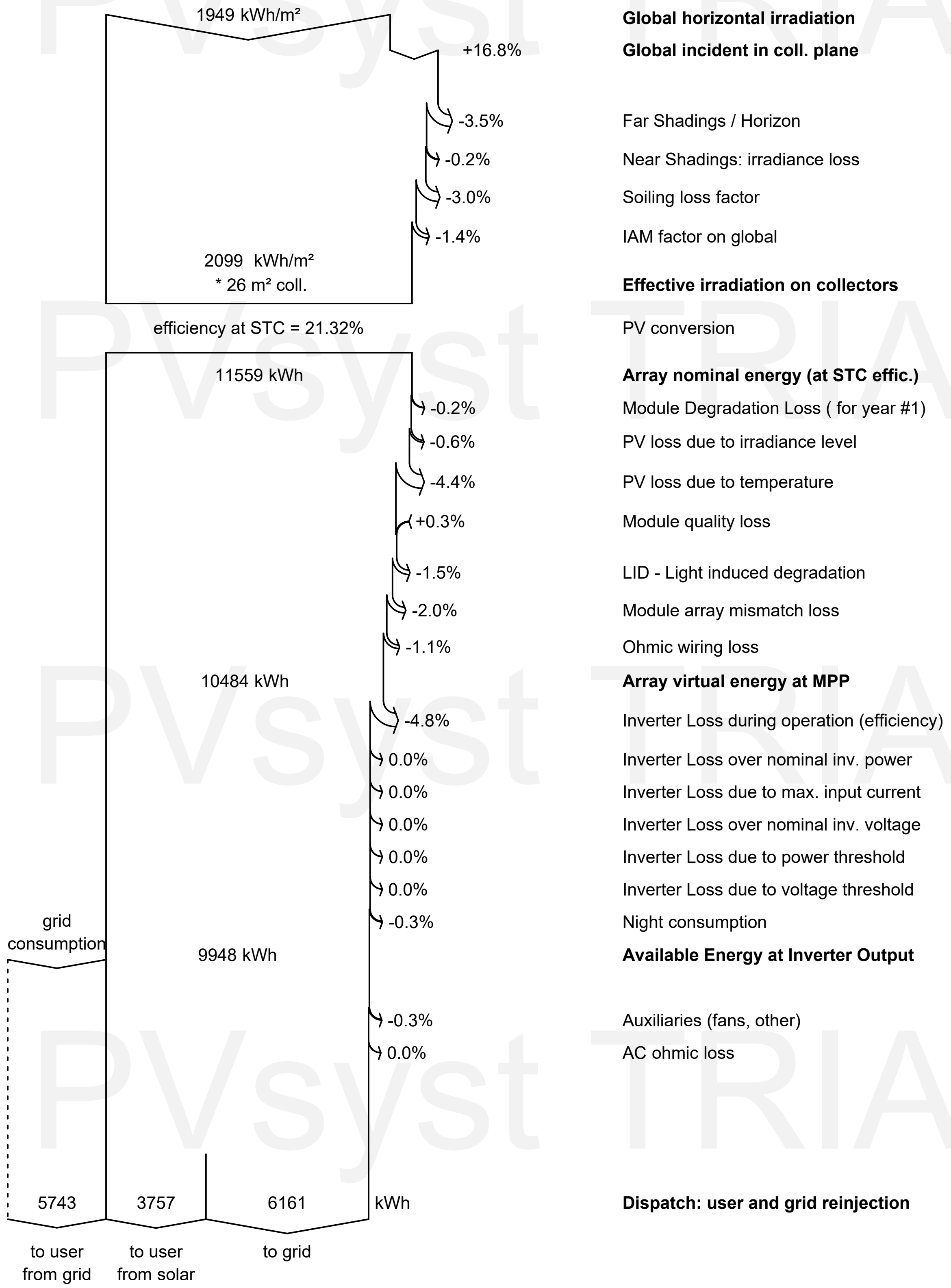
Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_User kWh	E_Solar kWh	E_Grid kWh	EFrGrid kWh
January	92.5	26.79	11.07	159.8	143.3	736	611	204	492	407
February	104.4	32.72	9.96	155.2	140.3	721	550	188	493	362
March	155.8	52.55	13.89	193.2	179.7	909	580	233	627	347
April	179.9	58.36	14.61	191.3	178.1	899	680	285	566	396
May	226.3	67.68	17.83	213.9	198.7	993	646	297	643	349
June	241.2	61.87	20.70	216.8	201.6	998	983	431	513	552
July	241.1	64.79	25.00	222.6	207.1	1007	1239	520	432	719
August	222.5	56.94	24.38	227.9	213.0	1036	1282	531	450	751
September	167.7	51.31	22.43	196.9	183.7	901	1084	419	434	665
October	136.5	44.01	19.49	189.6	175.4	873	667	258	569	409
November	95.3	32.03	16.15	153.5	139.1	702	585	194	469	390
December	86.0	27.20	13.72	156.2	138.5	707	593	196	472	397
Year	1949.3	576.24	17.49	2276.9	2098.6	10484	9500	3757	6161	5743

Legends

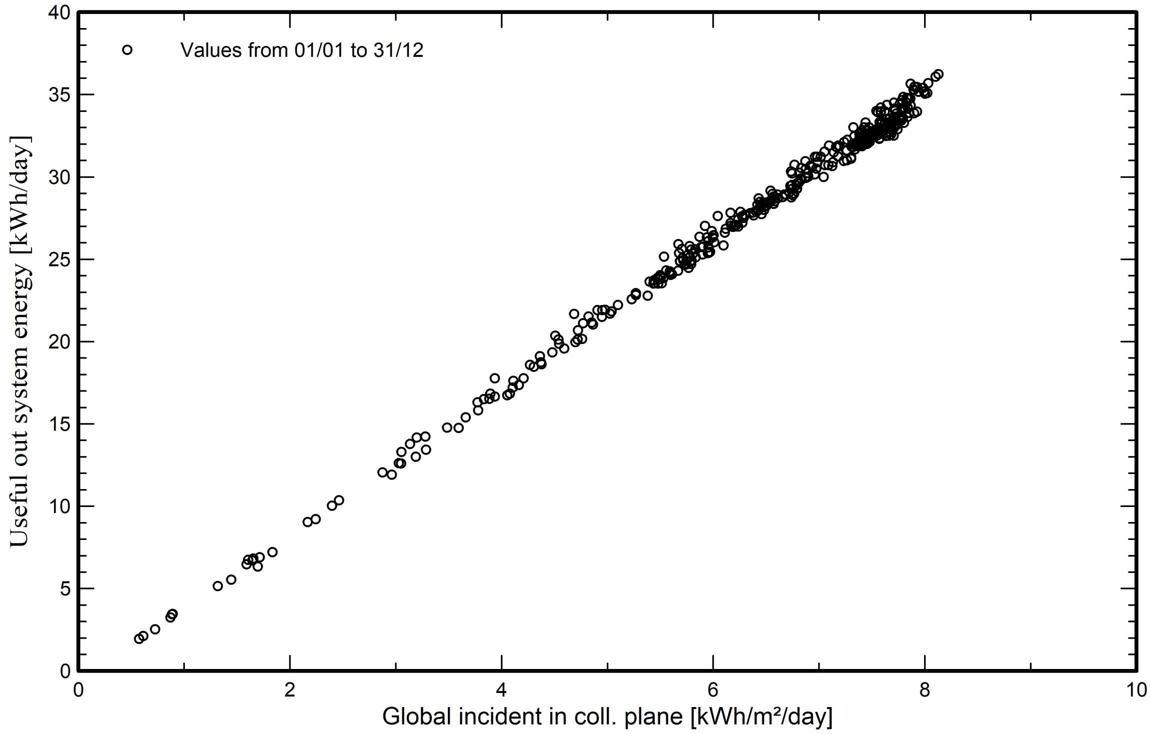
GlobHor	Global horizontal irradiation	EArray	Effective energy at the output of the array
DiffHor	Horizontal diffuse irradiation	E_User	Energy supplied to the user
T_Amb	Ambient Temperature	E_Solar	Energy from the sun
GlobInc	Global incident in coll. plane	E_Grid	Energy injected into grid
GlobEff	Effective Global, corr. for IAM and shadings	EFrGrid	Energy from the grid

Loss diagram

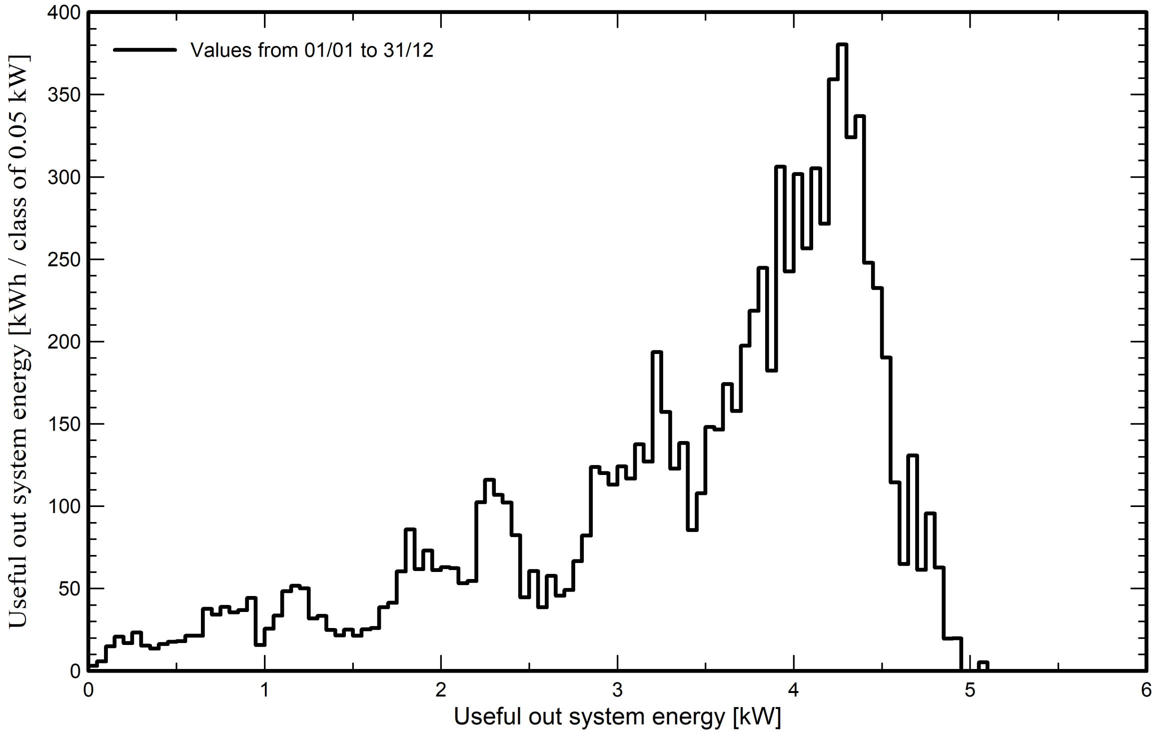


Predef. graphs

Daily Input/Output diagram

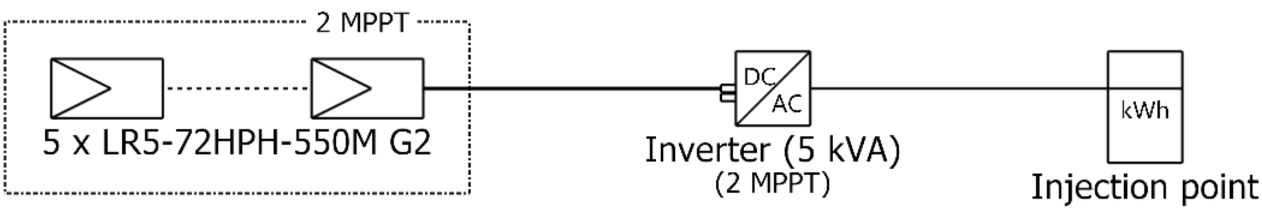


System Output Power Distribution



Single-line diagram

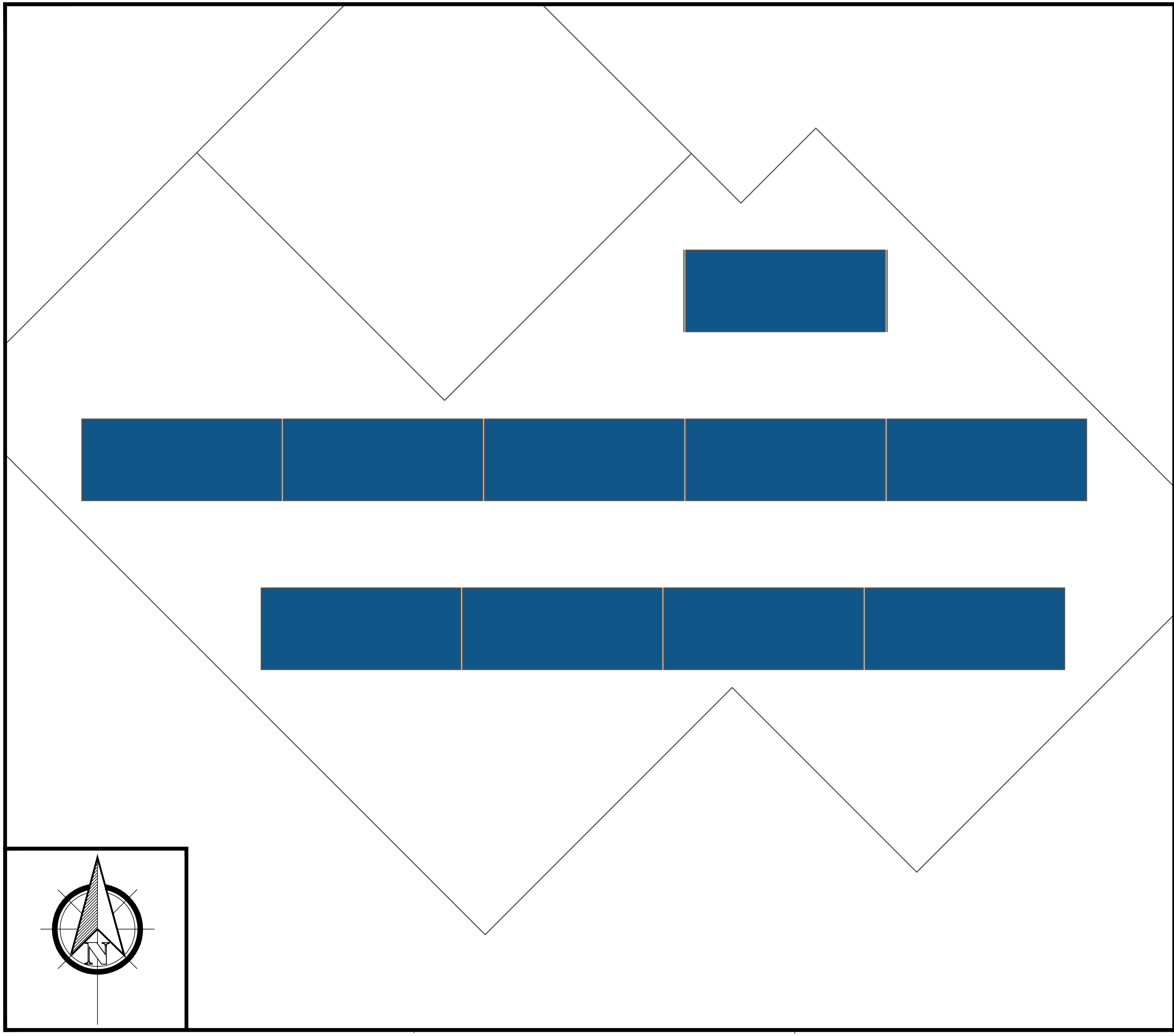
PVsyst V8.0.7
VCM, Simulation date:
25/03/25 13:20
with V8.0.7



PV module	LR5-72HPH-550M G2
Inverter	SUN2000-5KTL-M1-400V
String	5 x LR5-72HPH-550M G2

ISFV Mijas TFG	
VCM : 5,5 kWp 5 kWn 35 South Scenario 2	25/03/25

ANNEX IV. TECHNICAL DRAWINGS



LEGEND

Solar panels LONGi
LR5-72HPH-555M 550Wp

Number of modules: 10
Power of module: 550 Wp
Peak power: 5500 Wp
Nominal power: 5000 Wn

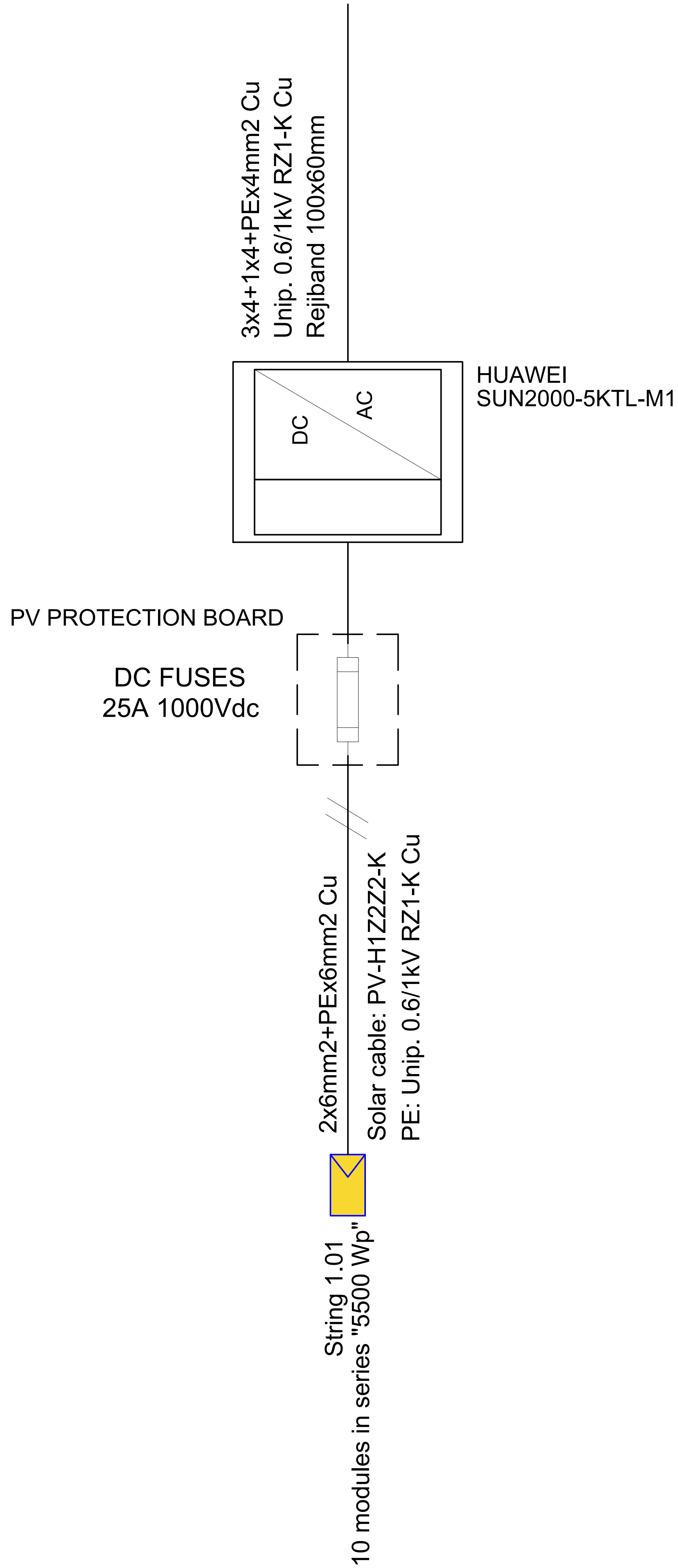
Date	Description	Revision
10/07/2025	Technical drawings	00

ICAI

ISFV "MIJAS TFG"
5 kWn / 5.5 kWp

SOLAR PANELS LAYOUT

Location:	**Address:** Calle Entrelagos 11 **Municipality:** Mijas **Postal code:** 29649 **Province:** Málaga
Coordinates:	36º32'17.69"N 04º42'50.76"O
Drawing reference:	**2**
Project type:	**Bachelor's Thesis**
Project date:	10/07/2025
Scale:	NTS
Designed by: AMG	
Reviewed by:	



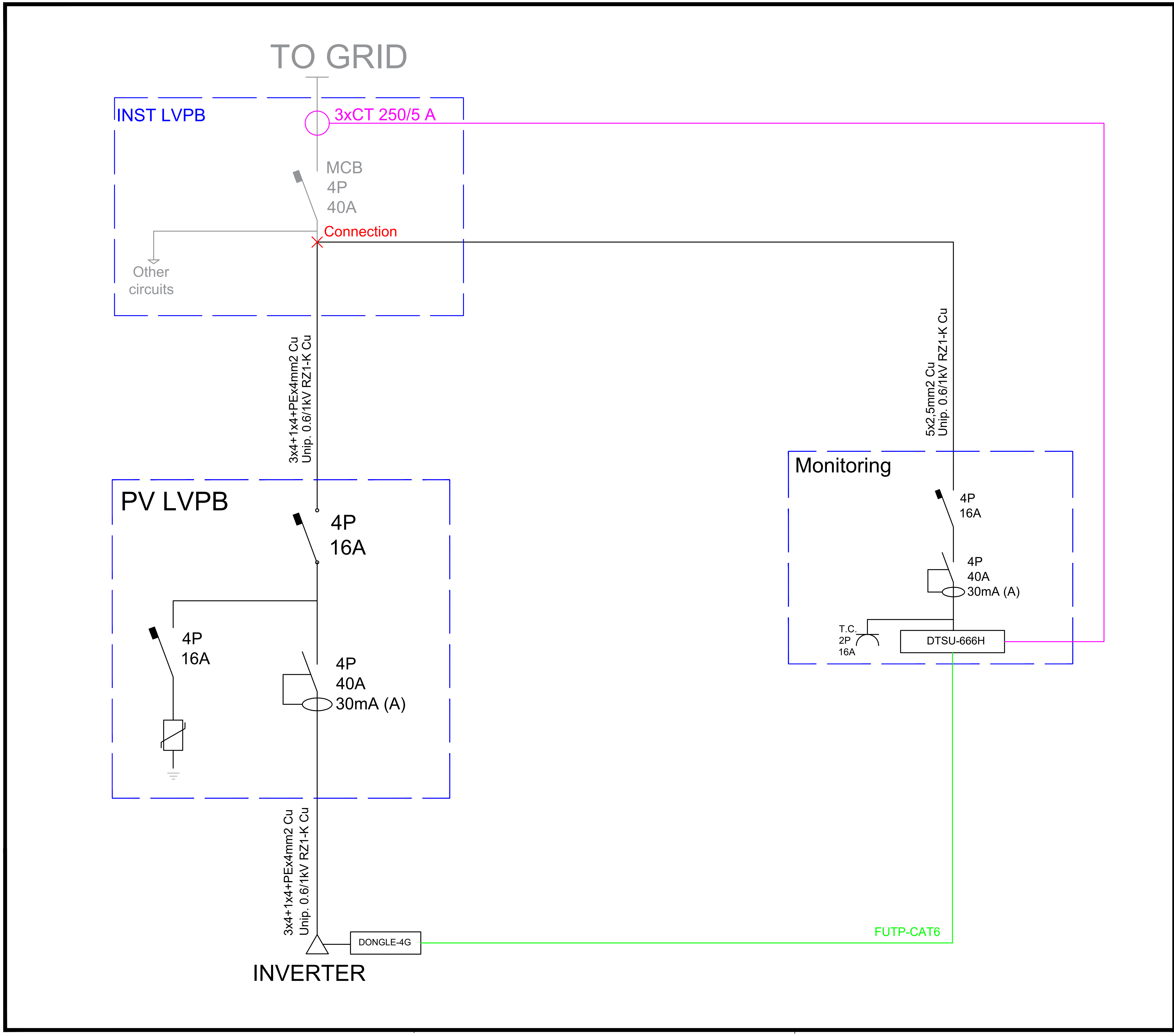
Date	Description	Revision
10/07/2025	Technical drawings	00

ICAI

ISFV "MIJAS TFG"
5 kWn / 5.5 kWp

UNIFILAR CC

Location:	**Address:** Calle Entrelagos 11 **Municipality:** Mijas **Postal code:** 29649 **Province:** Málaga
Coordinates:	36º32'17.69"N 04º42'50.76"O
Drawing reference:	**3.1**
Project type:	**Bachelor's Thesis**
Project date:	10/07/2025
Scale:	NTS
Designed by: AMG	
Reviewed by:	



Date	Description	Revision
10/07/2025	Technical drawings	00

ICAI

ISFV "MIJAS TFG"
5 kWn / 5.5 kWp

UNIFILAR AC

Location:	**Address:** Calle Entrelagos 11 **Municipality:** Mijas **Postal code:** 29649 **Province:** Málaga
Coordinates:	36°32'17.69"N 04°42'50.76"O
Drawing reference:	**3.2**
Project type:	**Bachelor's Thesis**
Project date:	10/07/2025
Scale:	NTS
Designed by: AMG	
Reviewed by:	

ANNEX V. ALIGNMENT WITH SUSTAINABLE DEVELOPMENT GOALS

ALIGNMENT WITH SUSTAINABLE DEVELOPMENT GOALS

The Sustainable Development Goals are a set of 17 global objectives, shown in the following figure, which were established by the United Nations in 2015 as part of the 2030 Agenda for Sustainable Development. These goals aim to address the world's most pressing challenges, including poverty, inequality, environmental degradation and climate change, while fostering peace and justice. They provide a blueprint for governments, organisations and individuals to work together towards a more equitable and sustainable world by 2030. Each goal is interconnected, reflecting the complex nature of sustainable development, which requires balancing economic growth, social inclusion, and environmental protection. The SDGs serve as a global framework to guide governments, businesses, and individuals in their efforts to achieve a more sustainable and equitable future.

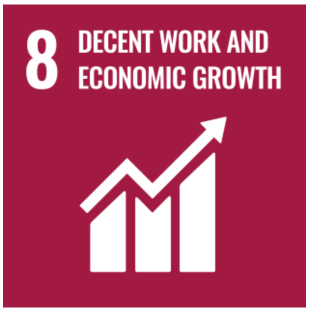
The primary goal a solar photovoltaic installation for self-consumption aligns with would be **SDG 7: Affordable and Clean Energy**. By providing clean and renewable electricity for residential use, photovoltaic installations ensure access to affordable, reliable, sustainable and modern energy for all. Solar PV systems harness energy from the sun, reducing reliance on fossil fuels. By enabling households to generate their electricity, the project contributes to increasing the share of renewable energy in the global energy mix. Furthermore, advancements in solar technology and the decrease in equipment costs thanks to mass production have made solar energy more accessible and affordable, supporting efforts to ensure reliable and sustainable energy for all. According to the PVsyst simulation, this PV installation will generate annually approximately between 10–11 MWh of clean and renewable electricity, avoiding the generation of such amount of energy by conventional and polluting power plants. In addition, the houseowner will save between 1000€–1300€ per year on energy costs, making it an affordable and economically attractive option.

Particularly linked to the one before, this project directly supports **SDG 13: Climate Action**. The adoption of solar photovoltaic systems significantly mitigates greenhouse gas emissions. Traditional energy production methods, such as coal and natural gas, release large amounts of CO_2 and other pollutants into the atmosphere. By switching to clean solar energy, this project contributes to lowering the carbon footprint of residential energy consumption. Considering an annual production of 10,484 kWh, a project lifespan of 25 years and that conventional energy generation units emit around 450 grams of CO_2 per kWh, this project avoids the emission of approximately 18 tonnes of CO_2 to the atmosphere, contributing to the fight against climate change and global warming.

The sustainability and resilience of urban and residential communities is also enhanced by this project, aligning with **SDG 11: Sustainable Cities and Communities**. By integrating solar energy solutions, households become less dependent on centralised energy grids and fossil fuels, making cities more adaptable to environmental and economic changes. The decentralised nature of solar energy systems fosters energy independence and increases the resilience of energy supplies during natural disasters or grid failures. With this solar power system, the household reduces its dependency on the grid and energy markets by around 40%, enhancing its resilience and sustainability.

Solar installations in residential areas encourage households to consume energy more responsibly by generating and managing their electricity. Homeowners often become more aware of their energy usage when they adopt solar power systems, leading to increased energy efficiency and reduced waste. By promoting self-consumption and reducing the dependence on non-renewable sources, this project aligns with **SDG 12: Responsible Consumption and Production**. Moreover, the absence of a battery storage system in this particular case incentivises the owner to manage the household loads in such a way that they demand power at times when the PV installation is producing energy, consequently reducing the surplus energy injection to the grid and avoiding congestions in the electric network.

To finish with the environmental and climate action related goals, one could argue that **SDG 15: Life on Land** is also enhanced by solar PV systems, which aims to protect, restore and promote sustainable use of terrestrial ecosystems, combat desertification, halt and reverse land degradation, and stop biodiversity loss. They help protect terrestrial ecosystems by reducing air pollution and environmental degradation associated with traditional energy production. As mentioned in the previous goals, solar energy production does not release harmful emissions, preserving air quality and promoting biodiversity. The widespread adoption of clean energy solutions also reduces the negative impact of resource extraction and pollution on land and natural habitats. Additionally, rooftop installations avoid land occupation, preserving natural habitats and agricultural land. In this way, the project aligns with the principles of sustainable land use and biodiversity conservation.



Moving into innovation and economic matters, it is well known that the solar energy sector is a significant driver of job creation in the green economy. This project supports **SDG 8: Decent Work and Economic Growth**, which promotes inclusive and sustainable economic growth, full and productive employment, and decent work for all by creating employment opportunities in areas such as system design, installation, maintenance and monitoring. The growth of the renewable energy industry stimulates economic development and provides decent work opportunities, contributing to a more sustainable and inclusive economy.

Finally, the development and deployment of solar photovoltaic systems promote technological innovation and contribute to building a modern and sustainable energy infrastructure. This project encourages the adoption of renewable technologies in the residential sector, fostering a culture of innovation. It also supports the growth of the green energy industry by stimulating the demand for renewable energy solutions and related services, stating clearly that it is aligned with **SDG 9: Industry, Innovation and Infrastructure**. Projects like this drive the development and adoption of clean technologies, strengthening local and national capacity for sustainable infrastructure. By implementing an innovative energy solution at the household level, this project helps lay the foundation for a more resilient, modern, and sustainable energy system.

The photovoltaic self-consumption system developed in this project aligns with the broader objectives of the United Nations Sustainable Development Goals by promoting a cleaner, more efficient, and more resilient energy model. Through the use of renewable energy at the household level, the project contributes to reducing greenhouse gas emissions, decreasing dependency on non-renewable resources, and supporting environmental preservation without occupying additional land.

Furthermore, the implementation of such systems encourages technological innovation and the development of modern energy infrastructure. It also supports the growth of a sustainable economy by creating opportunities for skilled employment in the renewable energy sector.

Overall, this project exemplifies how local, small-scale initiatives can contribute to global sustainability targets and demonstrates the role of engineering solutions in addressing the interconnected challenges of energy, environment, and development.

ANNEX VI. SOLAR PANELS DATASHEET

Hi-MO 5m

(G2)

LR5-72HPH
540~560M

- Based on M10-182mm wafer, best choice for ultra-large power plants
- Advanced module technology delivers superior module efficiency
  - M10 Gallium-doped Wafer • Smart Soldering • 9-busbar Half-cut Cell
- Excellent outdoor power generation performance
- High module quality ensures long-term reliability

12 — 12-year Warranty for Materials and Processing

25 — 25-year Warranty for Extra Linear Power Output

Complete System and Product Certifications

IEC 61215, IEC 61730, UL 61730

ISO9001:2015: ISO Quality Management System

ISO14001: 2015: ISO Environment Management System

ISO45001: 2018: Occupational Health and Safety

TS62941: Guideline for module design qualification and type approval

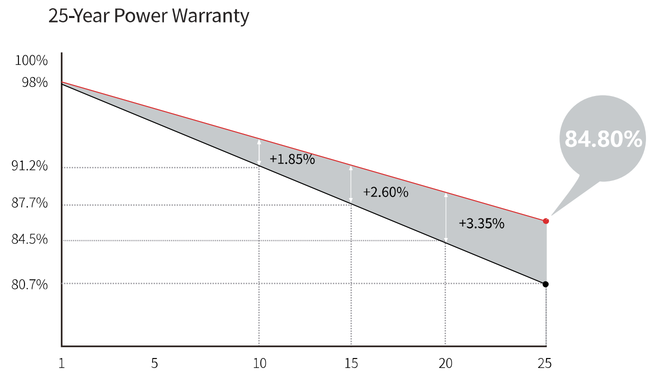
LONGi

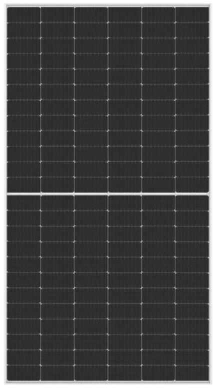
Hi-MO 5m

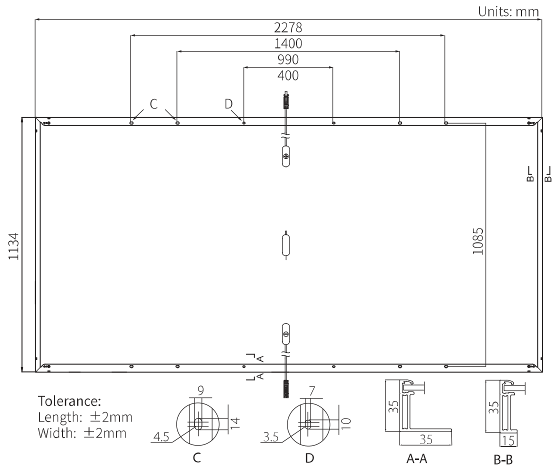
LR5-72HPH 540~560M

21.7%	0~3%	<2%	0.55%	HALF-CELL
MAX MODULE EFFICIENCY	POWER TOLERANCE	FIRST YEAR POWER DEGRADATION	YEAR 2-25 POWER DEGRADATION	Lower operating temperature

Additional Value







Mechanical Parameters

Cell Orientation	144 (6×24)
Junction Box	IP68, three diodes
Output Cable	$4mm^2$, +400, -200mm length can be customized
Connector	LONGi LR5 or MC4 EVO2
Glass	Single glass, 3.2mm coated tempered glass
Frame	Anodized aluminum alloy frame
Weight	27.5kg
Dimension	2278×1134×35mm
Packaging	31pcs per pallet / 155pcs per 20' GP / 620pcs per 40' HC

Electrical Characteristics

STC : AM1.5 1000W/m² 25°C NOCT : AM1.5 800W/m² 20°C 1m/s Test uncertainty for Pmax: ±3%

Module Type	LR5-72HPH-540M		LR5-72HPH-545M		LR5-72HPH-550M		LR5-72HPH-555M		LR5-72HPH-560M	
Testing Condition	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax/W)	540	403.6	545	407.4	550	411.1	555	414.8	560	418.6
Open Circuit Voltage (Voc/V)	49.50	46.54	49.65	46.68	49.80	46.82	49.95	46.97	50.10	47.11
Short Circuit Current (Isc/A)	13.85	11.20	13.92	11.25	13.98	11.31	14.04	11.35	14.10	11.40
Voltage at Maximum Power (Vmp/V)	41.65	38.69	41.80	38.83	41.95	38.97	42.10	39.11	42.25	39.25
Current at Maximum Power (Imp/A)	12.97	10.43	13.04	10.49	13.12	10.56	13.19	10.61	13.26	10.67
Module Efficiency(%)	20.9		21.1		21.3		21.5		21.7	

Operating Parameters

Operational Temperature	-40°C ~ +85°C
Power Output Tolerance	0 ~ 3%
Voc and Isc Tolerance	±3%
Maximum System Voltage	DC1500V (IEC/UL)
Maximum Series Fuse Rating	25A
Nominal Operating Cell Temperature	45±2°C
Protection Class	Class II
Fire Rating	UL type 1 or 2 IEC Class C

Mechanical Loading

Front Side Maximum Static Loading	5400Pa
Rear Side Maximum Static Loading	2400Pa
Hailstone Test	25mm Hailstone at the speed of 23m/s

Temperature Ratings (STC)

Temperature Coefficient of Isc	+0.050%/°C
Temperature Coefficient of Voc	-0.265%/°C
Temperature Coefficient of Pmax	-0.340%/°C

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ANNEX VII. INVERTER DATASHEET

Smart Energy Controller
SUN2000-3-10KTL-M1 (High Current Version)

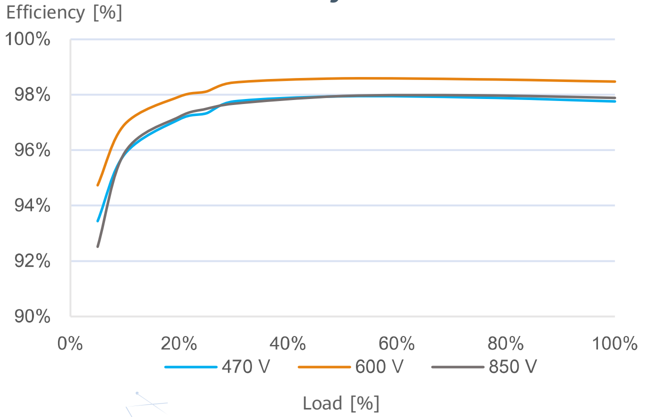
Active Safety
AI Powered
Active Arcing Protection

Higher Yields
Up to 30% More Energy
with Optimizer [1]

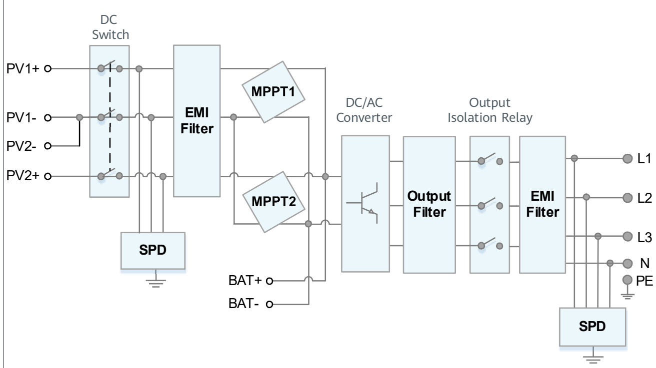
Battery Ready
Plug & Play battery interface [2]

Flexible Communication
WLAN, Fast Ethernet, 4G
Communication Supported

Efficiency Curve



Circuit Diagram



SUN2000-3/4/5/6/8/10KTL-M0/M1

*1 Only applicable to SUN2000-3/4/5/6/8/10KTL-M1 smart energy center.
*2. SUN2000-3/4/5/6/8/10KTL-M0 will be compatible with HUAWEI smart string ESS in Q1, 2021

Technical Specification

Technical Specification	SUN2000 -3KTL-M1	SUN2000 -4KTL-M1	SUN2000 -5KTL-M1	SUN2000 -6KTL-M1	SUN2000 -8KTL-M1	SUN2000 -10KTL-M1
Efficiency						
Max. efficiency	98.2%	98.3%	98.4%	98.6%	98.6%	98.6%
European weighted efficiency	96.7%	97.1%	97.5%	97.7%	98.0%	98.1%
Input (PV)						
Recommended max. PV power [1]	4,500 Wp	6,000 Wp	7,500 Wp	9,000 Wp	12,000 Wp	15,000 Wp
Max. input voltage [2]	1,100 V					
Operating voltage range [3]	140 V ~ 980 V					
Start-up voltage	200 V					
Rated input voltage	600 V					
Max. input current per MPPT	13.5 A					
Max. short-circuit current	19.5 A					
Number of MPP trackers	2					
Max. input number per MPP tracker	1					
Input (DC Battery)						
Compatible Battery	HUAWEI Smart String ESS 5kWh – 30kWh					
Operating voltage range	600 V ~ 980 V					
Max operating current	16.7 A					
Max charge Power	10,000 W					
Max discharge Power	3,300 W	4,400 W	5,500 W	6,600 W	8,800 W	10,000 W
Output (On Grid)						
Grid connection	Three-phase					
Rated output power	3,000 W	4,000 W	5,000 W	6,000 W	8,000 W	10,000 W
Max. apparent power	3,300 VA	4,400 VA	5,500 VA	6,600 VA	8,800 VA	11,000 VA [4]
Rated output voltage	220 Vac / 380 Vac, 230 Vac / 400 Vac, 3W / N+PE					
Rated AC grid frequency	50 Hz / 60 Hz					
Max. output current	5.1 A	6.8 A	8.5 A	10.1 A	13.5 A	16.9 A
Adjustable power factor	0.8 leading ... 0.8 lagging					
Max. total harmonic distortion	≤ 3 %					
Output (Off Grid)						
Backup Box	Backup Box – B1					
Maximum apparent power	3,000 VA	3,300 VA	3,300 VA	3,300 VA	3,300 VA	3,300 VA
Rated output voltage	220 V / 230 V					
Maximum output current	13.6 A	15 A	15 A	15 A	15 A	15 A
Power factor range	0.8 leading ... 0.8 lagging					
Features & Protections						
Input-side disconnection device	Yes					
Anti-Islanding protection	Yes					
DC reverse polarity protection	Yes					
Insulation monitoring	Yes					
DC surge protection	Yes, compatible with TYPE II protection class according to EN/IEC 61643-11					
AC surge protection	Yes, compatible with TYPE II protection class according to EN/IEC 61643-11					
Residual current monitoring	Yes					
AC overcurrent protection	Yes					
AC short-circuit protection	Yes					
AC overvoltage protection	Yes					
Arc fault protection	Yes					
Ripple receiver control	Yes					
Integrated PID recovery [5]	Yes					
Battery reverse charging from grid	Yes					
General Data						
Operating temperature range	-25 ~ + 60 °C (-13 °F ~ 140 °F)					
Relative operating humidity	0 %RH ~ 100 %RH					
Max. operating altitude	4,000 m (13,123 ft.) (Derating above 2000 m)					
Cooling	Natural convection					
Display	LED Indicators; Integrated WLAN + FusionSolar App					
Communication	RS485; WLAN/Ethernet via Smart Dongle-WLAN-FE; 4G / 3G / 2G via Smart Dongle-4G (Optional)					
Weight (incl. mounting bracket)	17 kg (37.5 lb)					
Dimension (incl. mounting bracket)	525 x 470 x 146.5 mm (20.7 x 18.5 x 5.8 inch)					
Degree of protection	IP65					
Nighttime Power Consumption	< 5.5 W [6]					
Optimizer Compatibility						
DC MBUS compatible optimizer	SUN2000-450W-P					
Standard Compliance (more available upon request)						
Certificate	EN/IEC 62109-1, EN/IEC 62109-2, IEC 62116					
Grid connection standards	G98, G99, EN 50438, CEI 0-21, VDE-AR-N-4105, AS 4777, C10/11, ABNT, UTE C15-712, RD 1699, TOR D4, NRS 097-2-1, IEC61727, IEC62116, DEWA					

*1 Inverter max input PV power is 20,000 Wp when long strings are designed and fully connected with SUN2000-450W-P power optimizers.
*2 The maximum input voltage is the upper limit of the DC voltage. Any higher input DC voltage would probably damage inverter.
*3 Any DC input voltage beyond the operating voltage range may result in inverter improper operating. *4 C10 / 11: 10,000 VA
*5 SUN2000-3~10KTL-M1 raises potential between PV- and ground to above zero through integrated PID recovery function to recover module degradation from PID. Supported module types include: P-type (mono, poly).
*6. <10 W when PID recovery function is activated.