



COMILLAS PONTIFICAL UNIVERSITY

**OFFICIAL MASTER'S DEGREE  
IN INDUSTRIAL ENGINEERING**

**MASTER THESIS**

**MODEL FOR THE DESIGN OF  
DISTRIBUTED GENERATION  
RESOURCES:  
PHOTOVOLTAIC PLANT FOR  
SELF-CONSUMPTION  
IN A SPORTS FACILITY**

Author: Adrián Cecilio Benito

External Supervisor: Ángel Sánchez Elipe

Supervisor: Beatriz Yolanda Moratilla Soria

Madrid

August 25, 2021



I declare, under my responsibility, that the Project presented with the title

*Model for the Design of Distributed Generation Resources:  
Photovoltaic Plant for Self-Consumption in a Sports Facility*

at ICAI School of Engineering - Comillas Pontifical University

in the academic course 2020/21 is a work of my authorship, original and  
unprecedented which has not been previously published for other purposes.

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



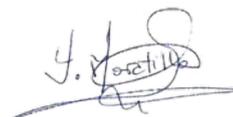
Adrián Cecilio Benito.

The publication of the Project is authorised by

THE SUPERVISORS OF THE PROJECT:



Ángel Sánchez Elipe.



Beatriz Yolanda Moratilla Soria.

August 25, 2021.





COMILLAS PONTIFICAL UNIVERSITY

**OFFICIAL MASTER'S DEGREE  
IN INDUSTRIAL ENGINEERING**

**MASTER THESIS**

**MODEL FOR THE DESIGN OF  
DISTRIBUTED GENERATION  
RESOURCES:  
PHOTOVOLTAIC PLANT FOR  
SELF-CONSUMPTION  
IN A SPORTS FACILITY**

Author: Adrián Cecilio Benito

External Supervisor: Ángel Sánchez Elipe

Supervisor: Beatriz Yolanda Moratilla Soria

Madrid

August 25, 2021



# Acknowledgements

I am extremely grateful to Dreamfit and especially to Ángel Sánchez Elipe for trusting me once again to solve an actual engineering issue. I have had the great pleasure of working with you for two years learning from your helpful advice, leveraging your invaluable knowledge as well as your professional career.

I would also like to extend my gratitude to Beatriz Yolanda Moratilla Soria for being the Director of this Master Thesis. Thank you for investing your time on this project and for your insightful suggestions.

Special thanks to Susana Provencio Fouetillou for conducting me through the site visit, this achievement would not have been possible without your support.

Many thanks to my family and friends who helped me through this *journey*.



# Abstract

The aim of this Master Thesis stands for developing a model to design photovoltaic plants for self-consumption at any building's roof of a Spanish gym chain in the medium term. The model provides a scalable solution based on two programming functions that performs a production and an economic study respectively, computing the optimal photovoltaic power to install and assessing the profitability of the project.

To this end, the model has been developed and applied to a *pilot project* that will be executed in practice. Therefore, the Master Thesis consists of a real engineering project that covers all the documents required by a Spanish technical project: project memory, technical specifications, health and safety study, project plans and project budget.

The photovoltaic plant designed through the application of the scalable model on this *pilot project* is expected to generate almost 200 *MWh* of clean energy per year, implying a yearly grid consumption reduction of almost 40% for the analysed facility, and avoiding the annual emission of more than 50 tonnes of carbon dioxide to the atmosphere.



# MODEL TO DESIGN DISTRIBUTED GENERATION RESOURCES: PV PLANT FOR SELF-CONSUMPTION IN A SPORTS FACILITY

**Author: Cecilio Benito, Adrián.**

External Supervisor: Sánchez Elipe, Ángel.

ICAI Supervisor: Moratilla Soria, Beatriz Yolanda.

Collaborating Entity: Dreamfit.

## EXECUTIVE SUMMARY

Collaborating with a Spanish gym chain, a model to design photovoltaic plants for self-consumption has been developed. The model is based on two programming functions that performs a production and an economic study of the project. Specifically, this Master Thesis includes a whole engineering project where the model has been applied to a sports facility.

**Keywords:** Photovoltaic (PV) Energy, PV Plant, Self-Consumption, Distributed Energy Resource (DER), Renewable Energy, PV Module.

## 1. Introduction

The global energetic context is currently focused on a decarbonisation economy fostered through diverse political measurements intended to boost renewable energies. In the particular case of Spain, where this project will be developed, the major regulatory examples are RITE, which determines minimum efficiency requirements and establishes the minimum renewable contribution for Sanitary Hot Water, and Royal Decree 244/2019, which simplifies domestic and industrial self-consumption from both a technical and a legal point of view.

The photovoltaic industry is part of this decarbonisation economy and will be a leading player within the core of the future energy sector. By 2010, the PV technology was not developed enough to be cost-effective, but the PV industry has currently reached its technological maturity and therefore PV projects can be profitable even for self-consumption purposes.

In fact, compared to 2018 levels, cumulative solar PV capacity is expected to grow sixfold by 2030, with a Compound Annual Growth Rate of nearly 9% up to 2050. Then, this project consists of the design of a photovoltaic plant for self-consumption in a Spanish sports facility.

### 1.1. Reference Framework

The development of a photovoltaic project for self-consumption requires mastering both the technical and the regulatory part, which are improved, adjusted and modified with frequency.

From a **technical point of view**, the photovoltaic industry at domestic or industrial level has been boosted considerably in the last decade due to a decrease in the generation cost. The emergence of perovskite solar cells, bi-facial modules or tracking systems apart from improvements in power electronics such as increasing the number of MPPTs per inverter are examples that have contributed favourably to the evolution of the photovoltaic technology.

From a **regulatory point of view**, considerable adjustments have been done in terms of regulation in Spain during the last decade, such as the last modification of ITC-BT-40 on low volt-

age generating facilities, or the publication of the Technical Specifications of Grid-Connected Facilities as well as the new electricity tariffs that came into force the first of June of 2021.

## 1.2. Context of the Master Thesis

Dreamfit® is a gym chain that was launched in 2009 due to the initiative of a Spanish entrepreneur's group professionally linked to sports. Nowadays, Dreamfit counts with approximately 400 workers and 25 gyms spread all over Spain, 20 of them already open and 5 in project or construction phase:

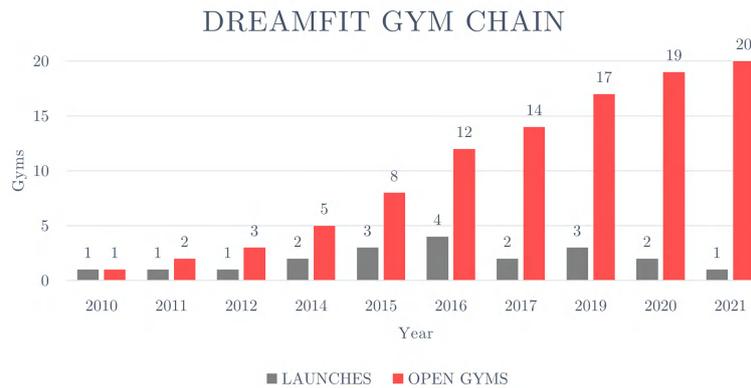


Figure 1. Dreamfit Gym Chain launches in the period 2010-2021.

Since year 2018 and not considering COVID-19 lockdown, Dreamfit has reinforced its commitment towards energy efficiency, reducing the yearly consumption of the whole gym chain more than a 25% in the period between 2018 and 2021. In this context, Dreamfit has the intention of including Distributed Energy Resources (DERs) in the short and the medium term at every gym through self-consumption facilities.

Among all the available alternatives, the company has decided to opt for photovoltaic plants since geothermal, for instance, requires much more construction costs due to the required civil works, exactly as any other solution. Moreover, the PV modules would be installed at the facility roof that is already deployed and owned by Dreamfit, simplifying the projects and making them more cost-efficient.

Thus, Dreamfit has given me the opportunity of projecting a solar PV plant at a specific gym of the company that will be actually executed in practice.

## 1.3. Target of the Project

The **main target** of the project stands for developing a **model** to include photovoltaic generation plants for self-consumption at any Dreamfit gym in the medium term. In this sense, the solution provided consists of the application of the model on a *pilot project* of 100  $kW_n$  at Dreamfit Alcorcón that is intended to be replicated in more gyms in the medium term.

There are other **sub-goals** that are derived from the main target of the project: self-consume more than 150  $MWh/year$ , what represents more than a 35% of the whole energy demanded yearly by Dreamfit Alcorcón, and avoid the emission of more than 50  $t_{eq} CO_2/year$ .

## 2. Methodology

### 2.1. Development of the Model

The model to design photovoltaic plants for self-consumption at any Dreamfit gym in the medium term has been carried out through two MATLAB® programming functions. These algorithms are based on the Royal Decree 244/2019 and the electricity tariff 3.0TD:

1. **Production Study - Function *tfm.m*.** The algorithm computes the optimal PV peak power to install in accordance with the consumption pattern of the facility. Additionally, a production study for that installed peak power is performed.
2. **Economic Study - Function *economic.m*.** The algorithm assesses both CAPEX and OPEX expenditures in order to evaluate the profitability of the project.

#### 2.1.1. Production Study - Function *tfm.m*

The most relevant **input data** required by the *tfm.m* MATLAB function in order to evaluate the production performance of the PV plant are presented below:

- **Global In-Plane Irradiance per Hour ( $G(i)$  [ $W/m^2$ ]).** Vector of 8,760 positions which contains the hourly global irradiance of a typical year for a specific location obtained through PVGIS® TMY Tool. The tilt and azimuth angles are the optimised ones according to the Technical Specifications of PV Facilities. The Peak Sun Hours (PSH) can be obtained through the irradiance since a PSH is defined as one hour in which the intensity of solar irradiance reaches an average of 1,000  $W$  of energy per square meter.
- **Hourly Consumption Data ( $E_c(i)$  [ $kWh$ ]).** Vector of 8,760 positions which contains the hourly consumption of a representative year for a specific facility. This hourly data is obtained through the Circutor® power analyser that Dreamfit installs at every gym. Consumption data from year 2020 cannot be used due to COVID-19 lockdown, so the most recent and representative consumption data available corresponds to year 2019. This is the reason why data from year 2019 has been utilised in this Master Thesis.

The programming function establishes the PV energy generated according to equation 1:

$$energy\_pv(i) = PSH(i) \cdot pp \cdot pr \quad (1)$$

Where:

- $energy\_pv(i)$  → Energy produced per hour  $i$  by the PV plant [ $kWh$ ].
- $PSH(i)$  → Peak Sun Hours per hour  $i$  obtained from the global in-plane irradiance [ $h$ ].
- $pp$  → Peak power installed at the photovoltaic field [ $kW$ ].
- $pr$  → Performance ratio that measures the yield of the facility<sup>1</sup> [-].

Then, the algorithm establishes the optimal PV peak power to install following a programming loop that maximises the self-consumed energy and minimises the surplus energy:

$$pp_{opt} \iff max \left( \sum_{i=1}^{8760} self\_consumed(i) - \sum_{i=1}^{8760} excess(i) \right) \quad (2)$$

<sup>1</sup>In this case: Performance Ratio  $pr = 0.887$  → Source PV<sub>system</sub>®.

Once the code is executed, the **optimal PV peak power** to install is returned by the program. Additionally, other optimisation vectors are automatically exported to a MS Excel file where data per hour, day, week, month and year can be analysed to perform the **production analysis**:

- **PSH.** The Peak Solar Hours available [ $h$ ].
- **Total Consumption.** Energy supplied to the user<sup>2</sup> [ $kWh$ ].
- **PV Production.** Energy generated by the Distributed Energy Resource [ $kWh$ ].
- **Surplus PV Energy.** Excessive energy produced injected into the DSO grid [ $kWh$ ].
- **Grid Consumption.** Energy supplied to the consumer from the DSO grid [ $kWh$ ].
- **Self-Consumption.** Energy produced by the plant and self-consumed by the user [ $kWh$ ].

### 2.1.2. Economic Study - Function *economic.m*

The input data required by the *economic.m* MATLAB function are once again the global in-plane irradiance per hour and the hourly consumption data utilised for the *tfn.m* function. Moreover, other hypothetical input data is needed for the financial study:

- **Initial Investment** [€]. In this particular case, the project budget (with no prices) has been sent to Elecnor® in order to obtain a trustworthy offer → 100,395.22€.
- **Annual Maintenance Cost** [€]. Maintenance fee offered by Elecnor® → 5,000€/year.
- **Annual Power Attenuation of PV Modules** [%]. Modules data sheet → 0.55%/year.
- **Consumer Price Index (CPI)** [%]. Obtained from the previous 25 years database of the Spanish National Institute of Statistic → 2.02%/year.
- **Power and Energy Prices** [€/kW, €/kWh]. Prices per period for the 3.0TD tariff have been consulted to a professional company from energy sector: *Symelec Renovables*®.
  - Power: [0.053690, 0.037759, 0.019193, 0.016729, 0.012053, 0.007225] €/kW.
  - Energy: [0.207797, 0.184083, 0.153379, 0.130097, 0.108142, 0.110010] €/kWh.
- **Surplus Energy Price** [€/kWh]. The price of the compensated energy injected into the grid has also been consulted to *Symelec Renovables*®, exactly as the annual surplus depreciation rate → 0.05€/kWh and 1.5%/year.

The programming function allocates per period and month the total energy demanded by the gym as well as the PV production and the energy surpluses respecting the distribution of periods regulated for the electricity tariff 3.0TD. Then, the function *economic.m* determines the six optimal contracted powers when the PV plant is included. Consequently, the program computes the powers that make the annual cost of the total power term minimum taking into account that the excessive power is charged according to the following expression:

$$F_{EP} = \sum_{i=1}^6 K_i \cdot 1.406368 \cdot \sqrt{\sum_{j=1}^n (P_{d_j} - P_{C_i})^2} \quad (3)$$

Where:

- $F_{EP}$  → Monthly excessive demanded power charge [€].
- $K_i$  → Pricing coefficient per period  $i$  [€/kW].
- $P_{d_j}$  → Demanded power at the  $n$  15-minutes intervals in which the demanded power of the period  $i$  has exceeded the contracted power of that period  $P_{C_i}$  [kW].

<sup>2</sup>Either through the PV plant or through the DSO network.

Once the code is executed, the **six optimal powers** to be contracted per period as well as the **payback period** are returned by the program. Additionally, economic information for the 25 years of useful life of the project is automatically exported to a MS Excel file where data per month and year can be analysed to perform the **financial analysis**:

- **Consumption Distribution.** Including the total energy demanded by the gym, the energy surpluses, the PV production, the self-consumption as well as the energy consumed from the grid per period, month and year for the electricity tariff 3.0TD [ $kWh$ ].
- **Power Penalty Cost.** The month by month cost of the penalty cost due to power excesses having and not having the PV plant are provided [€].
- **Energy Term Total Cost.** The month by month cost of the energy consumed from the grid having and not having the PV plant as well as the energy surpluses are obtained [€].
- **Power Term Total Cost.** The month by month fixed power cost is established having and not having the PV plant for the following 25 years. The results obtained are added to the power penalty cost in order to compute the total power cost per month and year [€].

## 2.2. Engineering Project

The scalable model developed to design PV plants for self-consumption has been applied to a *pilot project* that will be actually executed in practice at the roof of Dreamfit Alcorcón. Therefore, a whole engineering project has been included covering all the contents required according to the current regulation:

- **Project Memory.** Including descriptive memory, calculations, production and economic study, environmental impact and conclusions.
- **Technical Specifications.** In terms of works, components, materials and commissioning.
- **Health and Safety Study.** To ensure safety during and after the construction works.
- **Project Budget.** In order to assess the project from an economically point of view.
- **Plans.** Required to graphically represent and fully define the project.

### 2.2.1. Project Memory

The **descriptive memory** section of the project memory provides qualitative information of the Dreamfit Alcorcón PV plant in terms of regulation and main components. In contrast, the **calculations** section of the project memory provides quantitative information of the Distributed Generation Resource design.

After running the *tfm.m* optimisation function, the optimal PV peak power measured at the photovoltaic field of Dreamfit Alcorcón is  $111 kW_p$ , while the facility rated power measured at the inverter is  $100 kW_n$ .

In order to select the PV modules and the DC/AC inverter, a market research was performed:

- **PV Modules.** The design has been done selecting the World-Class Top Performer Trina-solar Vertex TSM-DE18M(II) PV monofacial modules with a peak power of  $505 W_p$ .
- **DC/AC Inverter.** The PV plant includes only one inverter, the Huawei internationally recognised Smart PV Controller SUN2000-100KTL-M1 with a rated power of  $100 kW_n$ .

The 220 modules are based on the multi-busbar technology with 150 PERC monocrystalline cells per module, reaching up to 21.2% of efficiency. The inverter integrates Artificial Intelligence, requiring no fuses, including a management and monitoring system and counting with 10 MPPTs that receive inputs from 20 PV strings, providing a maximum efficiency of 98.4%:

Table 1. Configuration of the photovoltaic system.

PHOTOVOLTAIC SYSTEM	
PV Modules Manufacturer	
PV Modules Model	TSM-DE18M-(II)-505
N <sup>o</sup> of PV Modules	220 PV modules
PV Module Peak Power	505 W <sub>p</sub>
PV System Peak Power	111.1 kW <sub>p</sub>
Inverter Manufacturer	
Inverter Model	SUN2000-100KTL-M1-400Vac
N <sup>o</sup> of Inverters, Strings	1 inverter, 20 strings (10 MPPTs)
Inverter Rated Power	100 kW <sub>n</sub>
PV System Rated Power	100 kW <sub>n</sub>

The Huawei inverter is equipped with a smart power meter to capture data of the PV plant performance that can be analysed in real-time at the Fusion-Solar Smart Management System. The maximum power point conditions as well as the open-circuit and the short-circuit conditions of the PV system have been analysed to ensure the compatibility among the 20 PV strings of 11 series-connected PV modules and the solar inverter:

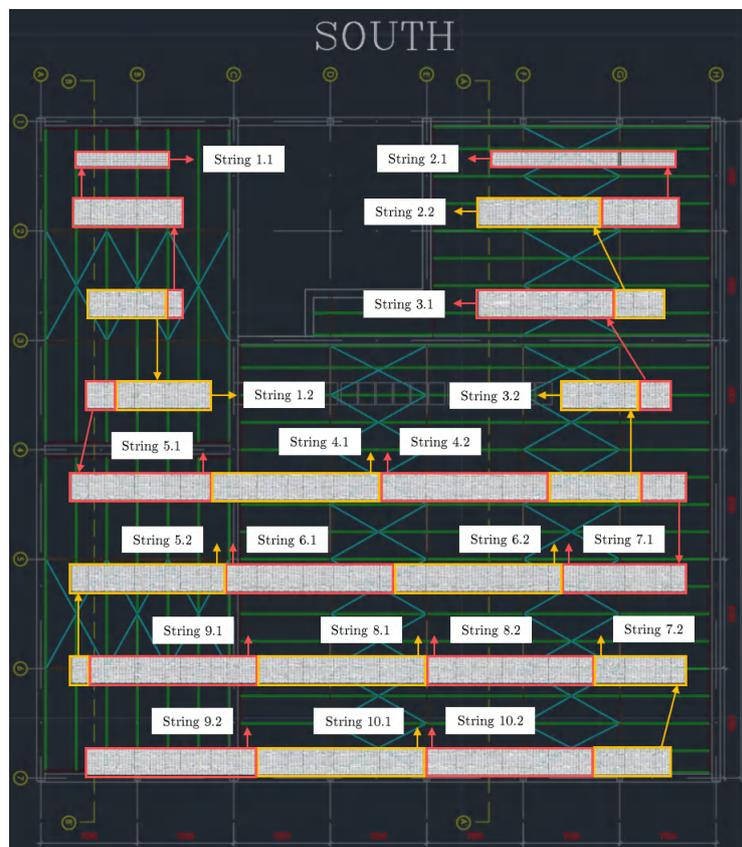


Figure 2. Physical distribution of the PV strings developed with Autocad®.

The orientation of the PV modules as well as the minimum distance between elements have been established according to the Technical Specifications of Grid-Connected Facilities. Additionally, a shades analysis has been performed to ensure that annual losses due to shadows never exceeds the 0.3% at any PV module. The shades study has been performed analysing the sun path chart of Dreamfit Alcorcón according to the Solar Radiation Monitoring Laboratory:

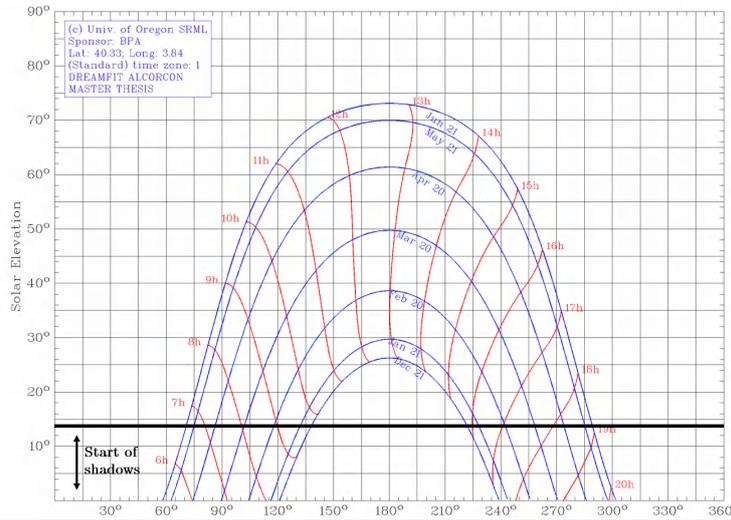


Figure 3. Sun path chart of Dreamfit Alcorcón.

Then, in order to maximise production:

- **Tilt Angle:**  $\beta_{opt} = 33.5^\circ$  with respect to the horizontal plane.
- **Azimuth Angle:**  $\alpha_{opt} = 0^\circ$ .
- **Distance between the First PV Row and the Perimeter Wall:** 1.99 m.
- **Distance between the First and the Second PV Row:** 2.50 m.
- **Distance between the Rest of the PV Rows:** 4.87 m.

Cable sections have been computed following ITC-BT-40 on low voltage generating facilities and the Technical Specifications of Grid-Connected Facilities. Thus, respecting both the thermal and the voltage drop criteria:

- **DC Side.** Voltage Drop:  $V_{max} < 1.5\%$ . Maximum Temperature:  $T_{max} < 90^\circ C$ .
  - Two poles:  $2 \cdot 6 \text{ mm}^2$ .
- **AC Side.** Voltage Drop:  $V_{max} < 1.5\%$ . Maximum Temperature:  $T_{max} < 90^\circ C$ .
  - Three phases and neutral:  $4 \cdot 70 \text{ mm}^2$  and  $4 \cdot 120 \text{ mm}^2$ .
- **Sections.** Conductors have been sized for 125% of the generator maximum current.

The facility counts with the required protections and the adequate electrical distribution panels to guarantee the safety of people, as well as to avoid damaging the equipment in case of system failures. The protections have been established in accordance with both the Royal Decree 1663/2000 related to the connection of PV facilities to the low voltage grid, Royal Decree 1699/2011 and the Spanish Electrotechnical Regulation for Low Voltage (REBT).

Moreover, the existing grounding system of the building will be used for the PV facility to ensure equipotentiality. Additional coated copper wires between  $6 \text{ mm}^2$  and  $60 \text{ mm}^2$  are going to unify the earth of all the metallic elements following ITC-BT-08 and ITC-BT-18.

Table 2 presents a summary of the protections included at the PV plant:

Table 2. Qualitative summary of the utilised protections.

PROTECTION	TYPE OF PROTECTION	DC	AC
DIRECT CONTACTS	ACTIVE ELEMENTS	INSULATION CLASS II	
	BARRIERS, ENCLOSURES AND OBSTACLES	TUBES, PROTECTION IP65	TUBES
	OUT OF REACH LOCATIONS	FACILITIES ZONE	FALSE CEILING, FACILITIES ZONE
INDIRECT CONTACTS	RESIDUAL CURRENT DEVICE	INSULATION CLASS II, INVERTER PROTECTIONS	INSULATION CLASS II, RESIDUAL CURRENT RELAY
OVERLOADS & SHORT-CIRCUITS	OVERCURRENT	INVERTER DC SWITCHES	AUTOMATIC CIRCUIT BREAKERS
EARTHING SYSTEM	INDIRECT CONTACTS	ELECTRICAL MASSES CONNECTED TO GND THROUGH COATED COPPER	

The electrical canalisation has been computed respecting the current regulation in terms of canalisation tubes and therefore following ITC-BT-21. It is based on halogen free conduits prepared to be used outdoors with a high UV resistance, requiring tubes with an internal diameter between 21.6 mm and 45 mm.

The photovoltaic modules are mounted on an aluminium structure capable of withstanding the loads derived from the facility itself and providing the proper orientation and inclination to the PV field in order to maximise the performance of the generation plant. No structural reinforcement is required to install the PV plant at the roof of the sports centre since the architect forecast an usage load for facilities and other usages of 25 kg/m<sup>2</sup>.

In accordance with the Royal Decree 244/2019, nowadays a Spanish PV plant for self-consumption purposes can be connected to the DSO grid sharing the connecting infrastructure with the consumer supply line. Hence, the PV plant can be directly interconnected to the national grid as an additional circuit of the gym's main electrical distribution panel:

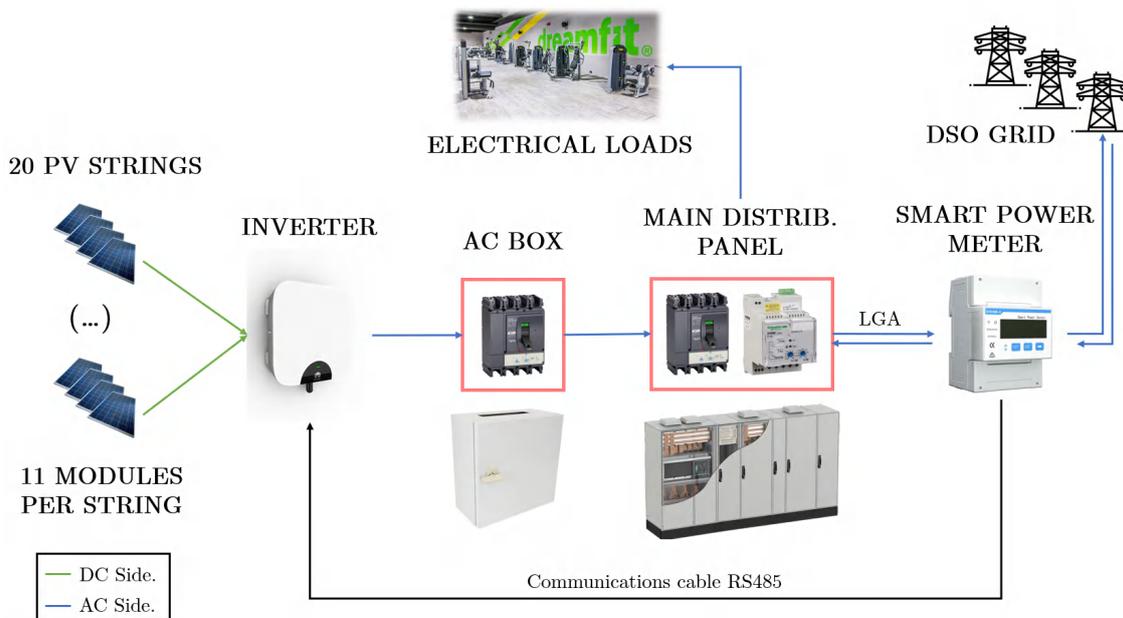


Figure 4. Interconnection schema of Dreamfit Alcorcón PV plant.

### 2.2.2. Technical Specifications

The target of the technical specifications document consists of establishing the minimum technical requirements that the grid-connected PV plant must meet. The specifications developed are intended as a guide both for project installers and manufacturers. The document defines the minimum specifications that the PV facility must comply with to ensure its quality for the sake of the client while fostering the development of the technology and the project itself.

The scope of the technical specifications extends to the mechanical, the electrical and the electronic systems that constitute the facility. The document is based on the current regulation: Royal Decree 1699/2011, Royal Decree 413/2014 or Royal Decree 900/2015.

### 2.2.3. Health and Safety Study

The health and safety study has the purpose of analysing, developing and complementing the provisions regarding risk prevention of occupational accidents as well as occupational diseases, the mandatory hygiene and the facilities well-being or any other regulatory requirement.

The health and safety study is based on the current regulation related to Law 31/1995, Royal Decree 485/1997, Royal Decree 773/1997 or Royal Decree 614/2001.

### 2.2.4. Project Budget

The project budget has been developed by means of the professional software Presto® considering the unitary prices offered by Elecnor®. Presto is an integrated cost management program specialised for construction projects.

Particularly, the budget document has been divided into six chapters:

1. **Main Equipment.** Including the PV modules, the inverter, the mounting structure and the power analyser.
2. **Protection and Wiring.** Considering both DC and AC sides.
3. **Auxiliary Services.** Covering the civil works assistance and the crane required to raise the construction materials to the roof of Dreamfit Alcorcón.
4. **Health and Safety.** Including all the Personal Protective Equipment.
5. **Waste Management.** Following the order 2726/2009 (Community of Madrid).
6. **Commissioning.** Including the legalisation of the facility.

Then, the total cost of the project amounts to 100,395.22€ (VAT not included).

### 2.2.5. Project Plans

The five plans that graphically define the project have been designed through Autocad®:

1. Situation and Location of the PV Project.
2. General Distribution - Plan View of Dreamfit Alcorcón Roof.
3. Electrical Canalisation.
4. Photovoltaic Mounting Structure.
5. Electrical Schematic of the Dreamfit Alcorcón PV Plant.

### 3. Results

This section presents the results obtained at the production and economic studies.

#### 3.1. Production Study Results

The main annual results derived from the production study based on the function  $tfm.m$  for an optimal peak power of  $111 kW_p$  and a rated power of  $100 kW_n$  are included below:

Table 3. Production study - Main annual results.

ANNUAL RESULTS	kWh/year
TOTAL CONSUMPTION	447,567.75
PV PRODUCTION	198,897.59
SURPLUS PV ENERGY	29,733.28
GRID CONSUMPTION	278,403.45
SELF-CONSUMPTION	169,164.30
OPTIMAL PEAK POWER	111 kW

Regarding table 3:

- **Self-Consumption Rate.** More than 85% of the energy generated by the PV plant will be self-consumed by the sports facility ✓.
- **Autarky Rate.** Almost 38% of the total energy consumed by Dreamfit Alcorcón per year will be generated through the PV plant ✓.

In addition, table 4 is included as a main results overview, representing a numerical monthly summary of the production study for the first year of the project:

Table 4. Production study - Balances and main monthly results.

PV PRODUCTION STUDY - YEAR 1						
MONTH	PSH (h)	TOTAL CONSUMPTION (kWh)	PV PRODUCTION (kWh)	SURPLUS PV ENERGY (kWh)	GRID CONSUMPTION (kWh)	SELF-CONSUMPTION (kWh)
JANUARY	98.14	43,352.51	9,662.73	727.07	34,416.85	8,935.66
FEBRUARY	117.20	37,012.88	11,538.99	1,126.77	26,600.66	10,412.22
MARCH	180.40	34,741.40	17,761.94	3,329.68	20,309.14	14,432.26
APRIL	195.81	32,663.31	19,278.55	4,699.46	18,084.22	14,579.09
MAY	178.32	34,512.61	17,556.79	2,903.12	19,858.95	14,653.67
JUNE	216.00	37,505.64	21,266.38	3,335.63	19,574.89	17,930.75
JULY	242.88	46,397.28	23,912.75	2,655.71	25,140.24	21,257.03
AUGUST	224.32	40,836.00	22,085.82	3,451.44	22,201.63	18,634.37
SEPTEMBER	201.23	37,022.64	19,812.73	2,839.92	20,049.83	16,972.81
OCTOBER	151.10	35,484.65	14,877.22	2,091.24	22,698.67	12,785.98
NOVEMBER	103.13	34,217.15	10,153.56	1,090.61	25,154.20	9,062.94
DECEMBER	111.62	33,821.68	10,990.14	1,482.63	24,314.16	9,507.51
<b>YEAR</b>	<b>2,020.15</b>	<b>447,567.75</b>	<b>198,897.59</b>	<b>29,733.28</b>	<b>278,403.45</b>	<b>169,164.30</b>

Installing a storage system would only be interesting for leveraging the surplus energy generated on Sundays and bank holidays since there are several sunny hours on those days where the sports centre remains closed. Hence, taking into account the self-consumption rate and considering that the technology has not reached yet its maturity, it has been decided not including a BESS. The surplus energy will be compensated according to Royal Decree 244/2019.

Finally, figure 5 compares the performance of the PV plant by contrasting the average working day of the most sunny month against the most cloudy month:

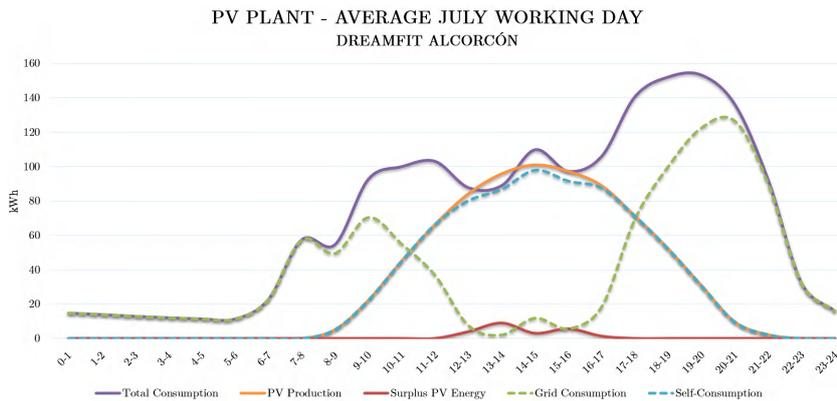
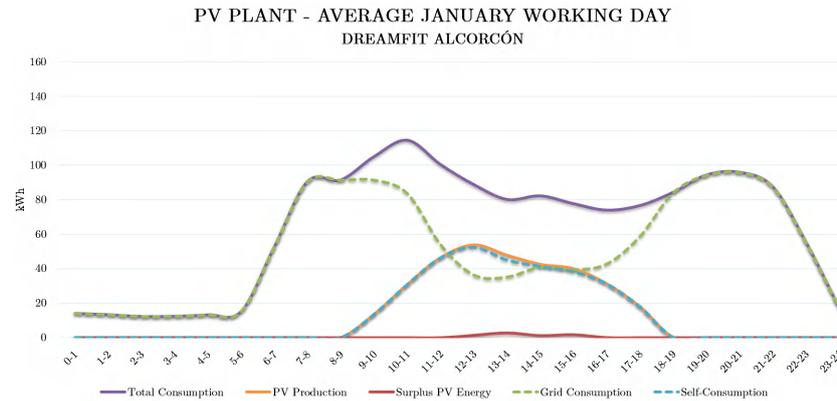


Figure 5. PV plant performance - Most sunny versus most cloudy day.

Analysing both graphics 5(a) and 5(b), a consistent inverse relationship between the energy consumed from the grid and the photovoltaic production can be observed. Besides, grid consumption gets visibly reduced during sunny hours.

### 3.2. Economic Study Results

After running the *economic.m* function, the optimal powers to be contracted per period for the 3.0TD electricity tariff of Dreamfit Alcorcón are included below<sup>3</sup>:

- $P_1 = 143 \text{ kW} \rightarrow P_{1 \text{ opt}} = 135 \text{ kW}$ .
- $P_2 = P_3 = P_4 = P_5 = 155 \text{ kW} \rightarrow P_{2 \text{ opt}} = P_{3 \text{ opt}} = P_{4 \text{ opt}} = P_{5 \text{ opt}} = 135 \text{ kW}$ .
- $P_6 = 155 \text{ kW} \rightarrow P_{6 \text{ opt}} = 155 \text{ kW}$ .

<sup>3</sup>Necessarily  $P_1 \leq P_2 \leq P_3 \leq P_4 \leq P_5 \leq P_6$  for electricity tariff 3.0TD.

Additionally, figure 6(a) presents the annual allocation of total consumption, PV production and self-consumption along the six periods of the 3.0TD tariff of Dreamfit Alcorcón:

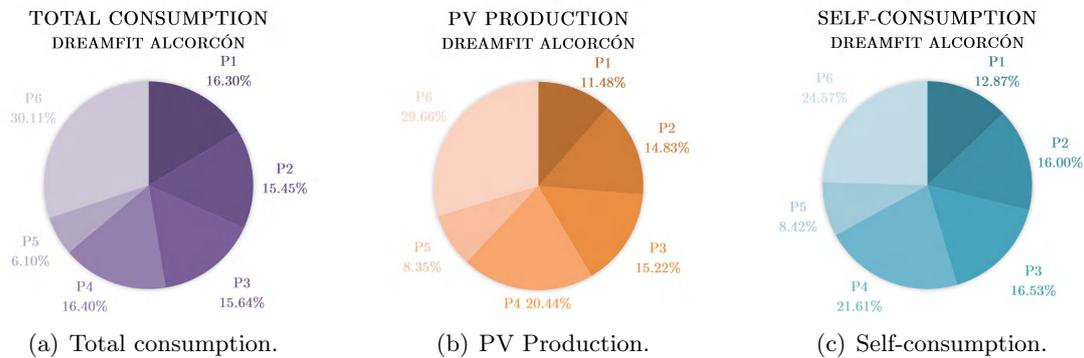


Figure 6. Economic study - Consumption and production allocation per 3.0TD tariff periods.

At this point, the profitability of the project is assessed through the Internal Rate of Return and the PayBack Period. Hence, the Internal Rate of Return (IRR) of the 25-year project is computed through the Cash Flows (CF):

$$0 = \sum_{n=0}^{25} \frac{CF_n}{(1 + IRR)^n} \rightarrow \boxed{IRR = 25.96\%} \tag{4}$$

The PayBack Period (PB) is computed taking into account that the summation of cash flows becomes positive between the third and the fourth year of the project lifetime:

$$0 = \sum_{n=0}^{PB} CF_n \rightarrow PB = 3.86 \text{ years} \rightarrow \boxed{PB \approx 4 \text{ years}} \tag{5}$$

Furthermore, the payback period is evaluated graphically in figure 7. The figure assesses the summation of cash flows considering CPI index as well as any other economical rate mentioned in subsection 2.1.2, id est, the graphic shows also the Net Present Value (NPV) of the project:

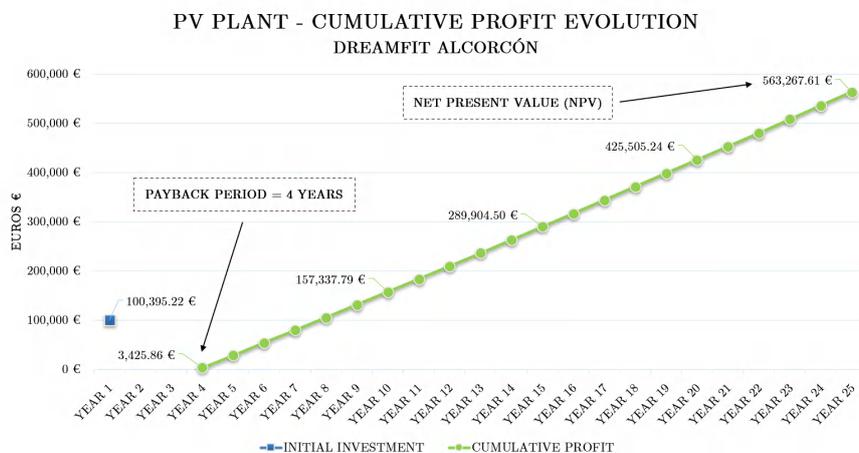


Figure 7. Economic study - Cumulative profit evolution of Dreamfit Alcorcón PV plant.

Then, the Internal Rate of Return and the Payback Period of the PV plant project are:

$$\boxed{IRR = 25.96\%} \quad \boxed{Payback\ Period = 4\ years} \quad (6)$$

### 3.3. Testing the Photovoltaic Model

The accuracy of the model developed in MATLAB has been contrasted with a simulation developed through the professional software PVsyst®. The production and economic studies have been replicated under the same hypothetical constraints, parameters and assumptions:

Table 5. MATLAB PV model assessment.

ANNUAL RESULTS		PVsyst	MATLAB	DEVIATION
PRODUCTION	PV PRODUCTION (kWh/year)	205,570.00	198,897.59	-3.25%
	SURPLUS PV ENERGY (kWh/year)	30,310.00	29,733.28	-1.90%
	GRID CONSUMPTION (kWh/year)	277,100.00	278,403.45	0.47%
	SELF-CONSUMPTION (kWh/year)	170,470.00	169,164.30	-0.77%
FINANCE	NET PRESENT VALUE YEAR 25 (€)	552,451.00	563,267.61	1.96%
	PAYBACK PERIOD (years)	4.50	3.86	-14.22%
	LEVELISED COST OF ENERGY (€/kWh)	0.071	0.070	-1.41%

- **Production Study.** Differences among the obtained results are due to simplifications in terms of power losses and technical specifications of the electrical devices.
- **Economic Study.** Differences among the obtained results are due to PVsyst does not compute the economical performance under the particular specifications of the Spanish 3.0TD electricity tariff, but with a single-period tariff that has been therefore adjusted.

## 4. Conclusions

All in all, the **main target** of the project has been achieved:

- Regarding table 5, a **scalable model** has been developed in MATLAB that could be replicated to any facility with an hourly consumption database ✓.
- Thanks to this Master Thesis, self-consumption PV plants could be designed and included at **any Dreamfit gym** in the medium term ✓.
- The model has been applied to Dreamfit Alcorcón developing a **whole engineering project** that will be actually executed during year 2022 ✓.

The other four **sub-goals** of the project have also been attained:

- **Self-Consumption.** Almost 170 *MWh* per year will be self-consumed by Dreamfit Alcorcón due to the deployment of the PV plant, self-consuming more than 85% of the annual energy generated by the Distributed Energy Resource ✓.
- **Emissions.** The emission of more than 50  $t_{eq} CO_2$  per year will be avoided due to this renewable energy project, reducing climate change and fostering the compliance with the Sustainable Development Goals according to IEA Life Cycle Emissions ✓.
- **Energy Efficiency and Profitability.** Dreamfit Alcorcón will reduce its grid consumption almost a 40% per year due to the PV modules ✓.
- **Health.** The gym will not only self-consume PV energy, but also will inject almost 30 *MWh* per year of green energy to the grid, supporting its motto *we are health* ✓.

## 5. Main References

1. IRENA, *Future of Solar Photovoltaic*, URL visited on 19/08/2021.
2. BOE - Royal Decree 1027/2007, *Regulation of Thermal Facilities in Buildings*, URL visited on 19/08/2021.
3. BOE - Royal Decree 244/2019, *Administrative and Economic Self-Consumption Conditions*, URL visited on 19/08/2021.
4. IDAE, *Technological and Economical Evolution of Renewable Energies*, URL visited on 19/08/2021.
5. IDAE, *Technical Specifications of Grid-Connected Facilities*, URL visited on 19/08/2021.
6. Dreamfit, *Low Cost Gym Chain*, URL visited on 19/08/2021.
7. Mathworks, *Matlab & Simulink*, URL visited on 19/08/2021.
8. European Commission, *PVGIS TMY Tool*, URL visited on 19/08/2021.
9. Circutor, *CVM-MINI Series*, URL visited on 19/08/2021.
10. INE, *Consumer Price Index*, URL visited on 19/08/2021.
11. UNE, *UNE 157001:2014*, URL visited on 19/08/2021.
12. Trinasolar, *Vertex TSM-DE18M(II) modules*, URL visited on 19/08/2021.
13. Huawei, *Smart PV Controller DC/AC Inverter SUN2000-100KTL-M1*, URL visited on 19/08/2021.
14. Huawei, *Fusion Solar Smart PV Management System*, URL visited on 19/08/2021.
15. University of Oregon, *Solar Radiation Monitoring Laboratory*, URL visited on 19/08/2021.
16. BOE - Royal Decree 1663/2000, *Connection of Photovoltaic Plants to the Low Voltage Grid*, URL visited on 19/08/2021.
17. BOE - Royal Decree 1699/2011, *Grid Interconnection of Reduced Power Generation Plants*, URL visited on 19/08/2021.
18. BOE - Royal Decree 842/2002, *Electrotechnical Regulation for Low Voltage*, URL visited on 19/08/2021.
19. BOE - Royal Decree 413/2014, *Regulation of Energy Generation through Renewable Sources*, URL visited on 19/08/2021.
20. BOE - Law 31/1995, *Labour Risk Prevention*, URL visited on 19/08/2021.
21. BOE - Royal Decree 485/1997, *Occupational Health and Safety Signs*, URL visited on 19/08/2021.
22. BOE - Royal Decree 773/1997, *Usage of Personal Protective Equipment*, URL visited on 19/08/2021.
23. BOE - Royal Decree 614/2001, *Minimal Health and Safety Provisions related Electrical Risk*, URL visited on 19/08/2021.
24. RIB Spain, *Presto iTWO*, URL visited on 19/08/2021.
25. Community of Madrid, *Order 2726/2009*, URL visited on 19/08/2021.
26. Autodesk, *Autocad*, URL visited on 19/08/2021.
27. PVsyst, *Photovoltaic Software*, URL visited on 19/08/2021.
28. IEA, *Spain - Countries & Regions*, URL visited on 19/08/2021.

### **UNESCO NOMENCLATURE:**

- Field: Technological Sciences (code 33).
- Discipline: Electrical Technology and Engineering (code 3306).
- Subdisciplines: Direct Current Power Utilisation (330601) and Electricity Applications (330602).

# MODELO PARA EL DISEÑO DE RECURSOS DE GENERACIÓN DISTRIBUIDA: PLANTA DE AUTOCONSUMO FOTOVOLTAICO EN UNA INSTALACIÓN DEPORTIVA

**Autor: Cecilio Benito, Adrián.**

Director Externo: Sánchez Elípe, Ángel.

Directora de ICAI: Moratilla Soria, Beatriz Yolanda.

Entidad Colaboradora: Dreamfit.

## RESUMEN EJECUTIVO

El presente proyecto desarrolla un modelo para el diseño de plantas de autoconsumo fotovoltaico en colaboración con una cadena de gimnasios española. El modelo realiza un análisis de producción y económico mediante dos funciones de programación. Concretamente, este trabajo consiste en un proyecto completo donde se aplica el modelo en una instalación deportiva.

**Palabras clave:** Energía Fotovoltaica (FV), Planta Fotovoltaica, Autoconsumo, Recursos de Generación Distribuida (GD), Energía Renovable, Módulo Fotovoltaico.

## 1. Introducción

El contexto energético actual se apoya en una economía de descarbonización fomentada por políticas nacionales e internacionales que tratan de impulsar las energías renovables. En el marco regulatorio específico de España, que es donde se va a desarrollar este proyecto, destaca el RITE, que establece exigencias mínimas de eficiencia energética como la contribución de las renovables en la producción de Agua Caliente Sanitaria (ACS), o el Real Decreto 244/2019, que simplifica el autoconsumo doméstico e industrial desde un punto de vista técnico-legal.

La industria fotovoltaica forma parte de esta economía de descarbonización y será uno de los protagonistas del sector energético del futuro. En el año 2010, la tecnología fotovoltaica no estaba suficientemente desarrollada como para ser rentable en todos los casos. Sin embargo, actualmente la fotovoltaica está alcanzando la madurez tecnológica, lo que favorece la rentabilidad incluso de los proyectos de autoconsumo a pequeña escala.

De hecho, se espera que para 2030 la potencia fotovoltaica instalada a nivel global se multiplique por seis en comparación con los niveles de 2018, con una tasa de crecimiento anual compuesto de aproximadamente el 9% hasta 2050. Por todo lo anterior, en este proyecto se ha diseñado una planta de autoconsumo fotovoltaico para una instalación deportiva.

### 1.1. Marco de Referencia

El desarrollo de un proyecto de autoconsumo fotovoltaico requiere el dominio tanto de la parte técnica como regulatoria, las cuales son mejoradas y modificadas con frecuencia.

Desde un **punto de vista técnico**, la fotovoltaica se ha visto favorecida por una reducción generalizada de los costes de generación en la última década. En concreto, la tecnología fotovoltaica se ha visto impulsada por avances técnicos como la aparición de células solares de perovskita, los módulos bifaciales o los sistemas de seguimiento, aparte de mejoras en la electrónica de potencia tales como el incremento de MPPTs por inversor.

Desde un **punto de vista regulatorio**, durante la última década se han realizado importantes ajustes normativos en España, como la última modificación de la ITC-BT-40 sobre Instalaciones Generadoras de Baja Tensión, el Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red o las nuevas tarifas eléctricas que entraron en vigor el pasado 1 de junio de 2021.

## 1.2. Contexto del Trabajo Fin de Máster

Dreamfit® es una cadena de gimnasios española que nace en el año 2009 por iniciativa de un grupo de empresarios españoles ligados profesionalmente al mundo del deporte. En la actualidad, Dreamfit cuenta con aproximadamente 400 trabajadores directos y 25 gimnasios repartidos por toda España, 20 de ellos abiertos y 5 en fase de proyecto o construcción:



Figure 8. Aperturas de la cadena de gimnasios Dreamfit en el periodo 2010-2021.

Desde el año 2018 y sin considerar los cierres por COVID-19, Dreamfit ha reforzado su compromiso con la eficiencia energética, reduciendo su consumo energético anual más de un 25% en el periodo entre 2018 y 2021. En este contexto, Dreamfit pretende incluir en el corto y medio plazo recursos de Generación Distribuida (GD) para autoconsumo en sus instalaciones.

Entre las alternativas existentes, la empresa ha decidido apostar por la fotovoltaica porque cualquier otra opción requeriría mayor obra civil, como es el caso por ejemplo de la geotermia. En este sentido, la instalación de los módulos en las cubiertas de edificio existentes ya gestionadas por Dreamfit simplificará los proyectos y minimizará la inversión requerida.

Por todo lo anterior, Dreamfit me ha dado la oportunidad de diseñar una planta de autoconsumo fotovoltaico que será realmente ejecutada en la práctica.

## 1.3. Objetivo del Proyecto

El **objetivo principal** del proyecto se basa en el desarrollo de un **modelo** para incluir plantas de autoconsumo fotovoltaico en cualquier gimnasio Dreamfit en el medio plazo. En este caso, el trabajo consiste en la aplicación de dicha modelo en un *proyecto piloto* de  $100 kW_n$  en Dreamfit Alorcón que se pretende replicar en más gimnasios de la cadena en los próximos años.

El proyecto cuenta con **otros subobjetivos** que derivan del objetivo principal: autoconsumir más de  $150 MWh/año$ , lo que representa más del 35% de toda la energía demandada anualmente por Dreamfit Alorcón, y evitar la emisión a la atmósfera de más de  $50 t_{eq} CO_2/año$ .

## 2. Metodología

### 2.1. Desarrollo del Modelo

El modelo para diseñar plantas de autoconsumo fotovoltaico en los Gimnasios Dreamfit se ha desarrollado mediante dos funciones de programación en MATLAB®. Los algoritmos se basan en el Real Decreto 244/2019 y en la nueva tarifa eléctrica 3.0TD:

1. **Estudio de Producción - Función *tfm.m***. El programa calcula la potencia pico fotovoltaica óptima a instalar en función de los patrones de consumo de la instalación. Adicionalmente, la función realiza un estudio de producción para dicha potencia óptima.
2. **Estudio Económico - Función *economic.m***. El programa evalúa tanto los gastos de capital como los gastos operativos con objeto de analizar la rentabilidad del proyecto.

#### 2.1.1. Estudio de Producción - Función *tfm.m*

Los **datos de entrada** más relevantes requeridos por la función de MATLAB *tfm.m* para evaluar el desempeño de la planta fotovoltaica son los siguientes:

- **Irradiancia Global en el Plano por Hora ( $G(i)$  [ $W/m^2$ ])**. Vector de 8,760 posiciones obtenido mediante la herramienta PVGIS® TMY. Contiene la irradiancia global por hora de un año típico en una ubicación concreta. Los ángulos de inclinación y azimut son los óptimos de acuerdo con las Especificaciones Técnicas de Instalaciones Fotovoltaicas. Las Horas Solares Pico (HSP) se obtienen mediante la irradiancia, pues HSP se define como una hora en la que la intensidad de la irradiancia solar alcanza un valor de 1,000  $W/m^2$ .
- **Consumo por Hora ( $E_c(i)$  [ $kWh$ ])**. Vector de 8,760 posiciones que contiene datos de consumo hora a hora de un año típico en una instalación específica. Estos datos se han obtenido mediante el analizador de redes Circutor® que Dreamfit instala en todos sus gimnasios. Los datos de consumo del año 2020 no se pueden emplear debido a los cierres por COVID-19, por lo que el año más reciente y representativo del que se tienen datos es el 2019. Por ello, este proyecto se ha realizado utilizando datos de consumo del año 2019.

La función de programación establece la energía fotovoltaica generada según la ecuación 7:

$$energy\_pv(i) = PSH(i) \cdot pp \cdot pr \quad (7)$$

Donde:

- $energy\_pv(i)$  → Energía producida en la hora  $i$  por la planta fotovoltaica [ $kWh$ ].
- $PSH(i)$  → *Peak Sun Hours* (HSP) por hora  $i$  obtenidas mediante la irradiancia [ $h$ ].
- $pp$  → Potencia pico instalada en el campo fotovoltaico [ $kW$ ].
- $pr$  → *Performance ratio* que mide el rendimiento de la instalación<sup>4</sup> [-].

Después, el algoritmo calcula la potencia pico fotovoltaica óptima según un bucle de programación que maximiza la energía autoconsumida y minimiza la energía excedentaria:

$$pp_{opt} \iff \max \left( \sum_{i=1}^{8760} self\_consumed(i) - \sum_{i=1}^{8760} excess(i) \right) \quad (8)$$

<sup>4</sup>En este caso: *Performance Ratio*  $pr = 0.887$  → Fuente PVsyst®.

Tras la ejecución del código, la función devuelve la **potencia pico FV óptima** a instalar. Adicionalmente, el **estudio de producción** se realiza mediante vectores de optimización cuyos datos son exportados automáticamente a un archivo de MS Excel:

- **HSP.** Las Horas Solares Pico disponibles [ $h$ ].
- **Consumo Total.** Energía suministrada al usuario<sup>5</sup> [ $kWh$ ].
- **Producción FV.** Energía generada mediante el Recurso de Generación Distribuida [ $kWh$ ].
- **Excedentes FV.** Energía excedentaria inyectada en la red de distribución [ $kWh$ ].
- **Consumo de red.** Energía suministrada al usuario desde la red de distribución [ $kWh$ ].
- **Autoconsumo.** Energía FV autoproducida y autoconsumida por el usuario [ $kWh$ ].

### 2.1.2. Estudio Económico - Función *economic.m*

Los datos de entrada requeridos por la función de MATLAB *economic.m* son, nuevamente, la irradiancia global en el plano por hora y el consumo por hora utilizados para la función *tfm.m*. Además, otras hipótesis de entrada son necesarias para realizar el análisis financiero:

- **Inversión Inicial** [€]. En este caso, las mediciones del proyecto se han enviado a Elecnor® con el objetivo de obtener una oferta económica fidedigna  $\rightarrow 100,395.22€$ .
- **Mantenimiento Anual** [€]. Cuota anual ofertada por Elecnor®  $\rightarrow 5,000€/año$ .
- **Atenuación de Potencial Anual de los Módulos FV** [%]. Ficha técnica  $\rightarrow 0.55\%/año$ .
- **Índice de Precios al Consumo (IPC)** [%]. Obtenido mediante la base de datos de los últimos 25 años del Instituto Nacional de Estadística  $\rightarrow 2.02\%/año$ .
- **Precios de Potencia y Energía** [€/kW, €/kWh]. Los precios por periodo para la tarifa 3.0TD han sido consultados a una empresa del sector energético: *Symelec Renovables*®.
  - Potencia: [0.053690, 0.037759, 0.019193, 0.016729, 0.012053, 0.007225] €/kW.
  - Energía: [0.207797, 0.184083, 0.153379, 0.130097, 0.108142, 0.110010] €/kWh.
- **Precio de Excedentes** [€/kWh]. El precio de compensación de excedentes inyectados en la red también se ha consultado a *Symelec Renovables*®, al igual que la tasa de depreciación anual de los excedentes  $\rightarrow 0.05€/kWh$  y  $1.5\%/año$ .

La función de programación asigna por periodo y mes la energía total demandada por el gimnasio, así como la producción FV y los excedentes respetando la distribución de periodos regulada para la tarifa eléctrica 3.0TD. Por tanto, la función *economic.m* determina las seis potencias óptimas a contratar si se incluyese la planta FV. En consecuencia, el programa calcula las potencias que minimizan el coste anual total del término de potencia, considerando que los excesos de potencia se facturan según la siguiente expresión:

$$F_{EP} = \sum_{i=1}^6 K_i \cdot 1.406368 \cdot \sqrt{\sum_{j=1}^n (P_{d_j} - P_{C_i})^2} \quad (9)$$

Donde:

- $F_{EP}$   $\rightarrow$  Penalización mensual por exceso de potencia demandada [€].
- $K_i$   $\rightarrow$  Coeficiente tarifario por periodo  $i$  [€/kW].
- $P_{d_j}$   $\rightarrow$  Potencia demandada en los  $n$  intervalos de 15 minutos en los que dicha potencia ha superado la potencia contratada en ese periodo  $P_{C_i}$  [kW].

<sup>5</sup>Ya sea mediante la planta FV o mediante la red de distribución eléctrica.

Tras la ejecución del código, la función devuelve las **seis potencias óptimas** a contratar, así como el periodo de retorno de la inversión. Adicionalmente, el **estudio económico** se realiza mediante información económica de los 25 años de vida útil del proyecto que es exportada automáticamente a un archivo de MS Excel:

- **Distribución del Consumo.** Incluyendo la energía total demandada por el gimnasio, los excedentes, la producción FV, el autoconsumo y la energía consumida de la red por periodo, mes y año para la tarifa eléctrica 3.0TD [ $kWh$ ].
- **Penalización por Exceso de Potencia.** La función calcula la penalización mensual por exceso de potencia teniendo y no teniendo la planta fotovoltaica [€].
- **Coste Total del Término de Energía.** Coste mensual de la energía consumida de la red teniendo y no teniendo la planta FV y considerando la compensación de excedentes [€].
- **Coste Total del Término de Potencia.** Se establece el coste de potencia fijo mensual teniendo y no teniendo la planta FV. Este resultado es sumado a la penalización por exceso de potencia para obtener el coste total del término de potencia mensual y anual [€].

## 2.2. Proyecto Técnico

El modelo escalable desarrollado para diseñar plantas de autoconsumo fotovoltaico ha sido aplicado en un *proyecto piloto* que será realmente ejecutado en la cubierta de Dreamfit Alcorcón. Por consiguiente, este Trabajo Fin de Máster incluye un proyecto de ingeniería completo que aborda todos los contenidos requeridos de acuerdo con la legislación vigente:

- **Memoria del Proyecto.** Incluyendo la memoria descriptiva, los cálculos, los estudios de producción y económico, el estudio de impacto ambiental y las conclusiones.
- **Especificaciones Técnicas.** En referencia a ejecución, materiales y puesta en marcha.
- **Estudio de Seguridad y Salud.** Para asegurar la seguridad durante y después de la obra.
- **Presupuesto de Proyecto.** Con objeto de evaluar la viabilidad del proyecto.
- **Planos.** Requeridos para representar gráficamente y definir por completo el proyecto.

### 2.2.1. Memoria de Proyecto

La **memoria descriptiva** de la memoria de proyecto proporciona información cualitativa de la planta de autoconsumo fotovoltaico de Dreamfit Alcorcón en términos de regulación y componentes principales. Por el contrario, la sección de **cálculos** de la memoria de proyecto proporciona información cuantitativa del diseño del Recurso de Generación Distribuida.

Tras la ejecución de la función de optimización *tfm.m*, la potencia fotovoltaica pico óptima para Dreamfit Alcorcón medida en campo fotovoltaico es de  $111 kW_p$ , mientras que la potencia nominal de la instalación medida en el inversor es de  $100 kW_n$ .

Para la selección de los principales componentes se ha realizado un estudio de mercado:

- **Módulos FV.** El diseño se ha llevado a cabo con el módulo FV monofacial *World-Class Top Performer* Trinasolar Vertex TSM-DE18M(II) con una potencia pico de  $505 W_p$ .
- **Inversor CC/CA.** La planta FV incluye el inversor internacionalmente reconocido Huawei *Smart PV Controller* SUN2000-100KTL-M1 con una potencia nominal de  $100 kW_n$ .

Los 220 módulos se basan en tecnología multi-busbar con 150 células monocristalinas PERC por módulo, alcanzando hasta un 21.2% de eficiencia. El inversor integra Inteligencia Artificial, diseño sin fusibles y un sistema de gestión y monitorización, así como 10 MPPTs con capacidad de conexión para 20 *strings* FV, aportando una máxima eficiencia del 98.4%:

Table 6. Configuración del sistema fotovoltaico.

SISTEMA FOTOVOLTAICO	
Fabricante de los Módulos FV	
Modelo de Módulos FV	TSM-DE18M-(II)-505
Nº de Módulos FV	220 módulos FV
Potencia Pico por Módulo FV	505 W <sub>p</sub>
Potencia Pico del Sistema FV	111.1 kW <sub>p</sub>
Fabricante del Inversor	
Modelo de Inversor	SUN2000-100KTL-M1-400Vac
Nº de inversores, Strings	1 inversor, 20 strings (10 MPPTs)
Potencia Nominal del Inversor	100 kW <sub>n</sub>
Potencia Nominal del Sistema FV	100 kW <sub>n</sub>

El inversor Huawei está equipado con un analizador de redes inteligente que recoge datos del desempeño de la planta FV que pueden ser analizados en tiempo real a través la plataforma *Fusion-Solar Smart Management System*. Las condiciones de trabajo del punto de máxima potencia así como las de circuito abierto y cortocircuito han sido analizadas de cara a garantizar la compatibilidad entre los 20 *strings* de 11 módulos FV conectados en serie y el inversor:

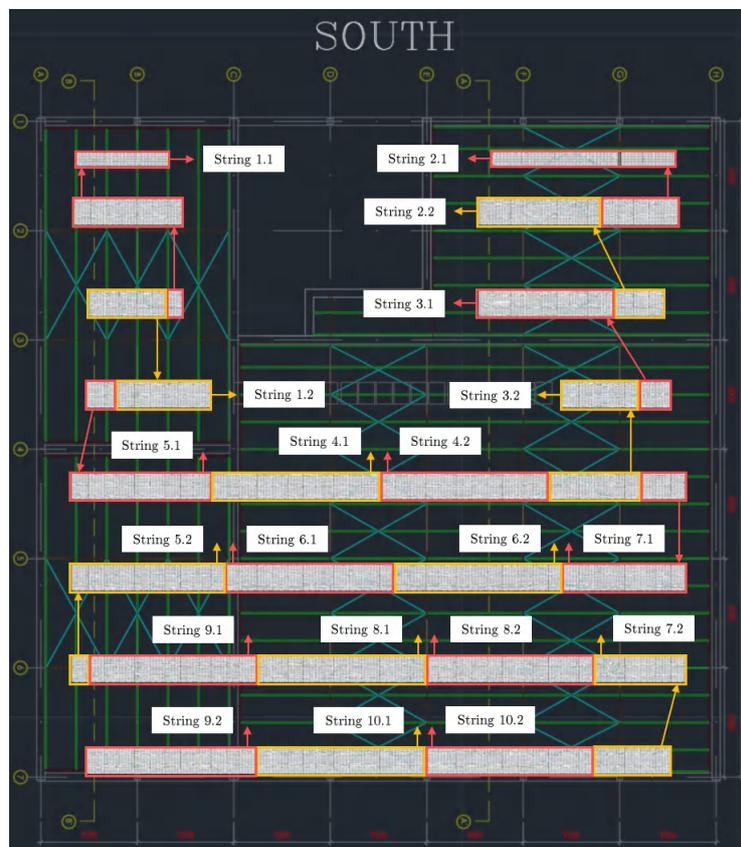


Figure 9. Distribución física de los paneles FV desarrollado con Autocad®.

La orientación de los paneles así como la distancia mínima entre elementos se ha calculado conforme a las Especificaciones Técnicas de las Instalaciones Conectadas a Red. Por otro lado, se ha llevado a cabo un estudio de sombras para asegurar que las pérdidas por sombreado anual no exceden el 0.3% en ningún módulo FV. El estudio de sombras aborda el análisis de la carta solar de Dreamfit Alcorcón según el *Solar Radiation Monitoring Laboratory*:

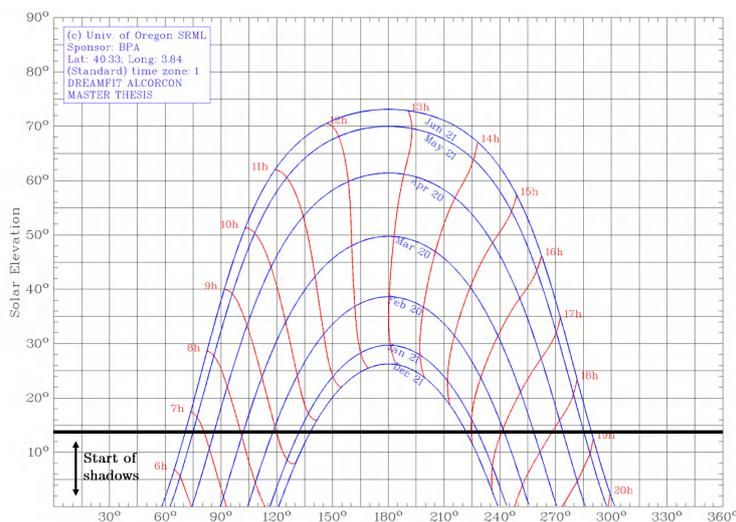


Figure 10. Carta solar de Dreamfit Alcorcón.

En resumen, de cara a maximizar la producción:

- **Ángulo de Inclinación:**  $\beta_{\text{ópt}} = 33.5^\circ$  con respecto al plano horizontal.
- **Ángulo Azimut:**  $\alpha_{\text{ópt}} = 0^\circ$ .
- **Distancia entre la Primera Fila de Paneles FV y el Muro Perimetral:** 1.99 m.
- **Distancia entre la Primera y la Segunda Fila de Paneles FV:** 2.50 m.
- **Distancia entre el Resto de Filas de Paneles FV:** 4.87 m.

Por su parte, las secciones de cableado se han dimensionado siguiendo la ITC-BT-40 sobre Instalaciones Generadoras de Baja Tensión y las Especificaciones Técnicas de las Instalaciones Conectadas a Red. Por tanto, respetando tanto el criterio térmico como el de caída de tensión:

- **Lado de CC.** Caída de Tensión:  $V_{\text{máx}} < 1.5\%$ . Temperatura Máxima:  $T_{\text{máx}} < 90^\circ\text{C}$ .  
– Dos polos:  $2 \cdot 6 \text{ mm}^2$ .
- **Lado de CA.** Caída de Tensión:  $V_{\text{máx}} < 1.5\%$ . Temperatura Máxima:  $T_{\text{máx}} < 90^\circ\text{C}$ .  
– Tres fases más neutro:  $4 \cdot 70 \text{ mm}^2$  y  $4 \cdot 120 \text{ mm}^2$ .
- **Secciones.** Conductores calculados para el 125% de la máxima corriente del generador.

La instalación cuenta con las protecciones eléctricas requeridas así como con los cuadros eléctricos adecuados para garantizar la seguridad tanto de las personas como de los propios equipos en caso de fallos en el sistema. Las protecciones se han dimensionado de acuerdo con Real Decreto 1663/2000 sobre conexión de instalaciones fotovoltaicas a la red de baja tensión, el Real Decreto 1699/2011 y el Reglamento Electrotécnico para Baja Tensión (REBT).

Asimismo, la planta FV se conectará a la red de tierras existente en el edificio para asegurar la equipotencialidad. Las tierras de todas las partes metálicas se unirán siguiendo la ITC-BT-08 y la ITC-BT-18 mediante cables de cobre revestido con secciones entre  $6 \text{ mm}^2$  y  $60 \text{ mm}^2$ .

La tabla 7 resume las protecciones incluidas en la planta de autoconsumo fotovoltaico:

Table 7. Resumen cualitativo de las protecciones eléctricas empleadas.

PROTECCIÓN	TIPO DE PROTECCIÓN	CC	CA
CONTACTOS DIRECTOS	AISLAMIENTO DE PARTES ACTIVAS	AISLAMIENTO CLASE II	
	BARRERAS, ENVOLVENTES Y OBSTÁCULOS	TUBOS, PROTECCIÓN IP65	TUBOS
	UBICACIONES FUERA DE ALCANCE	ZONA DE INSTALACIONES	FALSO TECHO, ZONA INSTALACIONES
CONTACTOS INDIRECTOS	CORRIENTE RESIDUAL	AISLAMIENTO CLASE II, PROTECCIONES DEL INVERSOR	AISLAMIENTO CLASE II, RELÉ DIFERENCIAL
SPBRECARGAS & CORTOCIRCUITOS	SOBREINTENSIDADES	INTERRUPTORES CC DEL INVERSOR	INTERRUPTORES AUTOMÁTICOS
PUESTA A TIERRA	CONTACTOS INDIRECTOS	MASAS CONECTADAS A TIERRA MEDIANTE CABLE DE COBRE REVESTIDO	

Las canalizaciones eléctricas se han diseñado respetando la normativa vigente relativa a tubos de canalización, es decir, siguiendo la instrucción técnica ITC-BT-21. La canalización se basa en tubos libres de halógenos preparados para su uso en intemperie, con alta resistencia a los rayos ultravioleta y con diámetros interiores entre 21.6 mm y 45 mm.

Por otro lado, los módulos fotovoltaicos se montan sobre una estructura de aluminio capaz de soportar las cargas derivadas de la propia instalación, y que proporciona los ángulos de inclinación y orientación adecuados para maximizar el desempeño de la planta de generación. La cubierta del edificio no requiere refuerzo estructural alguno porque el arquitecto calculó la estructura previendo una sobrecarga para instalaciones y otros usos de 25 kg/m<sup>2</sup>.

Conforme al Real Decreto 244/2019, actualmente una planta de autoconsumo fotovoltaico en España puede compartir la infraestructura de interconexión con la línea de suministro del usuario. En consecuencia, la planta FV puede ser directamente interconectada a la red de distribución como un circuito adicional del Cuadro General de Baja Tensión (CGBT):

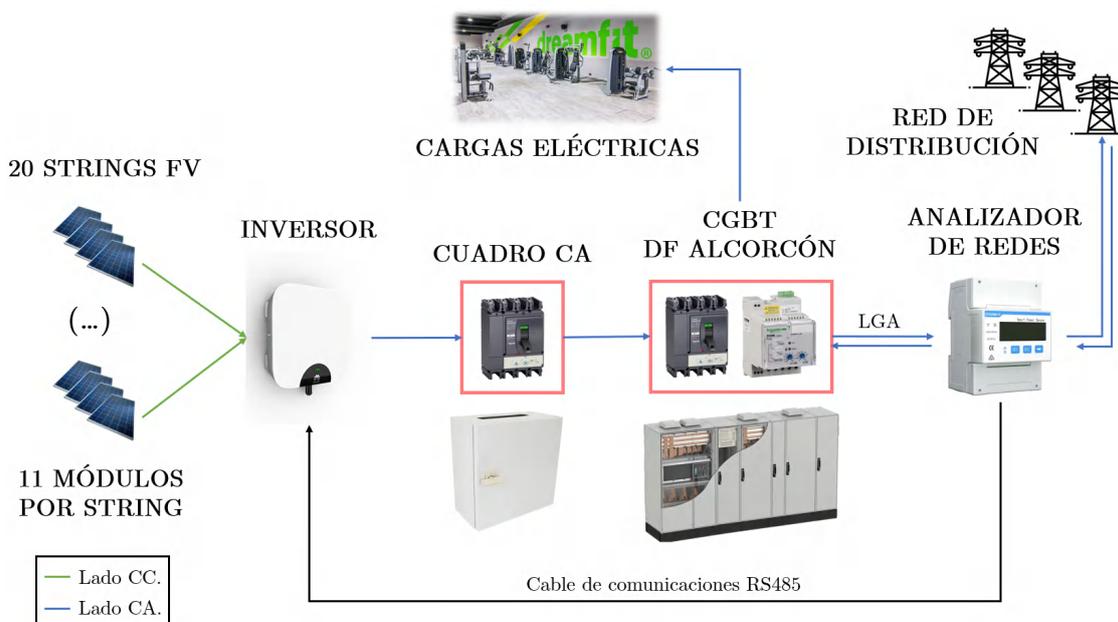


Figure 11. Esquema de interconexión de la planta FV de Dreamfit Alcorcón.

### 2.2.2. Especificaciones Técnicas

El objetivo de las especificaciones técnicas pasa por establecer los requerimientos mínimos que la planta fotovoltaica conectada a red debe cumplir. Las especificaciones desarrolladas sirven como guía tanto para instaladores como para fabricantes. El documento define las especificaciones mínimas que la instalación FV debe respetar para asegurar la calidad de los trabajos por el bien del cliente y del desarrollo de la propia tecnología y del proyecto en sí mismo.

El alcance de las especificaciones técnicas se extiende hasta los sistemas mecánicos, eléctricos y electrónicos que componen la instalación. Concretamente, el documento se basa en la regulación vigente: Real Decreto 1699/2011, Real Decreto 413/2014 o Real Decreto 900/2015.

### 2.2.3. Estudio de Seguridad y Salud

El estudio analiza, desarrolla y complementa las disposiciones relativas a la prevención de accidentes y enfermedades laborales, la regulación en torno a la higiene en el trabajo y el buen estado de las instalaciones, así como cualquier otro requerimiento de seguridad y salud.

El estudio de seguridad y salud se basa en la regulación vigente relacionada con la Ley 31/1995, el Real Decreto 485/1997, el Real Decreto 773/1997 o el Real Decreto 614/2001.

### 2.2.4. Presupuesto del Proyecto

El presupuesto del presente proyecto se ha desarrollado mediante el *software* profesional Presto®, considerando los precios unitarios ofertados por Elecnor®. Presto es un programa integral para la gestión de presupuestos especializado en proyectos de construcción.

En este sentido, el presupuesto del proyecto se ha dividido en seis capítulos:

1. **Equipos Principales.** Incluyendo los módulos FV, el inversor, la estructura de soporte y el analizador de redes inteligente.
2. **Protección y Cableado.** Considerando tanto el lado de CC como el CA.
3. **Servicios Auxiliares.** Cubre la asistencia requerida de obra civil, así como la grúa necesaria para subir los materiales de construcción a la cubierta de Dreamfit Alcorcón.
4. **Seguridad y Salud.** Incluyendo todos los Equipos de Protección Individual.
5. **Gestión de Residuos.** En conformidad con la orden 2726/2009 (Comunidad de Madrid).
6. **Puesta en Marcha.** Incluyendo la legalización de la instalación de autoconsumo.

En este caso, el importe total del proyecto asciende a 100,395.22€ (IVA no incluido).

### 2.2.5. Planos del Proyecto

Los cinco planos que definen gráficamente el proyecto se han diseñado mediante Autocad®:

1. Situación y Localización del Proyecto de Autoconsumo Fotovoltaico.
2. Distribución General - Vista en Planta de la cubierta de Dreamfit Alcorcón.
3. Canalización Eléctrica.
4. Estructura de Soporte Fotovoltaico.
5. Esquema Eléctrico de la Planta Fotovoltaica de Dreamfit Alcorcón.

### 3. Resultados

Esta sección resume los resultados obtenidos en los estudios de producción y económico.

#### 3.1. Resultados del Estudio de Producción

Los principales resultados anuales derivados del estudio de producción basado en la función  $tfm.m$  para una potencia pico óptima de  $111 kW_p$  y una potencia nominal de  $100 kW_n$  son:

Table 8. Estudio de producción - Principales resultados anuales.

RESULTADOS ANUALES	kWh/año
CONSUMO TOTAL	447,567.75
PRODUCCIÓN FV	198,897.59
EXCEDENTES FV	29,733.28
CONSUMO DE RED	278,403.45
AUTOCONSUMO	169,164.30
POTENCIA FV PICO ÓPTIMA	111 kW

Observando la tabla 8:

- **Porcentaje de Autoconsumo.** Más del 85% de la energía generada por la planta fotovoltaica será autoconsumida por la instalación deportiva ✓.
- **Cuota Autárquica.** Casi el 38% de la energía consumida al año por Dreamfit Alcorcón será generada por la planta FV ✓.

Igualmente, se incluye la tabla 9 a modo de resumen de resultados principales del estudio de producción desglosados por mes para el primer año de vida útil del proyecto:

Table 9. Estudio de producción - Balances y principales resultados mensuales.

ESTUDIO DE PRODUCCIÓN FV - AÑO 1						
MES	HSP (h)	CONSUMO TOTAL (kWh)	PRODUCCIÓN FV (kWh)	EXCEDENTES FV (kWh)	CONSUMO DE RED (kWh)	AUTOCONSUMO (kWh)
ENERO	98.14	43,352.51	9,662.73	727.07	34,416.85	8,935.66
FEBRERO	117.20	37,012.88	11,538.99	1,126.77	26,600.66	10,412.22
MARZO	180.40	34,741.40	17,761.94	3,329.68	20,309.14	14,432.26
ABRIL	195.81	32,663.31	19,278.55	4,699.46	18,084.22	14,579.09
MAYO	178.32	34,512.61	17,556.79	2,903.12	19,858.95	14,653.67
JUNIO	216.00	37,505.64	21,266.38	3,335.63	19,574.89	17,930.75
JULIO	242.88	46,397.28	23,912.75	2,655.71	25,140.24	21,257.03
AGOSTO	224.32	40,836.00	22,085.82	3,451.44	22,201.63	18,634.37
SEPTIEMBRE	201.23	37,022.64	19,812.73	2,839.92	20,049.83	16,972.81
OCTUBRE	151.10	35,484.65	14,877.22	2,091.24	22,698.67	12,785.98
NOVIEMBRE	103.13	34,217.15	10,153.56	1,090.61	25,154.20	9,062.94
DICIEMBRE	111.62	33,821.68	10,990.14	1,482.63	24,314.16	9,507.51
<b>AÑO</b>	<b>2,020.15</b>	<b>447,567.75</b>	<b>198,897.59</b>	<b>29,733.28</b>	<b>278,403.45</b>	<b>169,164.30</b>

La incorporación de una batería sólo sería interesante para aprovechar el excedente generado los domingos y días festivos, pues son los únicos días en los que la instalación se cierra al público cuando todavía quedan horas útiles de sol. Por tanto, teniendo en cuenta el alto porcentaje de autoconsumo obtenido y considerando que la tecnología de almacenamiento no ha alcanzado todavía la madurez, se ha decidido no incorporar una batería al proyecto. Los excedentes serán inyectados en la red y compensados de acuerdo con el Real Decreto 244/2019.

Finalmente, la figura 12 compara el desempeño de la planta FV contrastando el día laborable promedio del mes más soleado frente al día laborable promedio del mes más nublado del año:

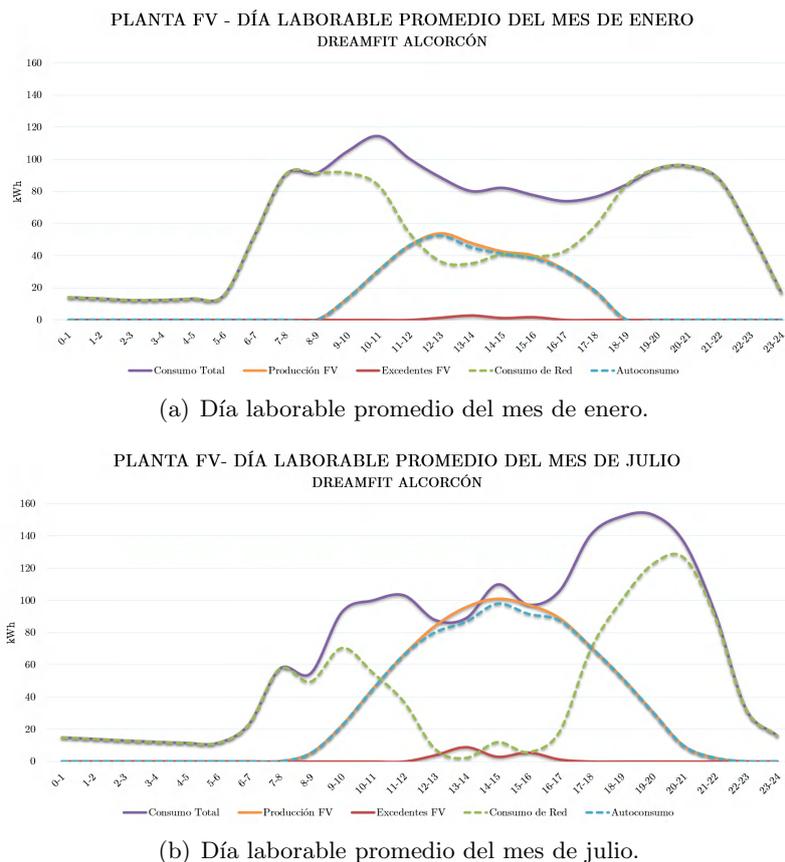


Figure 12. Desempeño de la planta FV - Día más soleado frente al más nublado.

Analizando las gráficas 12(a) y 12(b), se observa una relación coherente e inversamente proporcional entre la energía consumida de la red y la producción fotovoltaica. Igualmente, la energía consumida de la red se reduce visiblemente durante las horas de sol.

### 3.2. Resultados del Estudio Económico

Tras la ejecución de la función *economic.m*, las potencias óptimas a contratar por periodo para la tarifa eléctrica 3.0TD en Dreamfit Alcorcón son las siguientes<sup>6</sup>:

- $P_1 = 143 \text{ kW} \rightarrow P_1 \text{ ópt} = 135 \text{ kW}$ .
- $P_2 = P_3 = P_4 = P_5 = 155 \text{ kW} \rightarrow P_2 \text{ ópt} = P_3 \text{ ópt} = P_4 \text{ ópt} = P_5 \text{ ópt} = 135 \text{ kW}$ .
- $P_6 = 155 \text{ kW} \rightarrow P_6 \text{ ópt} = 155 \text{ kW}$ .

<sup>6</sup>Necesariamente  $P_1 \leq P_2 \leq P_3 \leq P_4 \leq P_5 \leq P_6$  para la tarifa eléctrica 3.0TD.

Adicionalmente, la figura 13 presenta la asignación por periodos para la tarifa 3.0TD de Dreamfit Alcorcón del consumo total, la producción fotovoltaica y el autoconsumo:

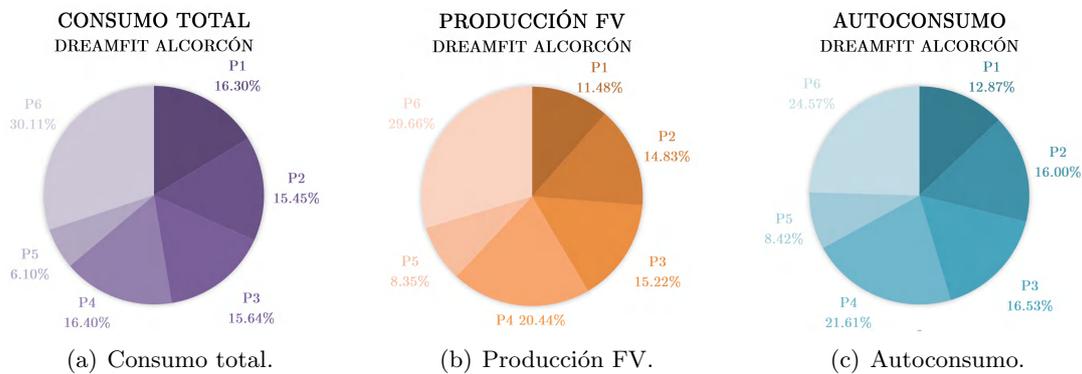


Figure 13. Estudio económico - Consumo y producción por periodos en tarifa 3.0TD.

En este punto se evalúa la viabilidad económica del proyecto mediante la Tasa Interna de Retorno y el Periodo de Retorno. Por tanto, la Tasa Interna de Retorno (TIR) del proyecto de 25 años de vida útil se calcula mediante los Flujos de Caja (FC):

$$0 = \sum_{n=0}^{25} \frac{FC_n}{(1 + TIR)^n} \rightarrow \boxed{TIR = 25.96\%} \quad (10)$$

El Periodo de Retorno (PR) se calcula considerando que la suma de los flujos de caja toma signo positivo entre el tercer y el cuarto año de vida del proyecto:

$$0 = \sum_{n=0}^{PR} FC_n \rightarrow PR = 3.86 \text{ años} \rightarrow \boxed{PR \approx 4 \text{ años}} \quad (11)$$

El Periodo de Retorno se analiza también gráficamente en la figura 14. La gráfica evalúa la suma de flujos de caja considerando el IPC así como cualquier otro ratio económico mencionado en la sección 2.1.2, esto es, se muestra igualmente el Valor Actual Neto (VAN) del proyecto:

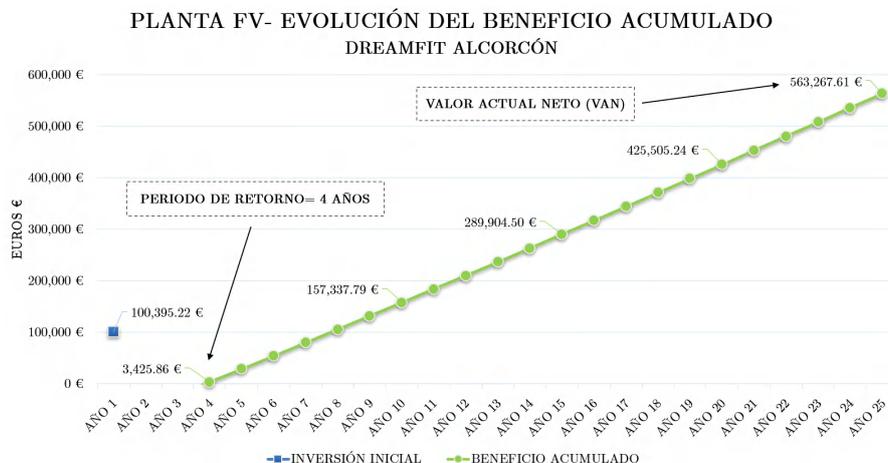


Figure 14. Estudio económico - Beneficio acumulado de la planta FV de Dreamfit Alcorcón.

En conclusión, la Tasa Interna de Retorno y el Periodo de Retorno de la planta FV son:

$$\boxed{TIR = 25.96\%} \quad \boxed{\text{Periodo de Retorno} = 4 \text{ años}} \quad (12)$$

### 3.3. Comprobación del Modelo Fotovoltaico

La precisión del modelo realizado en MATLAB se ha contrastado con una simulación desarrollada mediante el *software* profesional PVsyst®. Los estudios de producción y económico han sido replicados bajo las mismas hipótesis, restricciones y suposiciones:

Table 10. Evaluación del modelo FV en MATLAB.

RESULTADOS ANUALES		PVsyst	MATLAB	DESVIACIÓN
PRODUCCIÓN	PRODUCCIÓN FV (kWh/year)	205,570.00	198,897.59	-3.25%
	EXCEDENTES FV (kWh/year)	30,310.00	29,733.28	-1.90%
	CONSUMO DE RED (kWh/year)	277,100.00	278,403.45	0.47%
	AUTOCONSUMO (kWh/year)	170,470.00	169,164.30	-0.77%
FINANZAS	VALOR ACTUAL NETO AÑO 25 (€)	552,451.00	563,267.61	1.96%
	PERIODO DE RETORNO (años)	4.50	3.86	-14.22%
	COSTE NIVELADO DE ENERGÍA LCOE (€/kWh)	0.071	0.070	-1.41%

- **Estudio de Producción.** Las diferencias entre los resultados obtenidos se deben a simplificaciones en materia de pérdidas y especificaciones técnicas de los componentes eléctricos.
- **Estudio Económico.** Las diferencias entre los resultados obtenidos se deben a que PVsyst no realiza el análisis económico específicamente para la tarifa eléctrica española 3.0TD, sino que aplica una tarifa de precio único que ha sido correspondientemente ajustado.

## 4. Conclusiones

En conclusión, el **objetivo principal** del proyecto se ha conseguido:

- Observando la tabla 10, efectivamente se ha desarrollado un **modelo escalable** que podría replicarse en cualquier instalación con base de datos hora a hora de consumo ✓.
- Gracias a este Trabajo Fin de Máster se podrían diseñar e incluir plantas de autoconsumo fotovoltaico en **cualquier gimnasio Dreamfit** en el medio plazo ✓.
- El modelo se ha aplicado en Dreamfit Alcorcón, desarrollándose un **proyecto de ingeniería completo** que será ejecutado en la práctica en el año 2022 ✓.

El resto de **subobjetivos** del proyecto también se han logrado:

- **Autoconsumo.** Casi 170 *MWh* al año serán autoconsumidos por Dreamfit Alcorcón gracias a la inclusión de la planta FV, autoconsumiendo más del 85% de la energía generada anualmente por el Recurso de Generación Distribuida ✓.
- **Emisiones.** Se evitará la emisión a la atmósfera de más de 50  $t_{eq\ CO_2}$  al año gracias a este proyecto de energía renovable, reduciendo el cambio climático y fomentando los Objetivos de Desarrollo Sostenible de acuerdo con las *IEA Life Cycle Emissions* ✓.
- **Eficiencia Energética y Rentabilidad.** Dreamfit Alcorcón reducirá el consumo de energía eléctrica procedente de la red casi un 40% anual gracias a los módulos FV ✓.
- **Salud.** El gimnasio no sólo va a autoconsumir energía, sino que inyectará en la red casi 30 *MWh* anuales de energía verde excedentaria, respaldando su lema *somos salud* ✓.

## 5. Referencias Principales

1. IRENA, *Futuro de la Energía Solar Fotovoltaica*, URL visitada el 19/08/2021.
2. BOE - Real Decreto 1027/2007, *Reglamento de Instalaciones Térmicas en los Edificios*, URL visitada el 19/08/2021.
3. BOE - Real Decreto 244/2019, *Condiciones Administrativas y Económicas del Autoconsumo*, URL visitada el 19/08/2021.
4. IDAE, *Evolución Tecnológica y Prospectiva de Costes de las Energías Renovables*, URL visitada el 19/08/2021.
5. IDAE, *Pliogo de Condiciones Técnicas de Instalaciones Conectadas a Red*, URL visitada el 19/08/2021.
6. Dreamfit, *Cadena de Gimnasios Low Cost*, URL visitada el 19/08/2021.
7. Mathworks, *Matlab & Simulink*, URL visitada el 19/08/2021.
8. Comisión Europea, *Herramienta PVGIS TMY*, URL visitada el 19/08/2021.
9. Circutor, *Serie CVM-MINI*, URL visitada el 19/08/2021.
10. INE, *Índice de Precios al Consumo*, URL visitada el 19/08/2021.
11. UNE, *UNE 157001:2014*, URL visitada el 19/08/2021.
12. Trinasolar, *Módulos Vertex TSM-DE18M(II)*, URL visitada el 19/08/2021.
13. Huawei, *Inversor DC/AC Smart PV Controller SUN2000-100KTL-M1*, URL visitado el 19/08/2021.
14. Huawei, *Fusión Solar Smart PV Management System*, URL visitado el 19/08/2021.
15. Universidad de Oregon, *Laboratorio de Monitorización de Radiación Solar*, URL visitada el 19/08/2021.
16. BOE - Real Decreto 1663/2000, *Conexión de Instalaciones Fotovoltaicas a la Red*, URL visitado el 19/08/2021.
17. BOE - Real Decreto 1699/2011, *Conexión a Red de Instalaciones de Pequeña Potencia*, URL visitado el 19/08/2021.
18. BOE - Real Decreto 842/2002, *Reglamento Electrotécnico para Baja Tensión*, URL visitado el 19/08/2021.
19. BOE - Real Decreto 413/2014, *Generación Eléctrica mediante Fuentes Renovables*, URL visitada el 19/08/2021.
20. BOE - Ley 31/1995, *Prevención de Riesgos Laborales*, URL visitada el 19/08/2021.
21. BOE - Real Decreto 485/1997, *Señalización de Seguridad y Salud en el Trabajo.*, URL visitada el 19/08/2021.
22. BOE - Real Decreto 773/1997, *Utilización de Equipos de Protección Individual*, URL visitada el 19/08/2021.
23. BOE - Real Decreto 614/2001, *Protección de los Trabajadores frente al Riesgo Eléctrico*, URL visitada el 19/08/2021.
24. RIB España, *Presto iTWO*, URL visitada el 19/08/2021.
25. Comunidad de Madrid, *Orden 2726/2009*, URL visitada el 19/08/2021.
26. Autodesk, *Autocad*, URL visitada el 19/08/2021.
27. PVsyst, *Software Fotovoltaico*, URL visitada el 19/08/2021.
28. IEA, *España - Países & Regiones*, URL visitada el 19/08/2021.

### **NOMENCLATURA UNESCO:**

- Campo: Ciencias Tecnológicas (código 33).
- Disciplina: Ingeniería y Tecnología Eléctrica (código 3306).
- Subdisciplinas: Utilización de la Corriente Continua (330601) y Aplicaciones Eléctricas (330602).

# Table of Contents

## Documents

List of Figures	3
List of Tables	7
I PROJECT MEMORY	9
II TECHNICAL SPECIFICATIONS	163
III HEALTH AND SAFETY STUDY	185
IV PROJECT BUDGET	211
V PLANS	219
Bibliography	232



# List of Figures

1	Dreamfit Gym Chain launches in the period 2010-2021. . . . .	II
2	Physical distribution of the PV strings developed with Autocad®. . . . .	VI
3	Sun path chart of Dreamfit Alcorcón. . . . .	VII
4	Interconnection schema of Dreamfit Alcorcón PV plant. . . . .	VIII
5	PV plant performance - Most sunny versus most cloudy day. . . . .	XI
6	Economic study - Consumption and production allocation per 3.0TD tariff periods. . . . .	XII
7	Economic study - Cumulative profit evolution of Dreamfit Alcorcón PV plant. . . . .	XII
8	Aperturas de la cadena de gimnasios Dreamfit en el periodo 2010-2021. . . . .	II
9	Distribución física de los paneles FV desarrollado con Autocad®. . . . .	VI
10	Carta solar de Dreamfit Alcorcón. . . . .	VII
11	Esquema de interconexión de la planta FV de Dreamfit Alcorcón. . . . .	VIII
12	Desempeño de la planta FV - Día más soleado frente al más nublado. . . . .	XI
13	Estudio económico - Consumo y producción por periodos en tarifa 3.0TD. . . . .	XII
14	Estudio económico - Beneficio acumulado de la planta FV de Dreamfit Alcorcón. . . . .	XII

## I PROJECT MEMORY

1.1	Cumulative solar PV capacity [1]. . . . .	22
1.2	Evolution of generation cost for rooftop PV plants [3]. . . . .	23
1.3	Dreamfit Gym Chain launches in the period 2010-2021. . . . .	25
1.4	Total energy consumption per year in Dreamfit Alcorcón. . . . .	26
1.5	Location of Dreamfit Alcorcón [4]. . . . .	27
1.6	Chosen manufacturers for the PV facility. . . . .	30
1.7	Trinasolar's Vertex backsheet performance warranty [9]. . . . .	31
1.8	Trinasolar Vertex PV modules dimensions [9]. . . . .	32
1.9	Layers of conventional and PERC solar cells [13]. . . . .	33
1.10	Curves of Trinasolar Vertex TSM-DE18M(II)-495W PV module [9]. . . . .	33
1.11	Fusion-Solar Management System - Plant overview [17]. . . . .	35

---

1.12	Fusion-Solar Management System - Smart power sensor and energy balance [17]. . .	36
1.13	Smart Power Sensor DTSU666-H wiring terminals [18]. . . . .	36
1.14	Mounting rails positioning with respect to the long side frame [22]. . . . .	42
1.15	Installation method of clamps [22]. . . . .	42
1.16	Photovoltaic mounting structure [23]. . . . .	43
1.17	Interconnection schema of Dreamfit Alcorcón PV plant. . . . .	43
2.1	Orientation of the PV modules [25]. . . . .	48
2.2	Optimal orientation of the PV system [28]. . . . .	48
2.3	Peak Sun Hours. . . . .	49
2.4	Power Analyser of Dreamfit Alcorcón [35]. . . . .	51
2.5	Operating procedure followed by the PV peak power optimisation algorithm. . . .	53
2.6	Optimal PV peak power of Dreamfit Alcorcón returned by MATLAB. . . . .	53
2.7	MATLAB - Annual results - PV production. . . . .	54
2.8	Circuit diagram of the inverter [38]. . . . .	56
2.9	Minimum distance between elements [42]. . . . .	60
2.10	Solar elevation [42]. . . . .	60
2.11	Sun path chart of Dreamfit Alcorcón [43]. . . . .	61
2.12	Projected vertical height of PV modules. . . . .	62
2.13	Height of the perimeter wall. . . . .	63
2.14	Modules susceptible to higher power losses due to shadows [46]. . . . .	64
2.15	Profile of obstacles for the orange PV module. . . . .	65
2.16	Profile of obstacles for the pink PV module. . . . .	66
2.17	Profile of obstacles for the yellow PV module. . . . .	67
2.18	Profile of obstacles for the blue PV module. . . . .	68
2.19	Profile of obstacles for the red PV module. . . . .	69
2.20	Profile of obstacles for the green PV module. . . . .	70
2.21	Physical distribution of the PV strings [46]. . . . .	76
2.22	Electrical canalisation and inverter location [46]. . . . .	77
2.23	Location of the electrical AC box [46]. . . . .	78
2.24	Cable tube between the facility zone and the main electrical distribution panel [46].	79
2.25	Electrical installation of the PV modules [22]. . . . .	79

---

2.26	Section view of the PV modules structure [46]. . . . .	96
3.1	Incidence Angle Modifier (IAM) [58]. . . . .	102
3.2	Evolution of self-consumption and autarky rates along the 8,760h of the year. . . . .	105
3.3	PV plant performance - Most sunny versus most cloudy day. . . . .	108
3.4	Monthly performance results of Dreamfit Alcorcón PV plant. . . . .	109
3.5	Production study - Balances and main results along the useful life of the project. . . . .	111
3.6	Electricity tariff 3.0TD seasons and pricing periods. . . . .	114
3.7	Electricity tariff 3.0TD at weekends and national bank holidays. . . . .	114
3.8	Reactive energy penalty for electricity tariff 3.0TD. . . . .	117
3.9	Simplified Energy Compensation Mechanism [62]. . . . .	118
3.10	Optimal contracted powers and payback period returned by MATLAB. . . . .	121
3.11	Tariff 3.0TD - Annual consumption allocation per period of Dreamfit Alcorcón. . . . .	122
3.12	Cumulative profit evolution of Dreamfit Alcorcón PV plant. . . . .	124
4.1	Saved $CO_2$ emissions along the useful life of the PV plant. . . . .	130
6.1	Sustainable Development Goals [69]. . . . .	136
<b>IV PROJECT BUDGET</b>		
1	Current status of the roof of Dreamfit Alcorcón. . . . .	213



# List of Tables

1	Configuration of the photovoltaic system. . . . .	VI
2	Qualitative summary of the utilised protections. . . . .	VIII
3	Production study - Main annual results. . . . .	X
4	Production study - Balances and main monthly results. . . . .	X
5	MATLAB PV model assessment. . . . .	XIII
6	Configuración del sistema fotovoltaico. . . . .	VI
7	Resumen cualitativo de las protecciones eléctricas empleadas. . . . .	VIII
8	Estudio de producción - Principales resultados anuales. . . . .	X
9	Estudio de producción - Balances y principales resultados mensuales. . . . .	X
10	Evaluación del modelo FV en MATLAB. . . . .	XIII

## **I PROJECT MEMORY**

1.1	Basic and advanced features of the inverter management system [15]. . . . .	34
1.2	Utilised wiring per stretch. . . . .	37
1.3	Utilised earthing wiring per stretch. . . . .	41
1.4	Qualitative summary of the utilised protections. . . . .	41
1.5	Internal diameter of the utilised canalisation tubes. . . . .	41
1.6	Theoretical evaluation of the volume and tons of waste. . . . .	45
2.1	MATLAB - Annual results - PV production. . . . .	54
2.2	Description of the PV system. . . . .	55
2.3	Main electrical features of every PV module. . . . .	55
2.4	Main electrical features of the inverter. . . . .	56
2.5	Angles required to construct the profile of obstacles. . . . .	71
2.6	Reference table of solar irradiance losses due to shadows [48]. . . . .	72
2.7	Percentage of annual power losses due to shadows for the orange PV module. . . . .	73
2.8	Percentage of annual power losses due to shadows for the pink PV module. . . . .	73

---

2.9	Percentage of annual power losses due to shadows for the yellow PV module. . . . .	74
2.10	Percentage of annual power losses due to shadows for the blue PV module. . . . .	74
2.11	Percentage of annual power losses due to shadows for the red PV module. . . . .	75
2.12	Percentage of annual power losses due to shadows for the green PV module. . . . .	75
2.13	Voltage drop and operating temperature per line. . . . .	86
2.14	Section required for protection wires [53]. . . . .	94
2.15	Protection wire length requirements. . . . .	94
2.16	Dimensions of the canalisation tubes. . . . .	95
3.1	Technical hypothesis for Dreamfit Alcorcón PV plant. . . . .	104
3.2	Self-consumption rate analysis per day of week and month. . . . .	106
3.3	PV plant performance - Most sunny versus most cloudy day. . . . .	107
3.4	Production study - Balances and main results. . . . .	112
3.5	Monthly distribution of periods in electricity tariff 3.0TD. . . . .	115
3.6	Economical hypothesis for Dreamfit Alcorcón PV plant. . . . .	120
3.7	Contracted powers with and without PV plant. . . . .	121
3.8	Economic study - Detailed results for the first useful year. . . . .	125
3.9	Economic study - Detailed results for the last useful year. . . . .	126
3.10	Economic CAPEX & OPEX study - Balances and main results. . . . .	127
4.1	PV system Life Cycle Emissions. . . . .	130
4.2	Environmental impact - Balances and main results. . . . .	131
5.1	Production study assessment. . . . .	133
5.2	Economic study assessment. . . . .	134
6.1	Consumption tariff for PVsyst economic study. . . . .	138

Document I

# PROJECT MEMORY



# Document I. Project Memory

## Table of Contents

<b>List of Figures</b>	<b>15</b>
<b>List of Tables</b>	<b>19</b>
<b>1 Descriptive Memory</b>	<b>21</b>
1.1 Introduction . . . . .	22
1.2 Reference Framework . . . . .	23
1.3 Motivation . . . . .	23
1.4 Target of the Project . . . . .	24
1.5 Collaboration with Dreamfit . . . . .	25
1.6 Definition of the Project . . . . .	26
1.7 Initial Information . . . . .	27
1.7.1 Location of the PV Facility . . . . .	27
1.7.2 Project Writer Team . . . . .	27
1.7.3 Precedents . . . . .	27
1.8 Applicable Regulation . . . . .	28
1.8.1 Electrical Regulation . . . . .	28
1.8.2 Health and Safety Regulation . . . . .	28
1.8.3 Environmental Regulation . . . . .	29
1.9 Photovoltaic Installed Power . . . . .	29
1.10 Main Components and Features of the PV Facility . . . . .	30
1.11 Photovoltaic Modules . . . . .	31
1.12 Inverter . . . . .	34
1.12.1 Monitoring System . . . . .	35
1.13 Wiring . . . . .	37
1.14 Protections . . . . .	38
1.14.1 Direct Current Side Protections . . . . .	38
1.14.2 Alternating Current Side Protections . . . . .	39
1.14.3 Inverter Protections . . . . .	40
1.15 Earthing System . . . . .	40
1.16 Electrical Canalisation . . . . .	41
1.17 Photovoltaic Mounting Structure . . . . .	42

- 1.18 Interconnection Schema . . . . . 43
- 1.19 Construction Waste Management . . . . . 44
  - 1.19.1 Identification of Residues . . . . . 44
  - 1.19.2 Estimate of Generated Residues . . . . . 45
  - 1.19.3 Destination of Residues . . . . . 45
  - 1.19.4 Expected Waste Management Cost . . . . . 45
- 2 Calculations . . . . . 47**
  - 2.1 Orientation of the system . . . . . 48
  - 2.2 Optimal Photovoltaic Peak Power Algorithm . . . . . 49
    - 2.2.1 Optimal Peak Power Algorithm Explanation - *tfm.m* . . . . . 51
  - 2.3 Photovoltaic System . . . . . 55
    - 2.3.1 Photovoltaic Modules . . . . . 55
    - 2.3.2 Inverter . . . . . 56
    - 2.3.3 Configuration of the Photovoltaic System . . . . . 56
      - 2.3.3.1 Maximum Power Point Conditions . . . . . 57
      - 2.3.3.2 Open-Circuit Conditions . . . . . 58
      - 2.3.3.3 Short-Circuit Conditions . . . . . 59
  - 2.4 Minimum Distance between Elements . . . . . 60
    - 2.4.1 Minimum Distance between the First and the Second PV Row . . . . . 63
    - 2.4.2 Minimum Distance between the Rest of the PV Rows . . . . . 63
    - 2.4.3 Minimum Distance between the First PV Row and the Perimeter Wall . . . . . 63
  - 2.5 Shades Analysis . . . . . 64
  - 2.6 Wiring Section . . . . . 76
    - 2.6.1 Direct Current Wiring Section . . . . . 80
      - 2.6.1.1 Stretch 1 - Wiring between the PV Modules and the Inverter . . . . . 81
    - 2.6.2 Alternating Current Wiring Section . . . . . 82
      - 2.6.2.1 Stretch 2 - Wiring between the Inverter and the AC Box . . . . . 83
      - 2.6.2.2 Stretch 3 - Wiring between the AC Box and the Main Panel . . . . . 84
    - 2.6.3 Wiring Summary . . . . . 85
  - 2.7 Protections . . . . . 87
    - 2.7.1 DC Protections . . . . . 87
      - 2.7.1.1 DC Switches . . . . . 87
      - 2.7.1.2 Over-Voltage Protection . . . . . 88
    - 2.7.2 AC Protections . . . . . 88
      - 2.7.2.1 Automatic Circuit Breakers . . . . . 89
      - 2.7.2.2 Automatic Residual Current Circuit Breaker . . . . . 91
      - 2.7.2.3 Voltage and Frequency Control . . . . . 92
      - 2.7.2.4 General Manual Circuit Breaker . . . . . 92
  - 2.8 Earthing System . . . . . 92
  - 2.9 Electrical Canalisation . . . . . 95
  - 2.10 Photovoltaic Mounting Structure . . . . . 96

<b>3</b>	<b>Production and Economic Study</b>	<b>99</b>
3.1	Production Study . . . . .	100
3.1.1	Input and Output Data . . . . .	100
3.1.2	System Yield and Losses . . . . .	100
3.1.2.1	Mismatch or Coupling Losses . . . . .	101
3.1.2.2	Losses due to Dust or Dirt at the PV Modules . . . . .	101
3.1.2.3	Array Incidence Losses - Incidence Angle Modifier . . . . .	101
3.1.2.4	Losses with respect to the Rated Power . . . . .	102
3.1.2.5	PV Modules Efficiency and Temperature Relation . . . . .	102
3.1.2.6	Ohmic Losses in DC and AC Wiring . . . . .	103
3.1.2.7	Errors while Tracking the Maximum Power Point . . . . .	103
3.1.2.8	Inverter Energy Efficiency . . . . .	103
3.1.2.9	Losses due to Generator Layout and Shading . . . . .	103
3.1.3	Performance Ratio . . . . .	103
3.1.4	Results of the Production Study . . . . .	104
3.2	Economic Study . . . . .	113
3.2.1	Electricity Tariff 3.0TD . . . . .	113
3.2.1.1	Seasons and Periods of Tariff 3.0TD . . . . .	113
3.2.1.2	Power Fixed Term of Tariff 3.0TD . . . . .	115
3.2.1.3	Excessive Power Penalty of Tariff 3.0TD . . . . .	116
3.2.1.4	Energy Term of Tariff 3.0TD . . . . .	116
3.2.1.5	Reactive Energy Penalty of Tariff 3.0TD . . . . .	116
3.2.2	Simplified Compensation Mechanism . . . . .	118
3.2.3	Economic Study Algorithm Explanation - <i>economic.m</i> . . . . .	119
3.2.4	Results of the Economic Study . . . . .	120
<b>4</b>	<b>Environmental Impact</b>	<b>129</b>
4.1	Introduction . . . . .	129
4.2	Methodology . . . . .	129
4.3	Results of the Environmental Impact Study . . . . .	130
<b>5</b>	<b>Conclusions</b>	<b>133</b>
<b>6</b>	<b>Annexes</b>	<b>135</b>
	Annex 1. Alignment with the Sustainable Development Goals . . . . .	136
	Annex 2. Levelised Cost of Energy - PVsyst Check . . . . .	138
	Annex 3. Maintenance Plan . . . . .	140
	Annex 4. Gantt Chart . . . . .	142
	Annex 5. Matlab <i>tfm.m</i> Function . . . . .	143
	Annex 6. Matlab <i>economic.m</i> Function . . . . .	144
	Annex 7. PVsyst Simulation Report . . . . .	148
	Annex 8. PV Modules Data Sheet . . . . .	159
	Annex 9. Inverter Data Sheet . . . . .	161



# Document I. Project Memory

## List of Figures

---

1.1	Cumulative solar PV capacity [1]. . . . .	22
1.2	Evolution of generation cost for rooftop PV plants [3]. . . . .	23
1.3	Dreamfit Gym Chain launches in the period 2010-2021. . . . .	25
1.4	Total energy consumption per year in Dreamfit Alcorcón. . . . .	26
1.5	Location of Dreamfit Alcorcón [4]. . . . .	27
1.6	Chosen manufacturers for the PV facility. . . . .	30
1.7	Trinasolar's Vertex backsheet performance warranty [9]. . . . .	31
1.8	Trinasolar Vertex PV modules dimensions [9]. . . . .	32
1.9	Layers of conventional and PERC solar cells [13]. . . . .	33
1.10	Curves of Trinasolar Vertex TSM-DE18M(II)-495W PV module [9]. . . . .	33
1.11	Fusion-Solar Management System - Plant overview [17]. . . . .	35
1.12	Fusion-Solar Management System - Smart power sensor and energy balance [17]. . . . .	36
1.13	Smart Power Sensor DTSU666-H wiring terminals [18]. . . . .	36
1.14	Mounting rails positioning with respect to the long side frame [22]. . . . .	42
1.15	Installation method of clamps [22]. . . . .	42
1.16	Photovoltaic mounting structure [23]. . . . .	43
1.17	Interconnection schema of Dreamfit Alcorcón PV plant. . . . .	43
2.1	Orientation of the PV modules [25]. . . . .	48

## DOCUMENT I. LIST OF FIGURES

---

2.2	Optimal orientation of the PV system [28]. . . . .	48
2.3	Peak Sun Hours. . . . .	49
2.4	Power Analyser of Dreamfit Alcorcón [35]. . . . .	51
2.5	Operating procedure followed by the PV peak power optimisation algorithm. . . . .	53
2.6	Optimal PV peak power of Dreamfit Alcorcón returned by MATLAB. . . . .	53
2.7	MATLAB - Annual results - PV production. . . . .	54
2.8	Circuit diagram of the inverter [38]. . . . .	56
2.9	Minimum distance between elements [42]. . . . .	60
2.10	Solar elevation [42]. . . . .	60
2.11	Sun path chart of Dreamfit Alcorcón [43]. . . . .	61
2.12	Projected vertical height of PV modules. . . . .	62
2.13	Height of the perimeter wall. . . . .	63
2.14	Modules susceptible to higher power losses due to shadows [46]. . . . .	64
2.15	Profile of obstacles for the orange PV module. . . . .	65
2.16	Profile of obstacles for the pink PV module. . . . .	66
2.17	Profile of obstacles for the yellow PV module. . . . .	67
2.18	Profile of obstacles for the blue PV module. . . . .	68
2.19	Profile of obstacles for the red PV module. . . . .	69
2.20	Profile of obstacles for the green PV module. . . . .	70
2.21	Physical distribution of the PV strings [46]. . . . .	76
2.22	Electrical canalisation and inverter location [46]. . . . .	77
2.23	Location of the electrical AC box [46]. . . . .	78
2.24	Cable tube between the facility zone and the main electrical distribution panel [46]. . . . .	79
2.25	Electrical installation of the PV modules [22]. . . . .	79
2.26	Section view of the PV modules structure [46]. . . . .	96
3.1	Incidence Angle Modifier (IAM) [58]. . . . .	102

3.2	Evolution of self-consumption and autarky rates along the 8,760h of the year. . . . .	105
3.3	PV plant performance - Most sunny versus most cloudy day. . . . .	108
3.4	Monthly performance results of Dreamfit Alcorcón PV plant. . . . .	109
3.5	Production study - Balances and main results along the useful life of the project. .	111
3.6	Electricity tariff 3.0TD seasons and pricing periods. . . . .	114
3.7	Electricity tariff 3.0TD at weekends and national bank holidays. . . . .	114
3.8	Reactive energy penalty for electricity tariff 3.0TD. . . . .	117
3.9	Simplified Energy Compensation Mechanism [62]. . . . .	118
3.10	Optimal contracted powers and payback period returned by MATLAB. . . . .	121
3.11	Tariff 3.0TD - Annual consumption allocation per period of Dreamfit Alcorcón. . .	122
3.12	Cumulative profit evolution of Dreamfit Alcorcón PV plant. . . . .	124
4.1	Saved $CO_2$ emissions along the useful life of the PV plant. . . . .	130
6.1	Sustainable Development Goals [69]. . . . .	136

---



## Document I. Project Memory

### List of Tables

---

1.1	Basic and advanced features of the inverter management system [15]. . . . .	34
1.2	Utilised wiring per stretch. . . . .	37
1.3	Utilised earthing wiring per stretch. . . . .	41
1.4	Qualitative summary of the utilised protections. . . . .	41
1.5	Internal diameter of the utilised canalisation tubes. . . . .	41
1.6	Theoretical evaluation of the volume and tons of waste. . . . .	45
2.1	MATLAB - Annual results - PV production. . . . .	54
2.2	Description of the PV system. . . . .	55
2.3	Main electrical features of every PV module. . . . .	55
2.4	Main electrical features of the inverter. . . . .	56
2.5	Angles required to construct the profile of obstacles. . . . .	71
2.6	Reference table of solar irradiance losses due to shadows [48]. . . . .	72
2.7	Percentage of annual power losses due to shadows for the orange PV module. . . .	73
2.8	Percentage of annual power losses due to shadows for the pink PV module. . . .	73
2.9	Percentage of annual power losses due to shadows for the yellow PV module. . . .	74
2.10	Percentage of annual power losses due to shadows for the blue PV module. . . .	74
2.11	Percentage of annual power losses due to shadows for the red PV module. . . .	75
2.12	Percentage of annual power losses due to shadows for the green PV module. . . .	75
<hr/> MASTER THESIS		19

DOCUMENT I. LIST OF TABLES

---

2.13 Voltage drop and operating temperature per line. . . . . 86

2.14 Section required for protection wires [53]. . . . . 94

2.15 Protection wire length requirements. . . . . 94

2.16 Dimensions of the canalisation tubes. . . . . 95

3.1 Technical hypothesis for Dreamfit Alcorcón PV plant. . . . . 104

3.2 Self-consumption rate analysis per day of week and month. . . . . 106

3.3 PV plant performance - Most sunny versus most cloudy day. . . . . 107

3.4 Production study - Balances and main results. . . . . 112

3.5 Monthly distribution of periods in electricity tariff 3.0TD. . . . . 115

3.6 Economical hypothesis for Dreamfit Alcorcón PV plant. . . . . 120

3.7 Contracted powers with and without PV plant. . . . . 121

3.8 Economic study - Detailed results for the first useful year. . . . . 125

3.9 Economic study - Detailed results for the last useful year. . . . . 126

3.10 Economic CAPEX & OPEX study - Balances and main results. . . . . 127

4.1 PV system Life Cycle Emissions. . . . . 130

4.2 Environmental impact - Balances and main results. . . . . 131

5.1 Production study assessment. . . . . 133

5.2 Economic study assessment. . . . . 134

6.1 Consumption tariff for PVsyst economic study. . . . . 138

---

# Section 1

## Descriptive Memory

### Contents

---

1.1	Introduction . . . . .	<b>22</b>
1.2	Reference Framework . . . . .	<b>23</b>
1.3	Motivation . . . . .	<b>23</b>
1.4	Target of the Project . . . . .	<b>24</b>
1.5	Collaboration with Dreamfit . . . . .	<b>25</b>
1.6	Definition of the Project . . . . .	<b>26</b>
1.7	Initial Information . . . . .	<b>27</b>
1.7.1	Location of the PV Facility . . . . .	27
1.7.2	Project Writer Team . . . . .	27
1.7.3	Precedents . . . . .	27
1.8	Applicable Regulation . . . . .	<b>28</b>
1.8.1	Electrical Regulation . . . . .	28
1.8.2	Health and Safety Regulation . . . . .	28
1.8.3	Environmental Regulation . . . . .	29
1.9	Photovoltaic Installed Power . . . . .	<b>29</b>
1.10	Main Components and Features of the PV Facility . . . . .	<b>30</b>
1.11	Photovoltaic Modules . . . . .	<b>31</b>
1.12	Inverter . . . . .	<b>34</b>
1.12.1	Monitoring System . . . . .	35
1.13	Wiring . . . . .	<b>37</b>
1.14	Protections . . . . .	<b>38</b>
1.14.1	Direct Current Side Protections . . . . .	38
1.14.2	Alternating Current Side Protections . . . . .	39
1.14.3	Inverter Protections . . . . .	40
1.15	Earthing System . . . . .	<b>40</b>
1.16	Electrical Canalisation . . . . .	<b>41</b>
1.17	Photovoltaic Mounting Structure . . . . .	<b>42</b>
1.18	Interconnection Schema . . . . .	<b>43</b>
1.19	Construction Waste Management . . . . .	<b>44</b>
1.19.1	Identification of Residues . . . . .	44
1.19.2	Estimate of Generated Residues . . . . .	45
1.19.3	Destination of Residues . . . . .	45
1.19.4	Expected Waste Management Cost . . . . .	45

---

## 1.1 Introduction

The global energetic context is currently focused on a decarbonisation economy fostered through diverse political measurements intended to boost renewable energies. In the particular case of Spain, where this project will be developed, the major regulatory examples are RITE, which determines minimum efficiency requirements and establishes the minimum renewable contribution for Sanitary Hot Water, and Royal Decree 244/2019, which simplifies domestic and industrial self-consumption from both a technical and a legal point of view.

The photovoltaic industry is part of this decarbonisation economy and will be a leading player within the core of the future energy sector. By 2010, the PV technology was not developed enough to be cost-effective, but the PV industry has currently reached its technological maturity and therefore PV projects can be profitable even for self-consumption purposes.

In fact, compared to 2018 levels, cumulative solar PV capacity is expected to grow sixfold by 2030, with a Compound Annual Growth Rate of nearly 9% up to 2050:

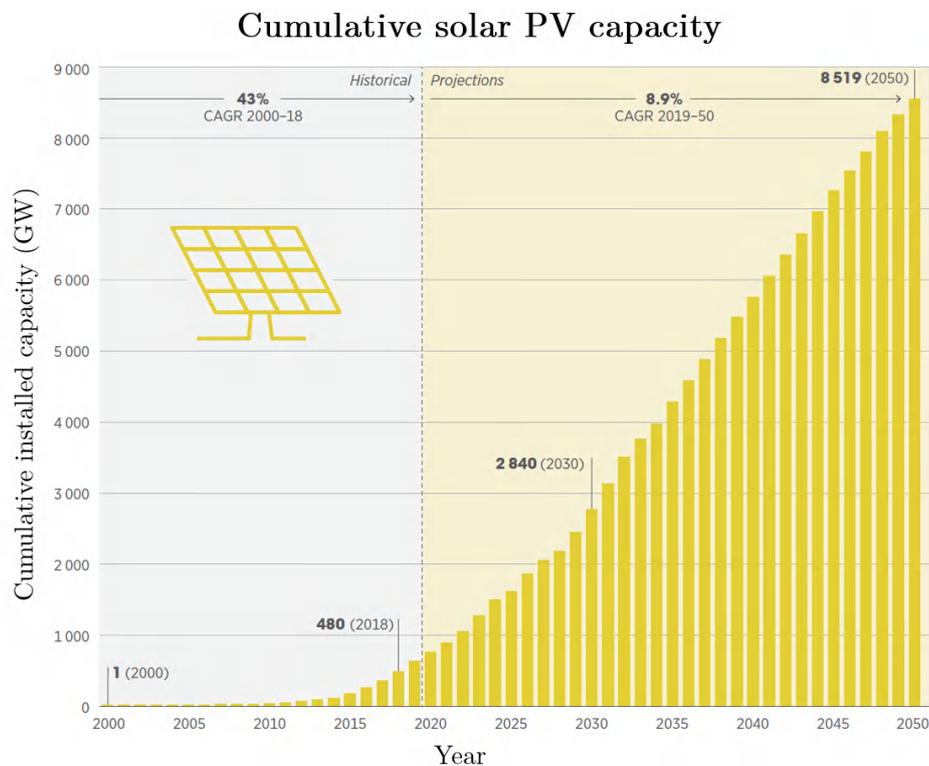


Figure 1.1. Cumulative solar PV capacity [1].

Then, the aim of this project consists of designing a photovoltaic plant for self-consumption in a Dreamfit® [2] sports facility and its technical-economic analysis in order to evaluate both its profitability and environmental impact.

Dreamfit is a gym chain that was launched in 2009 due to the initiative of a Spanish entrepreneur's group professionally linked to sports. Nowadays, Dreamfit counts with approximately 400 workers and 25 gyms spread all over Spain, 20 of them already open and 5 in project or construction phase. Since 2018, Dreamfit has given me the opportunity of being part of its workforce as a member of the Construction and Maintenance Department, being in charge of the remote control of the thermal and electrical facilities of the company.

## 1.2 Reference Framework

The photovoltaic industry at domestic or industrial level has been boosted considerably in the last decade due to a decrease in the generation cost derived from the PV learning curve progress, as well as due to regulation advancements. In this sense, figure 1.2 presents the evolution of generation costs for rooftop PV plants in the period between 2010 and 2030:

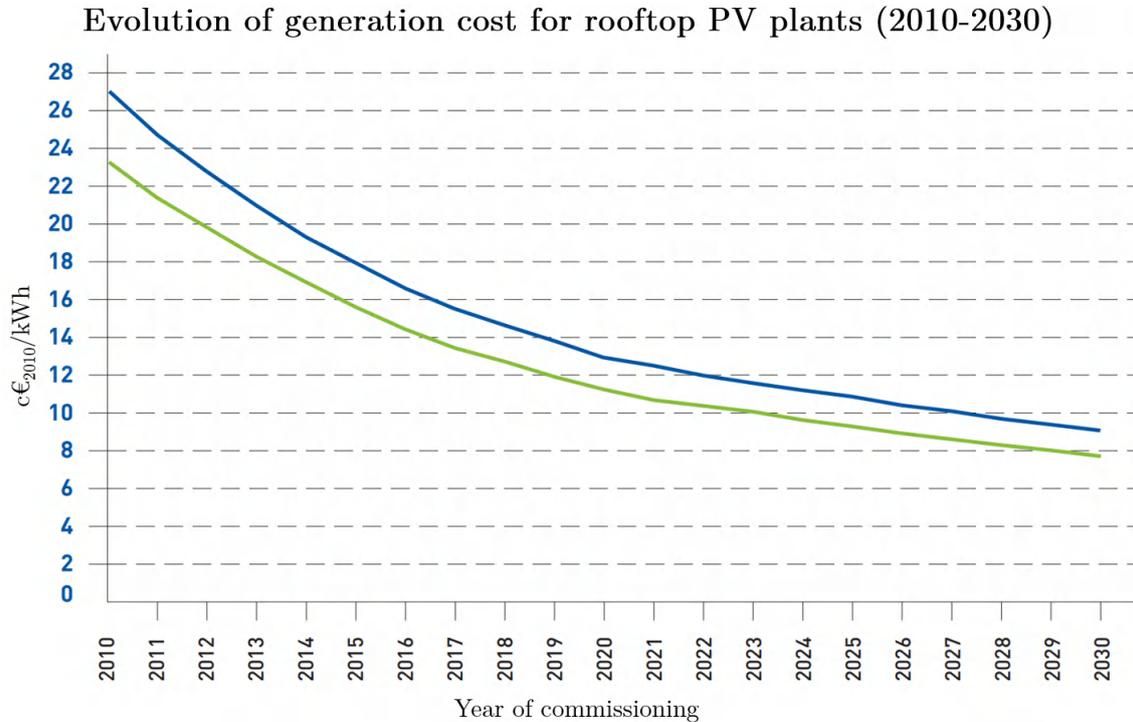


Figure 1.2. Evolution of generation cost for rooftop PV plants [3].

During the last decade, considerable adjustments have been done in terms of regulation in Spain such as the last modification of ITC-BT-40 on low voltage generating facilities, or the publication of the Technical Specifications of Grid-Connected Facilities as well as the new Spanish access electricity tariffs that came into force the first of June of 2021. Moreover, notable improvements have been developed in the technical PV field, most of them related to the PV modules and to the electronic control of inverters, increasing PV cells efficiency, improving the quality of the output AC signal, increasing the number of MPPTs included per inverter or even not requiring any over-current nor over-voltage protections at the DC side of the facility.

Thus, the development of a photovoltaic project for self-consumption requires mastering both the technical and the regulatory part, which are adjusted and modified with frequency.

## 1.3 Motivation

Dreamfit has the intention of including Distributed Energy Resources (DERs) in the short and the medium term at every gym through self-consumption facilities that would be developed internally when possible. Among all the available solutions, the company has decided to opt for photovoltaic plants since geothermal, for instance, requires much more construction costs due to the required civil works, exactly as any other alternative. Moreover, the installation of the PV

modules is made at the facility roof, which is already deployed and owned by Dreamfit, what makes the project much more simple and therefore cost-efficient.

Thus, the Master Thesis consists of projecting and designing a solar PV plant at a specific gym of the company that will be actually executed in practice.

Dreamfit proposes carrying out a feasibility analysis based on the incorporation of PV technology in their gyms in order to achieve the technical and electrical optimisation of the consumed energy, reducing the polluting emissions. Hence, the solution provided has been designed for a standard Dreamfit installation intended to be replicated in more gyms in the medium term.

Hitherto, the company has allocated a considerable amount of resources within the field of energy efficiency in the last five years through the improvement of the SCADA® system that enables the remote control of both the thermal and electrical facilities of every gym. Additionally, all gyms are equipped with an aerothermal heat-pump instead of boilers for Sanitary Hot Water purposes. Besides, all the gyms count with a network analyser that eases the assessment of the energy consumption performance by means of historical databases and real-time data.

Therefore, pursuing the company's philosophy of raising the bar, the next improvement in the energy field consists of including renewable generation in its facilities. This milestone will be conceived by the organisation as the next step to provide continuity to the important effort that has been done in energy management and efficiency since more than three years ago, when the position of *Energy Management and Efficiency Technician* was created within the company.

Since year 2018 and not considering COVID-19 lockdown, Dreamfit has reinforced its commitment towards energy efficiency, reducing the total energy consumption of the whole gym chain more than a 25% in the period between 2018 and 2021.

## 1.4 Target of the Project

The **main target** of the project stands for developing a **model** to include photovoltaic generation plants for self-consumption at any Dreamfit gym in the medium term. The model must provide the optimal PV peak power to install and assess the profitability of the project.

To this end, the Master Thesis consists of the application of the model on a *pilot project* of 100  $kW_n$  at Dreamfit Alcorcón that will be actually executed in practice, so this is the reason why a whole engineering project has been developed. The project is conceived as an **scalable solution** that will be incorporated to more Dreamfit gyms in the medium term if it is profitable.

There are four other sub-goals that are derived from the main target of the project:

1. **Self-consumption.** Self-consume more than 150  $MWh/year$ , which would represent more than a 35% of the whole energy demanded per year by Dreamfit Alcorcón.
2. **Emissions.** Reduction of polluting emissions in more than 50  $t_{eq} CO_2/year$ , considering both the self-consumed energy and the grid-injected energy.
3. **Energy Efficiency and Profitability.** Alignment with the Dreamfit core value of insisting on the highest standards applied in this case to the energy efficiency field.
4. **Health.** Dreamfit encourages a healthy life style by means of its motto *we are health*, which is not only related to the practice of sport, but also related to the social well-being fostering a sustainable usage of resources, including energy.

## 1.5 Collaboration with Dreamfit

Nowadays, Dreamfit counts with approximately 400 direct workers and 25 gyms spread all over Spain, 20 of them already open and 5 in project or construction phase. Besides, Dreamfit manages the *Las Ventas* Marketplace in Madrid, a building of more than 22,000  $m^2$  with more than 50 food stalls, a supermarket, a super-bazaar and a Dreamfit gym. Moreover, Dreamfit also owns and manages the *Los Fueros* Shopping Center located in Baracaldo, another building of more than 13,000  $m^2$  with 16 commercial establishments, a supermarket, a super-bazaar and a Dreamfit gym.

Since its inception, Dreamfit has had the intention of launching between two and three gyms per year with the objective of being present in all the main cities of Spain:

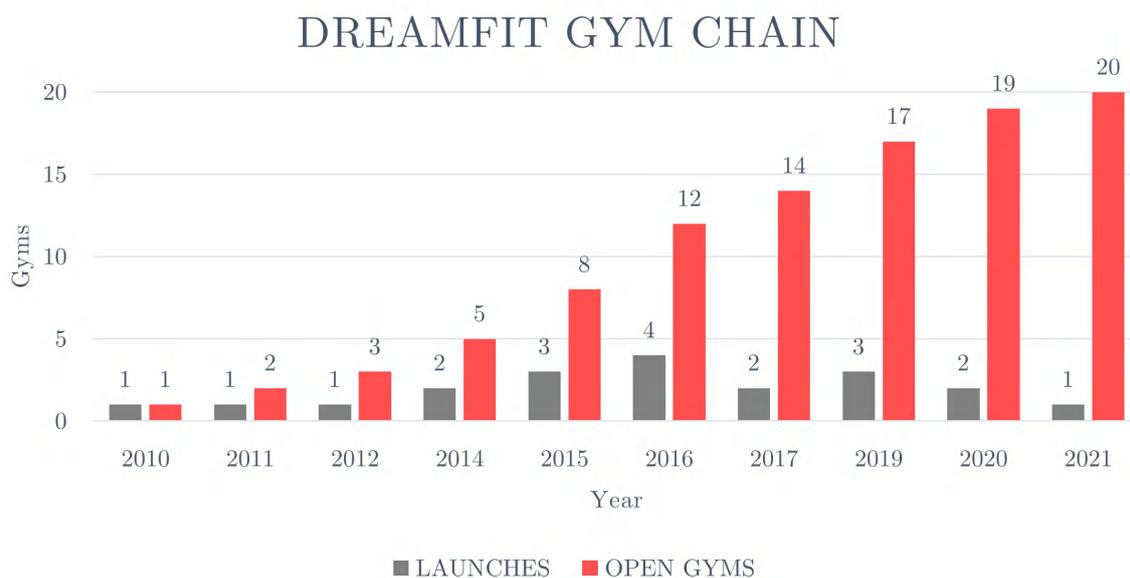


Figure 1.3. Dreamfit Gym Chain launches in the period 2010-2021.

The professional activity of Dreamfit can be separated into two main areas:

- The construction and maintenance of the gyms.** Dreamfit counts with a small internal department of two engineers and a technical architect in charge of managing both the construction and the maintenance of facilities. Until 2018, this department was integrated by just one engineer that was focused on the supervision of the construction works of all the new gyms in accordance with the company expansion plan. In the year 2018, Dreamfit decided to allocate financial resources in the energy efficiency field hiring a new engineer in charge of remotely managing the facilities by means of SCADA control systems. Finally, in the year 2019 the gym chain decided to expand the department hiring a technical architect to be in charge of the facilities maintenance management as well as to provide support in the energy efficiency and construction works supervision when needed.
- Daily operation of the gyms.** Apart from the three people within the Construction and Maintenance Department, the rest of the Dreamfit workforce is in charge of the daily operation of the gyms, being in close touch with the clients.

Additionally, Dreamfit intention involves including in its business model Distributed Energy Resources in the medium term at every gym through self-consumption Photovoltaic (PV) facilities that will be developed internally when possible. This is the reason why Dreamfit has given me the opportunity of developing this **real engineering project**, since I have been working for the company as the Energy Efficiency and Management Technician since 2018.

Thus, the project consists of designing a solar PV plant at **Dreamfit Alcorcón**. This specific gym is located at a 50-year concession plot, being therefore the best available alternative in comparison with the rest of gyms in which Dreamfit is just the premise lessee.

## 1.6 Definition of the Project

The project consists of constructing and installing a grid-connected solar power plant located at a sports facility roof with a rated power of 100 *kW*. The existing building will self-consume as much energy as possible depending on the binomial sun hours-consumption, while the energy surpluses will be poured into the grid.

Dreamfit undertakes a significant commitment to environmental sustainability as part of its business strategy, so with this project pretends to self-consume at least a 35% of the total energy consumed by Dreamfit Alcorcón in a standard year, which is a sports facility that has a yearly consumption of about 450 *MWh*. In this sense, the next figure presents the total energy consumed by Dreamfit Alcorcón in the last four years:

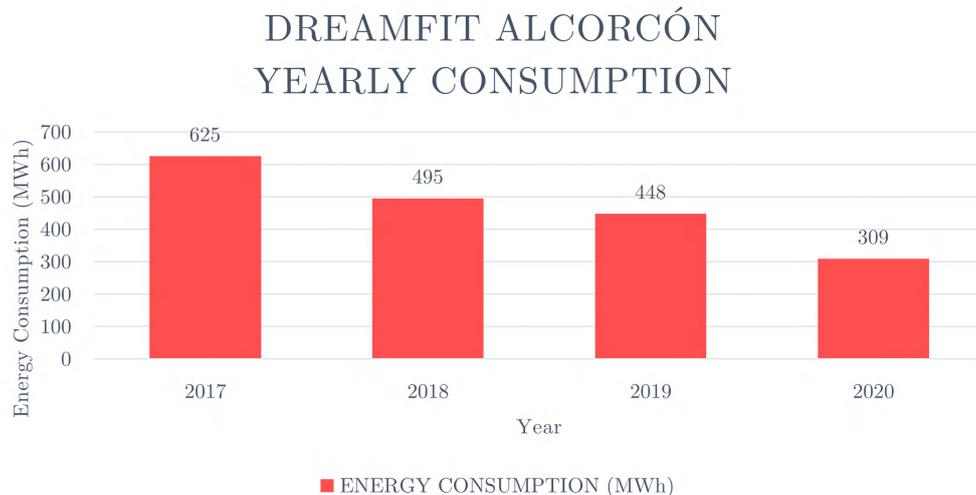


Figure 1.4. Total energy consumption per year in Dreamfit Alcorcón.

The figure 1.4 reveals a systematic reduction in the energy consumed per year by this gym due to the effort that Dreamfit is doing related to energy management since 2018. Nonetheless, the data from year 2020 cannot be compared with the other three years because the gym was closed for almost four months due to COVID-19 lockdown.

Then, this project includes a complete economic analysis as well as a description of the technical characteristics of the Solar Photovoltaic Plant for self-consumption, including the electrical configuration as well as both the required equipment and the wiring.

The **rated power of the PV facility measured at the inverter** will be of 100 *kW*, while the **peak power measured at the PV field** will be of 111 *kW<sub>p</sub>*.

## 1.7 Initial Information

### 1.7.1 Location of the PV Facility

The PV facility is installed at the roof of a building located in the address C/Los Robles S/N, 12B, 28922 ALCORCÓN, Comunidad de Madrid.

The geographic data can be summarised as follows:

- Latitude: 40°19'47.7" N.
- Longitude: 3°50'34.3" W.
- Altitude: 680 m.
- Land Register Reference: 8549101VK2684N0001PO.

Although the location is clearly specified in the plans (document V), a detailed picture of the whole plot is also included below:

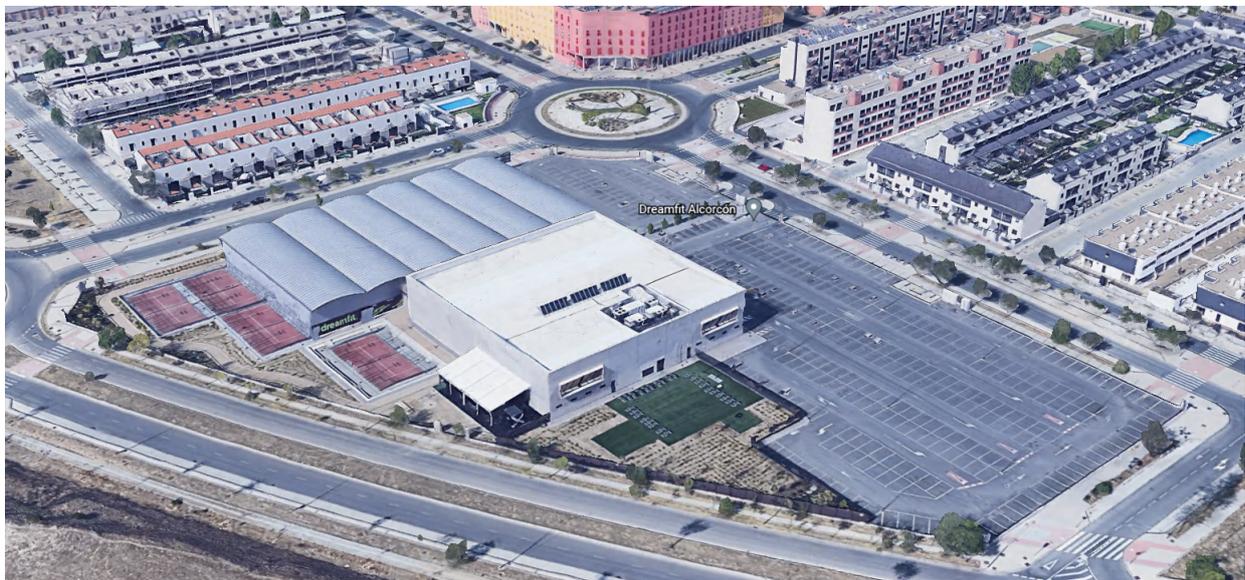


Figure 1.5. Location of Dreamfit Alcorcón [4].

### 1.7.2 Project Writer Team

The project has been both developed and written by the graduated in Industrial Technologies Engineering Adrián Cecilio Benito with the supervision of the Mines Engineer Ángel Sánchez Elipe and the Industrial Engineer Beatriz Yolanda Moratilla Soria.

### 1.7.3 Precedents

This document describes a PV solar system with a rated power of 100 kW measured at the inverter and a peak field power of 111 kW<sub>p</sub> in the installed modules. The basic operation of the system consists of exploiting the sun for the production of electricity for self-consumption by means of an inverter that transforms the direct current from the PV panels into three-phase alternating current, counting with the required DC and AC protections.

This project will be governed in its processing by the provisions of RD 900/2015 in which the technical characteristics of the self-consumption facilities are described and by the RD 244/2019, which updates the requisites specified in RDL 15/2018 on urgent measures for energy transition and consumer protection. Besides, the connection and access procedure is regulated according to the RD 1699/2011 and the RD 1955/2000.

In the execution of the photovoltaic installation, the provisions of the ITC-BT-40 on low voltage generating facilities will be respected as well as the Technical Specifications of Grid-Connected Facilities specified by IDAE [5].

## 1.8 Applicable Regulation

The current regulation according to the scope of this project is detailed below, which includes all the Spanish Royal Decrees and laws enforceable and organised chronologically:

### 1.8.1 Electrical Regulation

- Royal Decree 1955/2000, of first of December, which regulates the transport, distribution, retailing, supply and authorisation procedures for electrical energy facilities.
- Royal Decree 842/2002, of second of August, which approves the Electrotechnical Regulation for Low Voltage.
- Royal Decree 1454/2005, of second of December, which modifies certain provisions related to the electric power sector.
- Royal Decree 314/2006, of seventeenth of March, which approves the Spanish Technical Building Code.
- Royal Decree 661/2007, of twenty fifth of May, which regulates the production of electrical energy under special regime.
- Royal Decree 1110/2007, of twenty fourth of August, which approves the unified regulation on points of measurement in the electrical power system.
- Royal Decree 1699/2011, of eighteenth of November, which regulates the connection to the national grid of low power electric generation facilities.
- Law 24/2013, of twenty sixth of December, related to the electric power sector.
- Royal Decree 413/2014, of sixth of June, which regulates the electricity generation by means of renewable, cogeneration and waste facilities.
- Royal Decree 900/2015, of ninth of October, which regulates the administrative conditions, technical and economic modalities of electricity supply with self-consumption as well as the self-consumption production.
- Royal Decree-Law 15/2018, of fifth of October, which establishes urgent measures for energy transition and consumer protection.
- Royal Decree 244/2019, of fifth of April, which regulates the administrative, technical and economic conditions for self-consumption in Spain.

### 1.8.2 Health and Safety Regulation

- Royal Decree 3275/1982, of twelfth of November, on technical conditions and safety guarantees in power stations, substations and transformers.
- Royal Decree 7/1988, of eighth of January, related to the safety requirements of the electrical equipment intended to be used within certain voltage limits.
- Law 31/1995, of eighth of November, on labour risk prevention.

- Royal Decree 485/1997, of fourteenth of April, on the minimum provisions of both safety and health signs at work.
- Royal Decree 487/1997, of fourteenth of April, on minimum health and safety requirements when handling loads manually involving risks for workers, in particular at the lower back.
- Royal Decree 773/1997, of thirtieth of May, on minimum provisions of safety and health related to the use of personal protective equipment by the workers.
- Royal Decree 1215/1997, of eighteenth of July, which establishes the minimum health and safety requirements for the use of work equipment by the workers.
- Royal Decree 1627/1997, of twenty fourth of October, which establishes the minimum health and safety requirements in construction works.
- Royal Decree 614/2001, of eighth of June, on minimum provisions for protection of the health and safety of workers against electrical risks.
- Law 54/2003, of twelfth of December, which reforms the regulatory framework of the labour risk prevention.
- Royal Decree 171/2004, of thirtieth of January, which develops the article 24 within the Law 31/1995 related to labour risk prevention in order to coordinate business activities.
- Royal Decree 2177/2004, of twelfth of November, which modifies the Royal Decree 1215/1997, which establishes the minimum health and safety requirements for the use of work equipment by the workers, in terms of temporary work at height.
- Royal Decree 1311/2005, of fourth of November, on health and safety protection of workers exposed to risks that are derived or may be derived from mechanical vibrations.

### 1.8.3 Environmental Regulation

- Royal Decree 105/2008, of first of February, which regulates the demolition and construction waste production and management.
- Law 21/2013, of ninth of December, related to environmental assessment.
- Law 14/2014, of twenty sixth of December, on harmonisation and simplification in protection of the territory and natural resources.

## 1.9 Photovoltaic Installed Power

According to current regulation, the installed power of PV plants is the so-called rated PV power, id est, the facility PV power is measured at the inverter [6]. Hence, after computing the optimal power for Dreamfit Alcorcón, the rated power of the generation resource required is 100 kW, while the PV field power required is 111 kW.

The optimal PV peak power has been established through an optimisation algorithm exposed in section 2.2, which provides the optimal PV peak power by means of the annual global in-plane irradiance per hour of Alcorcón as well as the hourly electrical consumption of a representative year in Dreamfit Alcorcón. The data used corresponds with year 2019 since data from year 2020 cannot be considered as representative due to COVID-19 lockdown.

The programming function respects the simplified compensation process explained in the Royal Decree 244/2019, since the surplus energy generated by the Distributed Energy Resource will be injected to the national power grid. Then, the algorithm establishes the optimal PV peak power in order to both maximise the self-consumed energy while minimising the surplus energy injected to the grid.

For an installed peak power of 111 *kW*, the expected production of the PV plant for a representative year is presented below:

- **PV Energy Generated:** 198,897.56 *kWh/year*.
- **Self-Consumed Energy:** 169,164.30 *kWh/year*.
- **Surplus PV Energy Injected to the Grid:** 29,733.28 *kWh/year*.

Regarding the results exposed above and taking into account that the yearly consumption of Dreamfit Alcorcón is 447,567.75 *kWh/year*, the energy consumed from the grid in a representative year will be 278,403.45 *kWh/year*:

- **Self-Consumption.** A 37.80% of the energy consumed will be self-consumed.
- **Surplus.** Only a 14.94% of the PV production will be injected to the grid.

## 1.10 Main Components and Features of the PV Facility

The photovoltaic power plant consists of an electricity generation system that transforms the solar radiation into electricity through photovoltaic modules. This energy can be used for self-consumption purposes or injected into the DSO network as surplus energy.

The facility will incorporate all the required elements to always guarantee the physical protection of people, the quality of supply and not cause network breakdowns.

The PV peak power installed is 111.1 *kW* and counts with 220 PV modules of monocrystalline solar cells, brand Trinasolar® and model TSM-DE18M(II), which have an unitary PV peak power of 505 *W*. Additionally, the DER includes an inverter with 100 *kW* of rated power, brand Huawei® and model SUN2000-100KTL-M1, which is a smart PV controller:



(a) PV modules manufacturer [7].



(b) Inverter manufacturer [8].

Figure 1.6. Chosen manufacturers for the PV facility.

The modules are mounted on a structure of extruded aluminium profiles placed on the roof of the existing building with an inclination of 33.5° with respect to the horizontal plane. It is an outdoor structure resistant to adverse weather conditions. The panels are connected among them by means of connectors type MC4 EVO2/TS4. All the cables used at the facility comply with the norm UNE 21030-1:2014.

The PV generation plant is compound by the following elements:

- Photovoltaic Modules.
- Inverter.
- Wiring.
- Protections.
- Earthing System.
- Electrical Canalisation.
- PV Mounting Structure.

## 1.11 Photovoltaic Modules

After analysing different alternatives in terms of available technologies and manufacturers, finally the design has been done selecting the Trinasolar Vertex TSM-DE18M(II) PV monofacial modules with a peak power of  $505 W_p$ . Then, 220 PV modules are required to achieve a PV field peak power of  $111.1 kW_p$ .

The arguments why Trinasolar Vertex line has been chosen are covered below [9, 10]:

- **World-Class Top Performer.** Trinasolar is the world leading global PV and smart energy total solution provider, which has recently been recognised as the *Top Performer* among global PV module manufacturers by PV Evolution Labs® (PVEL) [11] and DNV GL® [12]. The company is one of the only two PV module manufacturers with worldwide reach to garner the prestigious recognition for fifth time in a row.
- **High Customer Value.** Low Levelised Cost of Energy (LCOE), reduced Balance of System cost (BOS), short payback time and high return on investment as it has been demonstrated in section 3. Designed for compatibility with existing mainstream system components. Low guaranteed first year and annual degradation:

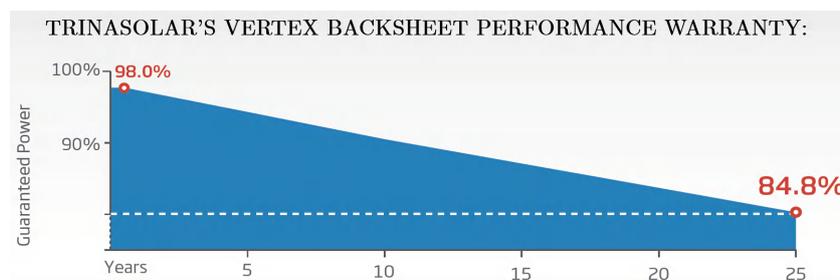


Figure 1.7. Trinasolar's Vertex backsheet performance warranty [9].

- **High Power.** Modules with a peak power of  $505 kW$  and large area cells based on  $210 mm$  silicon wafers as well as 1/3-cut cell technology. Up to 21.2% module efficiency with high density interconnect technology. Multi-busbar technology for better light trapping effect, lower series resistance and improved current collection.
- **High Reliability.** Minimised micro-cracks with innovative non-destructive cutting technology. Ensured PID resistance through cell process and module material control. Resistance to harsh environments such as salt, ammonia, sand, high temperature and high humidity areas. Optimised energy production under inter-row shading conditions.

The mechanical data of the modules according to its data sheet are exposed below<sup>1</sup>:

- **Solar Cells.** 150 PERC monocrystalline cells per module.
- **Cells Technology.** High density 1/3-cut multi-busbar technology.
- **Weight.** Light weight of  $26.5 kg$  per module.
- **Glass.** High transmission AR coated heat strengthened glass of  $3.2 mm$ .
- **J-box.** IP 68 rated.
- **Warranty.** 12 year product workmanship warranty and 25 year power warranty.
- **Attenuation.** 0.55% Annual power attenuation.

<sup>1</sup>The main electrical features of the PV modules are included in table 2.3.

The dimensions of the PV modules that have been considered in section 2.4 and section 2.5 are included in the following figure:

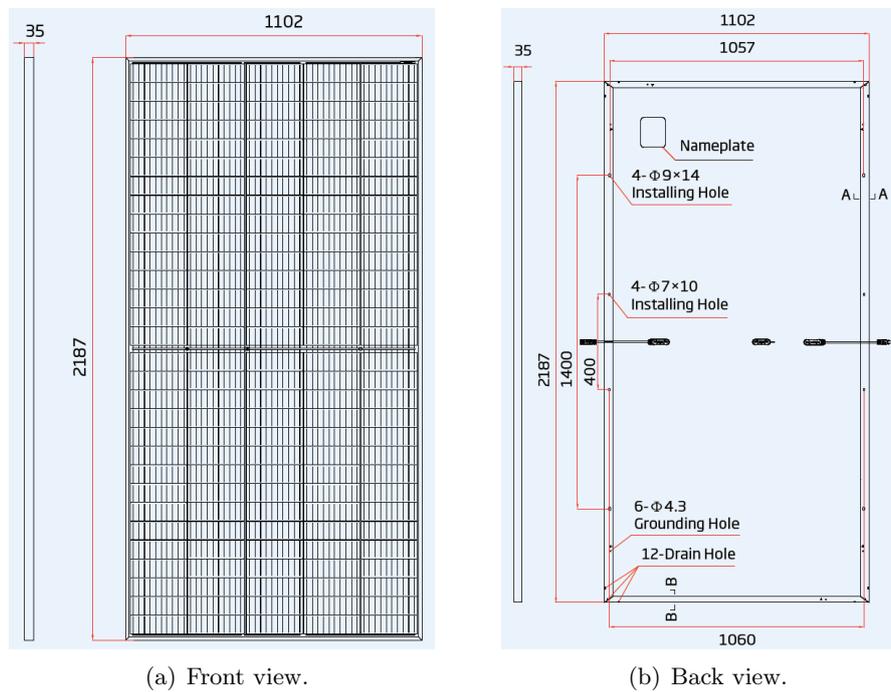


Figure 1.8. Trinasolar Vertex PV modules dimensions [9].

The conventional PV cell has three layers:

1. **Emitting Layer.** Upper silicon layer and therefore the most exposed to radiation.
2. **Base Layer.** Intermediate silicon layer in contact with the other two layers.
3. **Back Surface Field.** Inner layer of aluminium located at the deepest zone of the cell.

However, the selected PV module uses PERC technology. PERC stands for Passivated Emitter Rear Cell and consists of placing a reflective dielectric layer to leverage the solar radiation between the back surface field and the base layer.

The main advantages of PERC cells are summarised as follows [13]:

- **Better performance under low radiation conditions.** PERC cells can leverage light with greater wavelengths by reflecting the light and generating electrical currents between the base layer and the emitting layer. In conventional cells these greater wavelengths would pass through the aluminium, losing part of the energy. These light signals with greater wavelengths are more frequent during the first and last hours of sunny days as well as during cloudy days. Therefore, PERC cells have a better efficiency performance due to their improved sensitivity against greater wavelengths.
- **Lower temperature coefficient.** Light emitted with wavelengths greater than the infrared cannot generate energy, but this light increases the temperature of the PV module by heating the aluminium layer and consequently worsening the module yield. The PERC cells reflect these wavelengths away from the module ensuring a lower temperature and therefore improving the whole performance of the PV cell.

The graphical difference between conventional and PERC cells can be observed in figure 1.9:

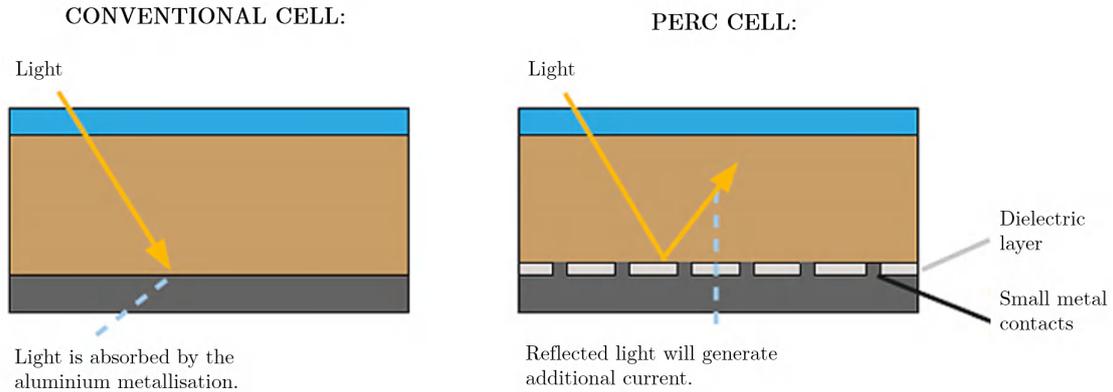


Figure 1.9. Layers of conventional and PERC solar cells [13].

Nonetheless, the performance of PV modules depends on weather conditions: irradiance, ambient temperature, wind speed, etc. Next figures shows how voltage, current and output DC power vary with solar radiation:

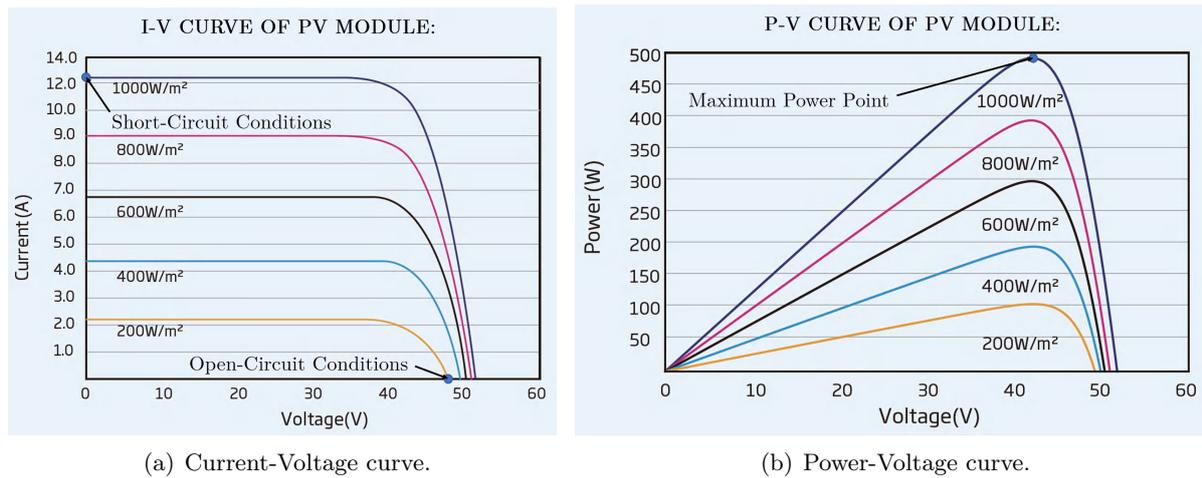


Figure 1.10. Curves of Trinasolar Vertex TSM-DE18M(II)-495W PV module [9].

Additionally, the distance between modules have been computed according to the Technical Specifications of Grid-Connected Facilities to ensure that the minimum shadows are projected between elements, maximising the yield of the generation plant. In fact, in section 2.5 it has been demonstrated that distance between modules and obstacles is enough to ensure that, in the worst-case scenario, the annual percentage of losses due to shadows will never exceed the 0.29% in any PV module.

Then, in order to maximise production as it was justified in sections 2.1 and 2.4:

- **Tilt Angle:**  $\beta_{opt} = 33.5^\circ$  with respect to the horizontal plane.
- **Azimuth Angle:**  $\alpha_{opt} = 0^\circ$ .
- **Distance between the First PV Row and the Perimeter Wall:** 1.99 m.
- **Distance between the First and the Second PV Row:** 2.50 m.
- **Distance between the Rest of the PV Rows:** 4.87 m.

## 1.12 Inverter

The PV plant includes only one solar inverter model Huawei Smart PV Controller SUN2000-100KTL-M1 which has a rated power of 100  $kW_n$ . The inverters works connected to the PV field at the DC side and both to the load and the national DSO grid at the AC side.

The arguments why Huawei SUN2000 has been chosen are covered below [8, 14]:

- **Innovation, Ultimate Safety and Better Experience.** The Huawei SUN2000 series smart inverter has been internationally recognised by the Intersolar Award in 2019 due to the integration of AI and Cloud. Besides, Huawei further incorporates diverse ICT technologies, thus making the solar power plant to be highly efficient, safe and reliable with smart operation, maintenance and grid supporting capabilities.
- **Improved Yield.** The solar inverter receives inputs from 20 PV strings and counts with 10 Maximum Power Point Trackers (MPPTs). The inverter provides a maximum efficiency of 98.4%, being able to adapt in a versatile way to the different arrangements and minimising deficiencies due to not uniform shadowing orientations.
- **Simple Operation and Maintenance.** Automatic management at string level by means of an intelligent monitoring of every string as well as an intelligent diagnosis support for current-voltage curves. The inverter includes a platform that allows querying alarms, setting parameters, and performing routine maintenance.
- **Safety and Reliability.** The inverter incorporates a Residual Current Monitoring Unit (RCMU) and its design requires no fuses at the DC side, minimising fire risk due to DC arcs. It integrates protection IP65 against corrosion and water penetration as well as over-current protection type II both at the DC and AC side.
- **Management System.** The Huawei Fusion-Solar Smart PV Management System enables the overall management of the PV plant, including yields, power output, alarms and operation and maintenance statistics from both web or app access. The system registers real-time data as historical data, creating a data back-up and providing access at anytime from anywhere to carry out an online diagnosis to find out low performances:

Table 1.1. Basic and advanced features of the inverter management system [15].



FEATURE LIST		WEB	APP
<b>Basic Feature</b>	Swift installation and registration	Yes	Yes
	Data collection	Yes	No
	Dashboard	Yes	Yes
	Energy flow	Yes	Yes
	Energy generation and consumption	Yes	Yes
	Device management	Yes	Yes
	Report management	Yes	Yes
	Alarm management	Yes	Yes
<b>Advanced Feature</b>	System configuration	Yes	Yes
	Intelligent operation and maintenance	Optional	No
	Mobile operation and maintenance	Optional	No
	Proactive diagnosis	Optional	Optional
	Smart I-V curve diagnosis	Optional	Optional

The solar inverter receives inputs from 20 PV strings of 11 series-connected PV modules per string. The DC power is then converted into three-phase AC power of 400 V and 50 Hz through an inverter circuit. Surge protection is supported on both the DC and AC sides [16].

Additionally, the inverter complies with the technical requirements defined on the Royal Decree 1699/2011, of eighteenth of November, which regulates the connection to the national grid of low power electric generation facilities.

Apart from a mechanism to control both the AC output voltage and the AC output frequency as it was stated in subsection 2.7.2.3, the solar inverter includes [16]<sup>2</sup>:

- Input-Side Disconnection Device.
- Anti-Islanding Protection.
- DC and AC Over-current Protection.
- DC Reverse-Polarity Protection.
- PV-Array String Fault Monitoring.
- DC Surge Arrester Type II.
- AC Surge Arrester Type II.
- DC Insulation Resistance Detection.
- Residual Current Monitoring Unit.

The PV configuration based on 220 PV modules distributed in 20 strings has been audited in section 2.3.3 in order to assess the compliance with the inverter operating parameter limits:

- **Maximum Power Point Conditions.** Both upper and lower voltage limit conditions have been verified in equations 2.14 and 2.17 respectively.
- **Open-Circuit Conditions.** The upper voltage limit has been verified in equation 2.20.
- **Short-Circuit Conditions.** The upper current limit has been verified in equation 2.23.

### 1.12.1 Monitoring System

The solar inverter is equipped with a system to capture data of the PV plant performance and operation. The system registers real-time data through a smart power meter, saving historical data, creating a data back-up and providing access to the information at anytime from anywhere.

The smart power meter is a bidirectional network analyser that generates input data that can be analysed in real-time at the Huawei Fusion-Solar Smart PV Management System:

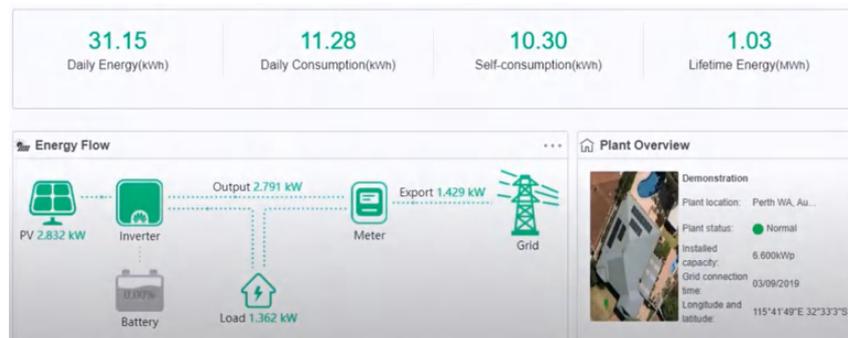


Figure 1.11. Fusion-Solar Management System - Plant overview [17].

<sup>2</sup>The main electrical features of the solar inverter are included in table 2.4.

Moreover, the smart power meter also generates input data that can be stored and analysed at any time at the Huawei Fusion-Solar Smart PV Management System. The three-phase network analyser generates data while being connected to the PV inverter by communications cable type RS485. Basically, the power sensor computes the energy generated by the PV field as well as the energy injected or absorbed from the grid:

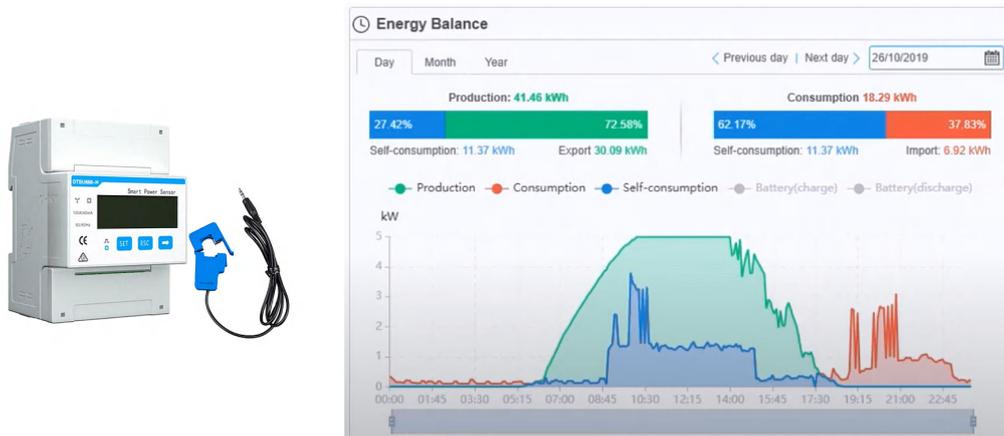


Figure 1.12. Fusion-Solar Management System - Smart power sensor and energy balance [17].

Hence, figures 1.11 and 1.12 reveal some of the advantageous functionalities that the incorporation of AI and Cloud by Huawei provides not only to the operation and maintenance of the inverter, but also to the whole PV plant.

The smart power sensor measures voltage through the references of each electrical phase as well as the current of each electrical phase. Then, the network analyser requires three current transformers which provide appropriate values for the device. The schema of the smart power sensor which has to be connected between the load and the DSO grid is included in figure 1.13:

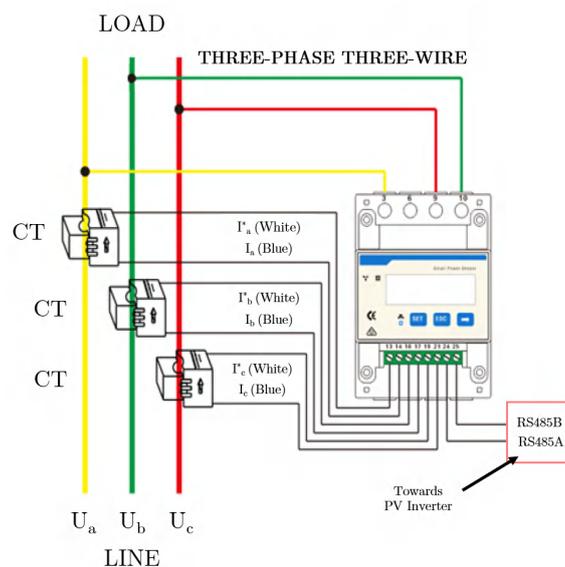


Figure 1.13. Smart Power Sensor DTSU666-H wiring terminals [18].

The PV modules as well as the inverter data sheets are included in the annexes.

### 1.13 Wiring

The proper design and sizing of wiring reduces system losses due to overheating or voltage drops, avoiding the appearance of hot spots and short-circuits. As it can be deduced from section 2.6, sections have been computed analysing the thermal and the voltage drop criteria.

As a consequence of the high voltage reached by the PV strings, these strings must withstand voltages greater than 600 V under low temperatures as it is demonstrated in subsection 2.3.3. Specifically, the maximum DC operating voltage per inverter MPPT is 1,000 V according to table 2.4. Thus, the selected cables require insulation with capability to withstand even 1 kV. Besides, all the wiring is flame and fire retardant as well as halogen free.

The wiring deployment will be as rectilinear as possible. Moreover, the minimum radius of curvature stipulated by each manufacturer will be taken into account. If the manufacturer provides no information related to the radius of curvature, this information can be obtained from norm UNE 20435. The laying of the conductors will be carried out carefully, avoiding the formation of kinks, as well as preventing damaging friction and excessive traction. Conductors will never be given greater curvatures than those admissible for each type.

The wiring insulation material is Halogen-Free Elastomer for the DC side and Cross-Linked Poly-Ethylene (XLPE) for the AC side. Then, the operating temperatures enable a proper performance under extreme conditions:

- **Maximum Wire Operating Temperature:** 90°C.
- **Minimum Wire Operating Temperature:** -40°C.

The quality of the utilised materials is a capital concern in this project, thus the selected manufacturer for the wiring will be a world-class recognised brand. Then, next table exposes a summary of the single-pole cables selected for the PV plant of Dreamfit Alcorcón:

Table 1.2. Utilised wiring per stretch.

UTILISED WIRING		
DC	Strings - Inverter	Solar Cable ZZ-F(AS) 0,6/1kV Cu (2·6 mm <sup>2</sup> )
AC	Inverter - AC Box	RZ1-K(AS) 0,6/1kV Cu (4·70 mm <sup>2</sup> )
	AC Box - Main Distribution Panel	RZ1-K(AS) 0,6/1kV Cu (4·120 mm <sup>2</sup> )

Cable sections have been computed following ITC-BT-40 on low voltage generating facilities and the Technical Specifications of Grid-Connected Facilities, respecting both the thermal and the voltage drop criteria. Thus, according to the voltage drops computed in section 2.6:

- **DC Side Voltage Drop** < 1.5% ✓.
- **AC Side Voltage Drop** < 1.5% ✓.
- **Sections.** Conductors have to be sized for 125% of the generator maximum current ✓.

Every PV string is compound by 11 modules and the required connections among panels are done with the PV modules conductor itself. If the PV module cable is not long enough for a particular string, the PV modules will be connected by means of a normalised hose type ZZ-F(AS) 0,6/1kV.

## 1.14 Protections

The facility has the required protections and the adequate distribution panels to guarantee the safety of people, as well as to avoid damaging the equipment in case of system failures. The protections have been established in accordance with both the Royal Decree 1663/2000 related to the connection of PV facilities to the low voltage grid, Royal Decree 1699/2011 and the Spanish Electrotechnical Regulation for Low Voltage (REBT) [19]:

- **ITC-BT-01.** Defines direct and indirect contacts:
  - **Direct Contact.** Contact of people or animals with active elements of the facility.
  - **Indirect Contact.** Contact of people or animals with elements that are under voltage due to an insulation failure.
- **ITC-BT-24.** Defines protections against electrical direct and indirect contacts.

### 1.14.1 Direct Current Side Protections

- **Protection Against DC Direct Contacts:**
  - **Insulation of Active Elements.** The whole PV plant is composed of insulating materials class II, id est, separating the accessible parts of the facility from its active parts by means of double insulation or reinforced insulation. Apart from class II insulation materials, PV modules must equally comply with the European Directives 89/33/EEC, 73/23/EEC, TÜV Rheinland Class II certification for use in systems up to 700  $V_{DC}$  [20], and IEC 61215. The positive and negative poles of each string are conducted separately and protected, being suitable for outdoor applications according to norm UNE 21123. Each cable end is conveniently identified by plastic labels with indelible notes. The deployment of electrical conductors follows the guidelines stipulated at ITC-BT-07, ITC-BT-19, ITC-BT-20 and ITC-BT-21.
  - **Protection through Barriers, Enclosures and Obstacles.** The PV inverter has a protection degree IP65 according to its data sheet, being therefore designed to be located outdoors. Additionally, all the active elements will be protected and insulated, avoiding fortuitous contact with any active part of the DC circuit.
  - **Protection Through Out of Reach Locations.** The constructive characteristics of the PV plant difficult the access to PV modules, distribution panels and wiring. Hence, the probability of a fortuitous contact with any active part of the DC circuit is reduced. Nonetheless, the access to the facilities zone as well as to the roof of Dreamfit Alcorcón is restricted to authorised personnel, avoiding any fortuitous contact of not authorised people. The joints between PV modules on strings run stapled to the metallic structure in its lower part, thus remaining out of reach and preventing accidents. The interconnection between the modules and the inverters is carried out through tubes that runs alongside the roof structure through an inaccessible area in normal conditions. Active parts are not near the passage of people or animals at any moment, preventing any incidental contact from occurring.
- **Protection Against DC Indirect Contacts:**

As a matter of principle, the requirement of a class II insulation level could be sufficient to ensure that an insulation failure will not result in a dangerous situation related to indirect contacts. Even so, the inverter incorporates equipment for permanent isolation

surveillance, whose mission is to detect and warn of any failure in the insulation of the PV plant. Besides, the inverter displays a warning alarm that is sent through the Fusion-Solar platform if an insulation failure is detected.

- **Protection Against DC Overloads and Short-Circuits:**

According to the inverter data sheet as well as to the inverter user manual, the DC side of the PV plant does not require fuses since all these protective devices are incorporated in the inverter. Specifically, the inverter counts with 3 different automatic DC switches that protect against short-circuits and 3 DC surge protective devices type II against over-voltages. Moreover, in subsection 2.7.1.1 it has been demonstrated that the DC switches integrated at the inverter comply with the mandatory conditions for overload and short-circuit protection established at ITC-BT-22 and ITC-BT-40 ✓.

### 1.14.2 Alternating Current Side Protections

- **Protection Against AC Direct Contacts:**

- **Insulation of Active Elements.** The whole PV plant is composed of insulating materials class II, id est, separating the accessible parts of the facility from its active parts by means of double insulation or reinforced insulation. The interconnection between the inverter and the AC distribution panels is conducted entirely through unipolar cables with double insulation 0.6/1 kV, therefore guaranteeing the class II. Phases and neutral wires are always conducted separately and protected, being suitable for outdoor applications according to norm UNE 21123. Each cable end is conveniently identified by plastic labels with indelible notes. The deployment of electrical conductors follows the guidelines stipulated at ITC-BT-07, ITC-BT-19, ITC-BT-20 and ITC-BT-21.
- **Protection through Barriers, Enclosures and Obstacles.** Similarly to the DC wiring, AC cables are conducted through insulated and not accessible tubes. Besides, all active elements will be protected and insulated, avoiding fortuitous contact with any active part of the AC circuit.
- **Protection Through Out of Reach Locations.** The constructive characteristics of Dreamfit Alcorcón difficult the access to the facilities zone and to the false ceiling through which the AC cables will be conducted until the main electrical distribution panel, thus reducing the probability of a fortuitous contact with any active part of the AC circuit. Nonetheless, the access to the all facility zones is restricted to authorised personnel. Active parts are not near the passage of people or animals at any moment, preventing any incidental contact from occurring.

- **Protection Against AC Indirect Contacts - Residual Current Relay:**

Respecting the Royal Decree 1699/2011, a residual current circuit breaker is included at the main electrical distribution panel of the facility, which has to have a sensitivity ( $I_{\Delta n}$ ) of 30 mA according to ITC-BT-18. The mission of the residual current circuit breaker stands for disabling the circuit the moment a current shunt occurs.

Current shunts are not only caused by insulation faults, but also can occur due to a direct contact. Consequently, it can be considered that the differential switch also represents a protection against direct contacts. Nonetheless, the residual current switch does not protect under any circumstances against possible derivations at the DC side of the circuit, since the galvanic isolation included by the inverter makes both sides independent.

Then, the proposed device computed at subsection 2.7.2.2 consists of a residual current relay with a rated current greater than 200  $A$ , a sensitivity of 30  $mA$  and a toroid with enough diameter for the three 120  $mm^2$  phases and the neutral wire. Therefore, the inside section has to be greater than 480  $mm^2$  and will be located at the interconnection point of the PV plant, id est, located at the main electrical distribution panel of Dreamfit Alcorcón.

- **Protection Against AC Overloads and Short-Circuits:**

Respecting the Royal Decree 1699/2011, two automatic circuit breakers are included at the facility: one at the AC box of the PV plant, and the other at the main electrical distribution panel of the building. The mission of the automatic circuit breakers consists of deactivating the circuit in case of any kind of over-current.

Over-currents are not only caused by short-circuits, but also can occur due to a line overload during a specified amount of time. Consequently, the automatic circuit breakers have to be properly designed to deactivate the circuit in both situations.

Then, the proposed devices computed at subsection 2.7.2.1 consists of automatic circuit breakers with a rated current of 200  $A$  and a short-circuit breaking capacity of 36  $kA$ . Although both automatic circuit breakers have equal rated current, discrimination between them can be ensured if the rated current (overloads protection) and the magnetic current (short-circuits protection) are adjustable.

Moreover, in subsection 2.7.2.1 it has been demonstrated that the AC circuit breakers comply with the mandatory conditions for overload and short-circuit protection established at ITC-BT-22 and ITC-BT-40 ✓.

### 1.14.3 Inverter Protections

The inverter guarantees the total independence of the DC and AC circuits by means of the high frequency galvanic insulation. Likewise, the investor complies with the requirements established in the Royal Decree 1699/2011 related to the connection of photovoltaic plants to the low voltage network.

In fact, the inverter integrates protection for the interconnection of maximum and minimum frequency, taking values 50.5  $Hz$  and 48  $Hz$  with a maximum time delay of 0.5  $s$  and minimum 3  $s$  respectively, and protection for the maximum and minimum voltage, taking values  $1.15 \cdot V_m$  and  $0.85 \cdot V_m$  respectively [16, 21].

## 1.15 Earthing System

The grounding system complies with the provisions of the Royal Decree 1699/2011 related to grounding conditions in photovoltaic plants connected to the low voltage grid:

- The earthing of the interconnected facilities will always ensure that the grounding conditions of the DSO network are not altered, avoiding the transfer of defects to the distribution grid. In order to prevent any potential differences due to voltage drops from occurring, the earthing system of the PV plant will be connected to the existing earthing system of Dreamfit Alcorcón, not transferring any defect to the DSO grid ✓.
- The facility must have a galvanic separation between the DSO grid and generating facilities, either through a isolation transformer or through any other mean that complies with the

applicable regulation in terms of industrial quality and safety. In this case, the galvanic separation is provided by the inverter as stated in subsection 1.14.3 ✓.

- The electrical masses of the PV plant will be connected to an independent ground of the neutral of the distribution company. Moreover, the system will comply with the applicable regulation in terms of industrial quality and safety. In this case, the earthing system of the building is entirely independent of the DSO grounding system ✓.

Then, next table exposes a summary of the earthing network cables selected for the PV plant of Dreamfit Alorcón in accordance with the sections computed in section 2.8:

Table 1.3. Utilised earthing wiring per stretch.

UTILISED EARTHING WIRING		
DCTT	Strings - Inverter	Coated copper (1·6 mm <sup>2</sup> )
ACTT	Inverter - AC Box	Coated copper (1·35 mm <sup>2</sup> )
	AC Box - Main Distribution Panel	Coated copper (1·60 mm <sup>2</sup> )

All in all, next table presents a summary of the protections included at the PV plant:

Table 1.4. Qualitative summary of the utilised protections.

PROTECTION	TYPE OF PROTECTION	DC	AC
DIRECT CONTACTS	ACTIVE ELEMENTS	INSULATION CLASS II	
	BARRIERS, ENCLOSURES AND OBSTACLES	TUBES, PROTECTION IP65	TUBES
	OUT OF REACH LOCATIONS	FACILITIES ZONE	FALSE CEILING, FACILITIES ZONE
INDIRECT CONTACTS	RESIDUAL CURRENT DEVICE	INSULATION CLASS II, INVERTER PROTECTIONS	INSULATION CLASS II, RESIDUAL CURRENT RELAY
OVERLOADS & SHORT-CIRCUITS	OVERCURRENT	INVERTER DC SWITCHES	AUTOMATIC CIRCUIT BREAKERS
EARTHING SYSTEM	INDIRECT CONTACTS	ELECTRICAL MASSES CONNECTED TO GND THROUGH COATED COPPER	

## 1.16 Electrical Canalisation

The electrical canalisation has been computed respecting the current regulation in terms of canalisation tubes and therefore following ITC-BT-21. The electrical canalisation is based on halogen free conduits prepared to be used outdoors and with a high UV resistance. The design has been done regarding the strings distribution as well as cable sections.

Then, next table exposes a summary of the internal diameter of tubes selected for the PV plant of Dreamfit Alorcón in accordance with section 2.9:

Table 1.5. Internal diameter of the utilised canalisation tubes.

UTILISED CANALISATION TUBES - INTERNAL DIAMETER		
DC	Strings - Inverter	21.6 mm & 28 mm
AC	Inverter - AC Box - Main Distribution Panel	45 mm

## 1.17 Photovoltaic Mounting Structure

The photovoltaic modules are mounted on an aluminium structure capable of withstanding the loads derived from the facility itself and providing the proper orientation and inclination to the PV field in order to maximise the performance of the generation plant. The surface to be used by the photovoltaic modules is exclusively the available in the roof of the building, thus not requiring additional investment in this regard.

The proper orientation and inclination of PV modules to capture as much radiation as possible depends, among other things, on the PV mounting structure. Hence, the photovoltaic modules will be mounted on a modular system based on rails and made of extruded aluminium profiles to ensure a tilt angle of  $33.5^\circ$  with respect to the horizontal plane at every PV panel, exactly as exposed in section 2.10.

The PV structure will be bolted to the roof of Dreamfit Alcorcón, ensuring its impermeability. The panels will be anchored to the PV structure by means of four clamps on the long side<sup>3</sup>:

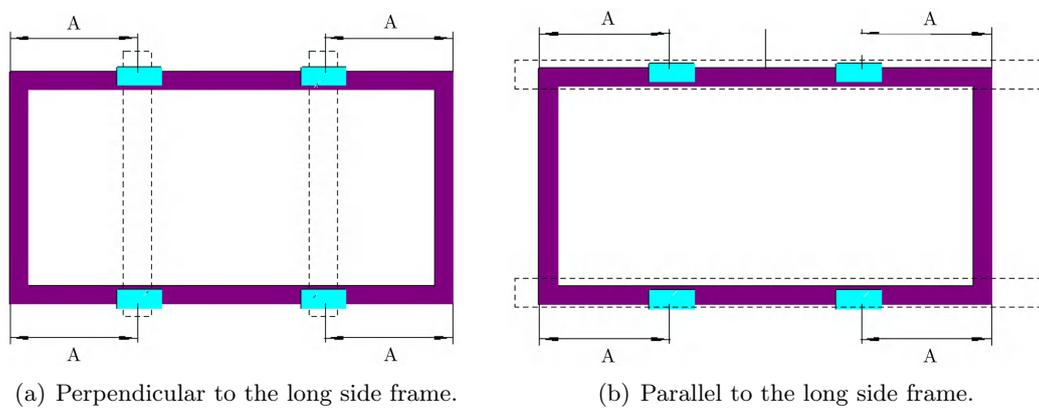


Figure 1.14. Mounting rails positioning with respect to the long side frame [22].

Taking into account the PV rows exposed in figure 2.26, the mounting rails position presented in figure 1.14(a) will be used in row 1, whereas the position presented in figure 1.14(b) will be used in rows 2-8 due to the placement of the modules.

Moreover, the installation method of clamps is shown in figure 1.15:

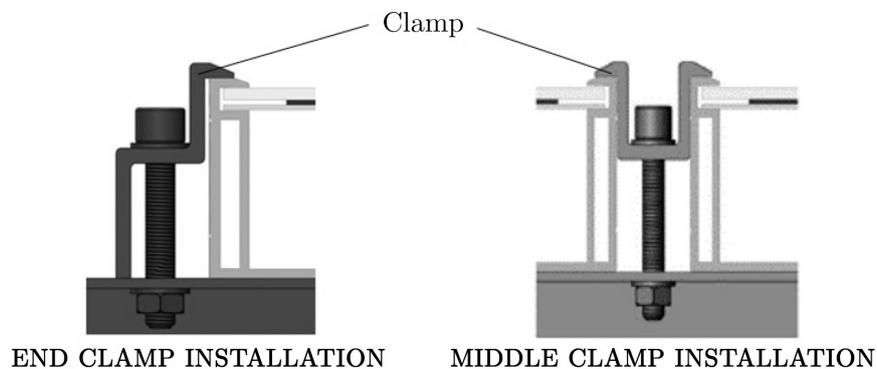


Figure 1.15. Installation method of clamps [22].

<sup>3</sup> $A \in [350, 450]$  mm [22].

The design of the PV structure and the fixing system of the photovoltaic modules allow thermal expansion, not transmitting any load that could affect the integrity of the modules. The photovoltaic modules fixing is carried out following the manufacturer's instructions, ensuring that there are no bending greater than those recommended:

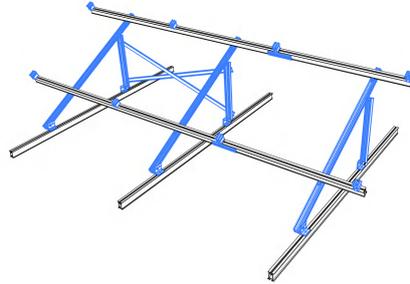


Figure 1.16. Photovoltaic mounting structure [23].

As it has been mathematically demonstrated in section 2.10 even for the worst-case scenario, no structural reinforcement is required to install the PV plant at the roof of the sports centre since the architect forecast an usage load for facilities and other usages of  $25 \text{ kg/m}^2 \checkmark$ .

## 1.18 Interconnection Schema

In accordance with the Royal Decree 244/2019, nowadays a Spanish PV plant for self-consumption purposes can be connected to the DSO grid sharing the connecting infrastructure with the consumer supply line. Hence, the PV plant can be directly interconnected to the national grid as an additional circuit of the gym's main electrical distribution panel.

Consequently, the proposed interconnection schema of the PV plant is included below:

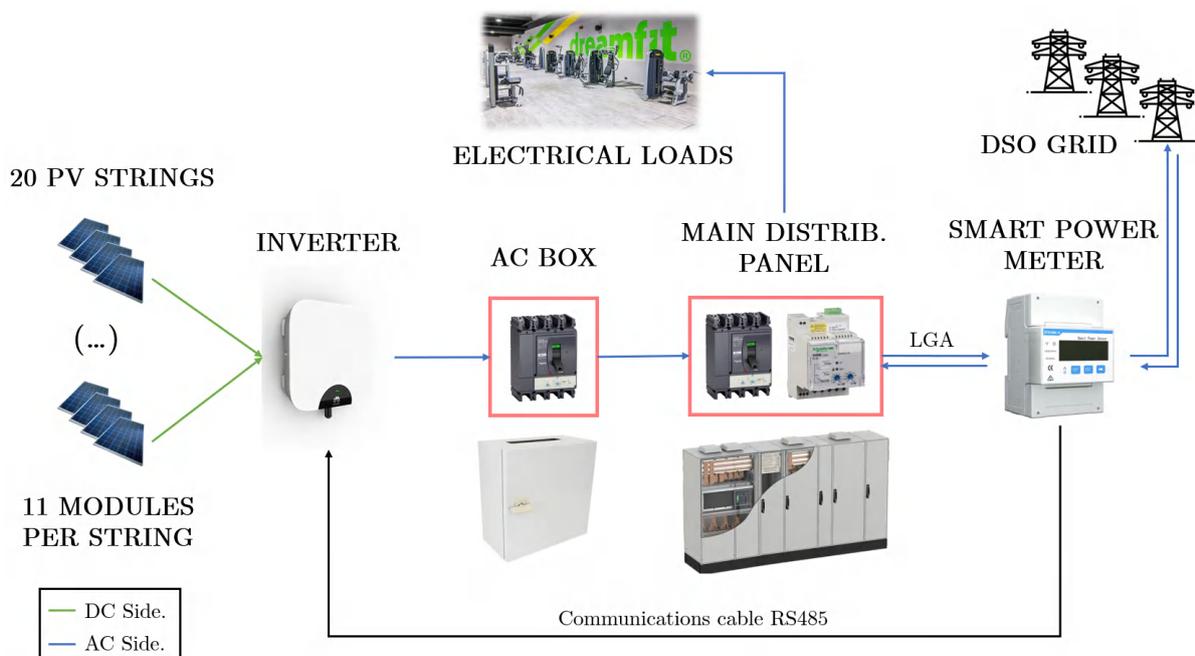


Figure 1.17. Interconnection schema of Dreamfit Alcorcón PV plant.

## 1.19 Construction Waste Management

According to the Royal Decree 105/2008, a residue is any kind of waste generated during construction works that comply with the definition provided at the third article of the Law 10/1998. Then, this section of the memory covers the following content:

- An estimate of the amount, expressed in tons and cubic meters, of the construction and demolition waste generated on the site, coded according to the published European waste list in the Order MAM/304/2002 and following the Order 2726/2009 (Community of Madrid).
- Preventive measures in order to separate the residues at the construction site.
- The reuse or elimination operations to which the generated waste will be conducted.
- An assessment of the expected cost due to managing construction and demolition waste that will be part of the of the project budget.
- Inventory of hazardous and non-hazardous waste generated.

The contractor must develop a plan to comply with its duties in terms of waste management. This plan has to be presented to the property and to the construction project manager and must be approved by all parts before the execution of the work.

### 1.19.1 Identification of Residues

There are two levels of residues in accordance with the Order MAM/304/2002:

- **Level I.** Unpolluted ground and stone materials from excavation works.
- **Level II.** Waste generated mainly during construction works, demolitions, home repairs and during the implementation of services.

In this specific project, the inventory of the residues generated is presented below:

- **Level I Residues.** There are no level I residues generated.
- **Level II Residues - Non-Hazardous:**
  - **Concrete - Code 17 01 01.** Hole in the facilities zone.
  - **Wood - Code 17 02 01.** Pallets and other transportation elements.
  - **Plastic - Code 17 02 03.** Containers, tubes, straps, etc.
  - **Copper, Bronze and Brass - Code 17 04 01.** GND cables.
  - **Aluminium - Code 17 04 02.** Mounting Structure.
  - **Steel - Code 17 04 05.** Screws and other remnants.
  - **Non-Hazardous Cables - Code 17 04 11.** Both DC and AC cables.
  - **Paper and Carton - Code 20 01 01.** Containers and boxes.
- **Level II Residues - Hazardous:**
  - **Insulation Materials - Code 17 06 04.** Cable protections.

### 1.19.2 Estimate of Generated Residues

In the absence of more verified data, an statistical estimate of ten centimetres height of waste mixture per square meter of intervention has been applied, considering a typical density among 0.5 and 1.5 tons per cubic meter. The intervention area has been approximated to the roof surface of Dreamfit Alcorcón, taking therefore a total area of 2,352  $m^2$ :

Table 1.6. Theoretical evaluation of the volume and tons of waste.

WASTE MANAGEMENT			
RESIDUE	TONNES (tons)	DENSITY (tons/ $m^3$ )	VOLUME ( $m^3$ )
Concrete	0.75	1.50	0.50
Wood	8.50	0.60	14.17
Plastic	3.75	0.90	4.17
Copper, Bronze and Brass	0.20	1.50	0.13
Aluminium	4.00	1.50	2.67
Steel	0.50	1.50	0.33
Non-Hazardous Cables	0.30	0.50	0.60
Paper and Carton	12.00	0.90	13.33
Insulation Materials	0.15	0.50	0.30
<b>TOTAL ESTIMATE</b>	<b>30.15</b>	<b>9.40</b>	<b>36.20</b>

### 1.19.3 Destination of Residues

Residues will be separated at the construction site in accordance with the information provided by table 1.6. Afterwards, the waste will be transported to the proper destination:

- **Concrete.** Construction and demolition waste recycling plant.
- **Wood.** Authorised operator of non-hazardous waste.
- **Plastic.** Authorised operator of non-hazardous waste.
- **Copper, Bronze and Brass.** Authorised operator of non-hazardous waste.
- **Aluminium.** Authorised operator of non-hazardous waste.
- **Steel.** Authorised operator of non-hazardous waste.
- **Non-Hazardous Cables.** Authorised operator of non-hazardous waste.
- **Paper and Carton.** Authorised operator of non-hazardous waste.
- **Insulation Materials.** Authorised operator of hazardous waste.

The constructor must provide official certificates of the utilised containers as well as the final destination of waste to the Project Manager of the construction work and to the property. The certificates have to be authorised by official entities and approved by the Community of Madrid.

Besides, the contractor has to keep the construction site and its surroundings clean of both debris and surplus materials, removing the temporary facilities when not required and adopting all the needed measures to ensure a safety workplace.

### 1.19.4 Expected Waste Management Cost

The expected cost due to waste management has been included to the project budget as an independent chapter. Then, according to the Elecnor® offer, the total cost allocated to waste management would be of 6,630.22 €, what represents less than the 7% of the whole budget.



## Section 2

# Calculations

### Contents

---

2.1	Orientation of the system . . . . .	<b>48</b>
2.2	Optimal Photovoltaic Peak Power Algorithm . . . . .	<b>49</b>
2.2.1	Optimal Peak Power Algorithm Explanation - <i>tfm.m</i> . . . . .	51
2.3	Photovoltaic System . . . . .	<b>55</b>
2.3.1	Photovoltaic Modules . . . . .	55
2.3.2	Inverter . . . . .	56
2.3.3	Configuration of the Photovoltaic System . . . . .	56
2.3.3.1	Maximum Power Point Conditions . . . . .	57
2.3.3.2	Open-Circuit Conditions . . . . .	58
2.3.3.3	Short-Circuit Conditions . . . . .	59
2.4	Minimum Distance between Elements . . . . .	<b>60</b>
2.4.1	Minimum Distance between the First and the Second PV Row . . . . .	63
2.4.2	Minimum Distance between the Rest of the PV Rows . . . . .	63
2.4.3	Minimum Distance between the First PV Row and the Perimeter Wall . . . . .	63
2.5	Shades Analysis . . . . .	<b>64</b>
2.6	Wiring Section . . . . .	<b>76</b>
2.6.1	Direct Current Wiring Section . . . . .	80
2.6.1.1	Stretch 1 - Wiring between the PV Modules and the Inverter . . . . .	81
2.6.2	Alternating Current Wiring Section . . . . .	82
2.6.2.1	Stretch 2 - Wiring between the Inverter and the AC Box . . . . .	83
2.6.2.2	Stretch 3 - Wiring between the AC Box and the Main Panel . . . . .	84
2.6.3	Wiring Summary . . . . .	85
2.7	Protections . . . . .	<b>87</b>
2.7.1	DC Protections . . . . .	87
2.7.1.1	DC Switches . . . . .	87
2.7.1.2	Over-Voltage Protection . . . . .	88
2.7.2	AC Protections . . . . .	88
2.7.2.1	Automatic Circuit Breakers . . . . .	89
2.7.2.2	Automatic Residual Current Circuit Breaker . . . . .	91
2.7.2.3	Voltage and Frequency Control . . . . .	92
2.7.2.4	General Manual Circuit Breaker . . . . .	92
2.8	Earthing System . . . . .	<b>92</b>
2.9	Electrical Canalisation . . . . .	<b>95</b>
2.10	Photovoltaic Mounting Structure . . . . .	<b>96</b>

---

## 2.1 Orientation of the system

The orientation of the PV modules have been established according to two angles [24]:

- **Tilt angle**  $\beta$ . Angle between the surface of the modules and the horizontal plane.
- **Azimuth angle**  $\alpha$ . Angle between the projection on the horizontal plane of the normal to the panel surface and the meridian of the location.

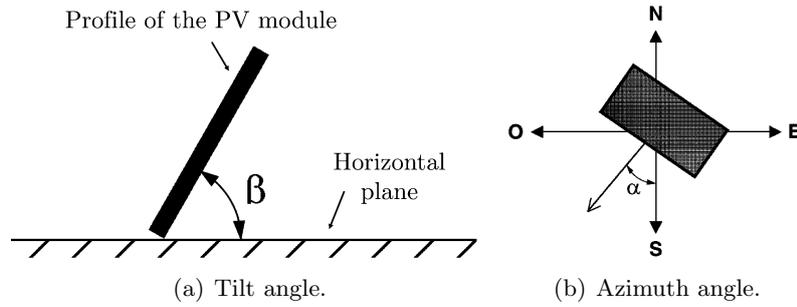


Figure 2.1. Orientation of the PV modules [25].

The optimal tilt and azimuth angles have been analysed following the recommendations of the current regulation. Hence, in accordance to a PV project developed in the northern hemisphere for an annual production [26]:

- $\beta_{opt} = \phi - 10^\circ$ , being  $\phi$  the latitude of the place measured in degrees.
- $\alpha_{opt} = 0^\circ$ .

The latitude of Dreamfit Alcorcón is  $\phi = 40.33^\circ$ . Consequently, the recommended tilt and azimuth angles are  $\beta = 30.33^\circ$  and  $\alpha = 0^\circ$ . Nonetheless, after running the system with the photovoltaic software PVsyst® [27], the optimal orientation has been adjusted according to the results obtained through the simulation:

$$\boxed{\beta_{opt} = 33.5^\circ} \quad \boxed{\alpha_{opt} = 0^\circ} \quad (2.1)$$

Graphically:

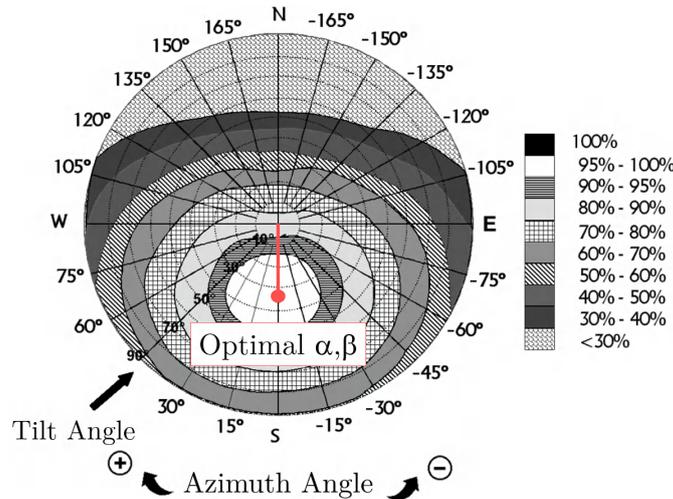


Figure 2.2. Optimal orientation of the PV system [28].

## 2.2 Optimal Photovoltaic Peak Power Algorithm

The establishment of the optimal PV peak power to install in Dreamfit Alcorcón has been computed by means of the optimisation function *tfm.m*, which determines the optimal PV peak power to both maximise the self-consumed energy as well as to minimise the compensated energy.

The algorithm has been developed programming in MATLAB® [29]:

- **Function *tfm.m* input matrix** → Imported hour by hour *data* matrix:
  - 8,760 rows since a year has 8,760 hours.
  - Column 1 → Global number of hour within a year  $\in [0, 8759]$ .
  - Columns 2-4 → Identifies each hour by:
    - \* Column 2 → Month  $\in [1, 12]$ .
    - \* Column 3 → Day  $\in [1, 31]$ .
    - \* Column 4 → Hour  $\in [0, 23]$ .
  - Column 5 → Global in-plane irradiance per hour  $G(i)$  [ $W/m^2$ ]:
    - \* Considering the optimal tilt and azimuth angles →  $\beta_{opt} = 33.5^\circ, \alpha_{opt} = 0^\circ$ .
    - \* Vector of global irradiance obtained through PVGIS® [30].
    - \* Tool utilised → Typical Meteorological Year (TMY) tool<sup>1</sup>.
  - Column 6 → Peak Sun Hours (PSH) [ $h$ ]:
    - \* A PSH is defined as one hour in which the intensity of solar irradiance reaches an average of 1,000 Watts (W) of energy per square meter [32]. Hour by hour:

$$PSH(i) = G(i) \cdot \frac{1 \text{ h}}{1,000 \text{ W/m}^2} \quad (2.2)$$

- \* Then, a PSH is the average sunlight a certain location receives throughout a day:

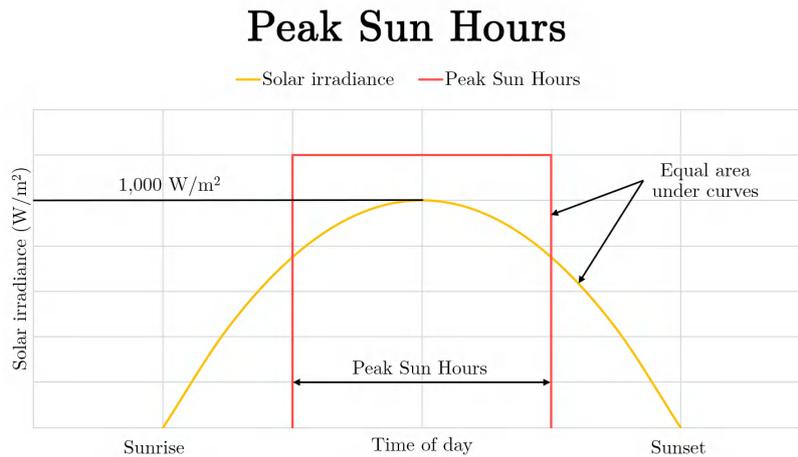


Figure 2.3. Peak Sun Hours.

- Column 7 → Hourly consumption of Dreamfit Alcorcón [ $kWh$ ].

<sup>1</sup>A TMY is a set of data with values for every hour in a year for a given geographical location. The data is selected from hourly databases in longer periods of time following the regulation UNE-EN ISO 15927-4:2011 [31].

- **Function *tfm.m* declared variables and vectors:**
  - **Global variables and vectors:**
    - \* *pr* → Performance Ratio variable obtained through that measures the quality of the PV facility by relating the actual and the rated yield.
    - \* *consumption* → Vector of 8,760 positions that includes the actual annual consumption of Dreamfit Alcorcón hour by hour.
  - **Iteration variables and vectors:**
    - \* *i* → Iteration variable to examine the 8,760 positions of every iteration vector as well as each of the optimisation vectors.
    - \* *pp* → Iteration variable that represents the peak power installed at the PV field.
    - \* *energy-pv* → Iteration vector of 8,760 positions that represents the PV energy generated hour by hour.
    - \* *excess* → Iteration vector of 8,760 positions that represents the excessive PV energy injected to the national grid hour by hour.
    - \* *grid* → Iteration vector of 8,760 positions that represents the energy consumed from the national grid hour by hour.
    - \* *self\_consumed* → Iteration vector of 8,760 positions that represents the self-consumed energy hour by hour.
  - **Control variable:**
    - \* *pow* → Control variable to determine if the iterative value of *pp* is the optimal peak power.
  - **Optimisation vectors** → Exported hour by hour vectors:
    - \* *energy-pv\_opt* → Iteration vector of 8,760 positions that represents the PV energy generated hour by hour for the optimal peak power.
    - \* *excess\_opt* → Iteration vector of 8,760 positions that represents the excessive PV energy injected to the national grid hour by hour for the optimal peak power.
    - \* *grid\_opt* → Iteration vector of 8,760 positions that represents the energy consumed from the national grid hour by hour for the optimal peak power.
    - \* *self\_consumed\_opt* → Iteration vector of 8,760 positions that represents the self-consumed energy hour by hour for the optimal peak power.
- **Function *tfm.m* output variable:**
  - *pp\_opt* → Output variable returned by the function which represents the result of the optimisation algorithm, id est, the optimal PV peak power to install.

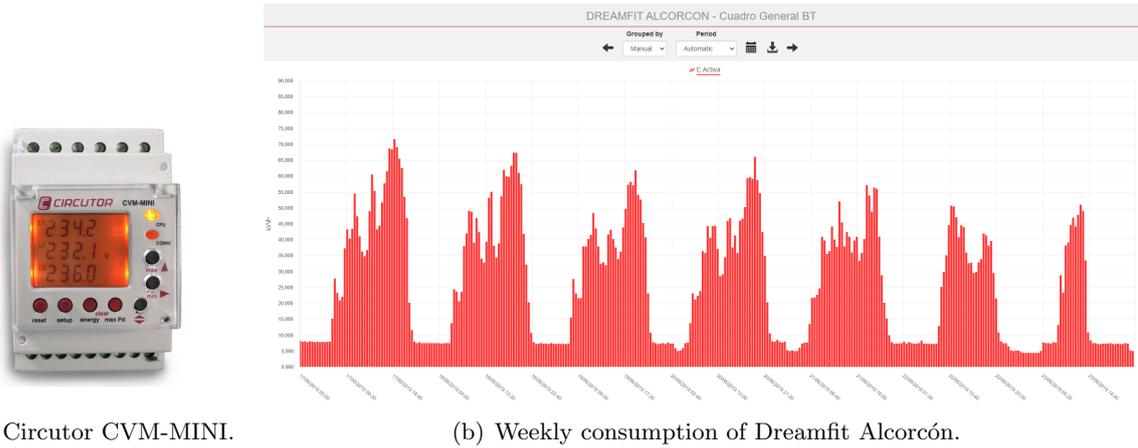
The input *data* matrix has been imported from a Microsoft Excel spreadsheet file to the software MATLAB through the instruction *xlsread()* [33]. On the contrary, the optimisation vectors have been exported to a Microsoft Excel spreadsheet file by means of the programming command *xlswrite()* [34].

The optimisation vectors with hour by hour data for the whole analysed year have been exported to simplify the development of the production study and the economic study of the PV engineering project.

### 2.2.1 Optimal Peak Power Algorithm Explanation - *tfm.m*

The hourly consumption of Dreamfit Alcorcón has been obtained by means of a power analyser that already existed in the facility. Dreamfit uses these data to develop strategies of energy efficiency and to assess the energy management.

The interface and the data provided by the power analyser of Dreamfit Alcorcón for a random week is included hereunder.



(a) Circutor CVM-MINI.

(b) Weekly consumption of Dreamfit Alcorcón.

Figure 2.4. Power Analyser of Dreamfit Alcorcón [35].

The input hourly data downloaded from the power analyser and therefore the hourly consumption data used to compute the optimal PV peak power corresponds to the year 2019. It is important to highlight that data from year 2020 cannot be used due to COVID-19 lockdown, since the pattern of consumption of 2020 cannot be considered a representative year. Hence, the most recent and representative consumption data available corresponds to the year 2019.

The surplus energy generated by the PV field will be injected to the national power grid and compensated. Therefore, according to the simplified compensation process explained in the Royal Decree 244/2019, the algorithm has been based on a loop that determines the optimal PV field peak power in order to:

- Maximise the self-consumed energy.
- Minimise the surplus compensated energy that is injected to the grid.

Taking into account the previous bullet points, the optimal PV peak power can be expressed as a value that maximises the difference between the annual self-consumed energy and the annual compensated energy. Then, the optimal peak power is established by the function *tfm.m* in an iterative manner as presented in equation 2.3:

$$pp_{opt} \iff \max \left( \sum_{i=1}^{8760} self\_consumed(i) - \sum_{i=1}^{8760} excess(i) \right) \quad (2.3)$$

The iterations to determine the optimal peak power have been completed for  $pp \in [50, 125] kW$ . In fact, the rated power of the PV facility cannot exceed 100 kW to enable the simplified compensation process of surplus energy regulated by the Royal Decree 244/2019.

Nonetheless, it must be considered that, in accordance with the current regulation, the installed PV power is the so-called rated PV power, id est, the facility PV power is measured at the inverter [6]. Hence, the PV field power or PV peak power has to be greater than the rated power of the inverter to overcome the power losses. This is the reason why the peak power can exceed the value of 100 kW.

The PV energy available hour by hour has been computed respecting the current regulation for grid-connected facilities. Then [36]:

$$E_p(i) = \frac{G_{dm}(\alpha, \beta) \cdot P_{mp} \cdot PR}{G_{cem}} \quad (2.4)$$

Where:

- $E_p(i)$  → PV energy produced in the hour  $i$  [kWh].
- $G_{dm}(\alpha, \beta)$  → Irradiance measured at the PV modules plane in the hour  $i$  [kWh/m<sup>2</sup>].
- $P_{mp}$  → Peak PV field power [kW].
- $PR$  → Performance ratio [%]. Measures the energetic yield and depends on [37]:
  - The relation between PV efficiency and temperature.
  - The wires efficiency and Joule effect.
  - Losses due to dispersion of parameters and dirt.
  - Losses due to MPPT errors when adjusting to the maximum power point.
  - Inverter energy efficiency.
  - Other causes: shadows, position of the generators, etc.
- $G_{cem} = 1$  kW/m<sup>2</sup>.

Delving into the equation 2.4:

- $E_p(i) \equiv energy\_pv(i)$  → Regarding the naming used in the *tfm.m* function exposed above.
- Dividing  $G_{dm}(\alpha, \beta)$  by  $G_{cem}$  and regarding equation 2.2:

$$\frac{G_{dm}(\alpha, \beta)}{G_{cem}} = \overbrace{G(i) \cdot \frac{1 \text{ h}}{1,000 \text{ W/m}^2}}^{\text{Equation 2.2}} = PSH(i) \quad (2.5)$$

- $P_{mp} \equiv pp$  → Regarding the naming used in the *tfm.m* function exposed above.
- $PR \equiv pr$  → Regarding the naming used in the *tfm.m* function exposed above.

Consequently, the PV energy available hour by hour has been computed adapting the expression 2.4 through the *tfm.m* function developed in MATLAB:

$$energy\_pv(i) = PSH(i) \cdot pp \cdot pr \quad (2.6)$$

It should be taken into account that the equations 2.4 and 2.6 are equivalent as it has been illustrated above. The value of the performance ratio has been computed by means of a system simulation considering the location, the system shades, the manufacturer, the model of both the PV modules and the inverter, etc. Therefore  $pr = 0.887$ .

There is an additional constraint that limits the maximum PV field peak power which is directly related to the maximum active power withstood by the inverter. Although the iteration variable  $pp \in [50, 125]$  kW, the maximum active power withstood by the inverter limits the possible values of the variable  $pp_{opt}$ . In the end, the power that reaches the inverter cannot be higher than 110 kW in accordance with the manufacturer data sheet.

Summarising, the operating procedure followed by the algorithm is a loop that returns the optimal PV peak power depending on the hour by hour irradiance of the particular location and the hour by hour consumption data for a whole year.

Mathematically, the optimisation loop is based on two equations:

- Equation 2.3 to determine if the iterative peak power is in fact the optimal PV peak power.
- Equation 2.6 to compute the hour by hour PV production per each loop iteration.

Graphically, the operating procedure followed by the function *tfm.m* is included below:

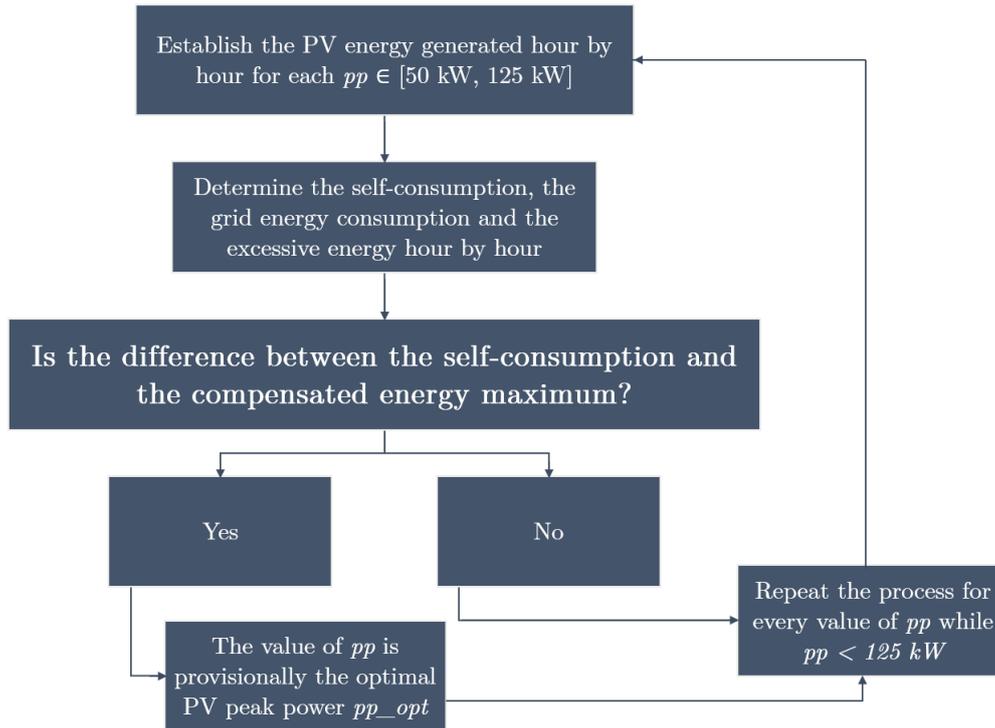


Figure 2.5. Operating procedure followed by the PV peak power optimisation algorithm.

All in all, the optimal PV peak power for Dreamfit Alcorcón after running the simulation is:

$$\boxed{pp_{opt} = 111 \text{ kW}} \quad (2.7)$$

Including directly a MATLAB Command Window screenshot, the optimal power returned by the programming function *tfm.m* is actually 111 kW ✓:

MATLAB Command Window

```
>> [pp_opt] = tfm()
```

```
pp_opt =
```

```
111
```

Figure 2.6. Optimal PV peak power of Dreamfit Alcorcón returned by MATLAB.

Then, the annual results obtained for an optimal peak power of 111  $kW$  are presented below:

Table 2.1. MATLAB - Annual results - PV production.

ANNUAL RESULTS	kWh/year
TOTAL CONSUMPTION	447,567.75
PV PRODUCTION	198,897.59
SURPLUS PV ENERGY	29,733.28
GRID CONSUMPTION	278,403.45
SELF-CONSUMPTION	169,164.30
<b>OPTIMAL PEAK POWER</b>	<b>111 kW</b>

In accordance with the data included in the table 2.1, the expected PV production will be of approximately 200  $MWh$  per year. Additionally, taking into account the actual PV energy self-consumed, id est, discarding the surplus energy, more than a 35% of the total annual energy demanded by Dreamfit Alcorcón will be produced by the solar modules.

The graphic relation obtained through MATLAB between the total consumption, the PV production, the surplus energy, the energy consumed from the grid and the energy self-consumed along the 8,760h of a year is featured as follows<sup>2</sup>:

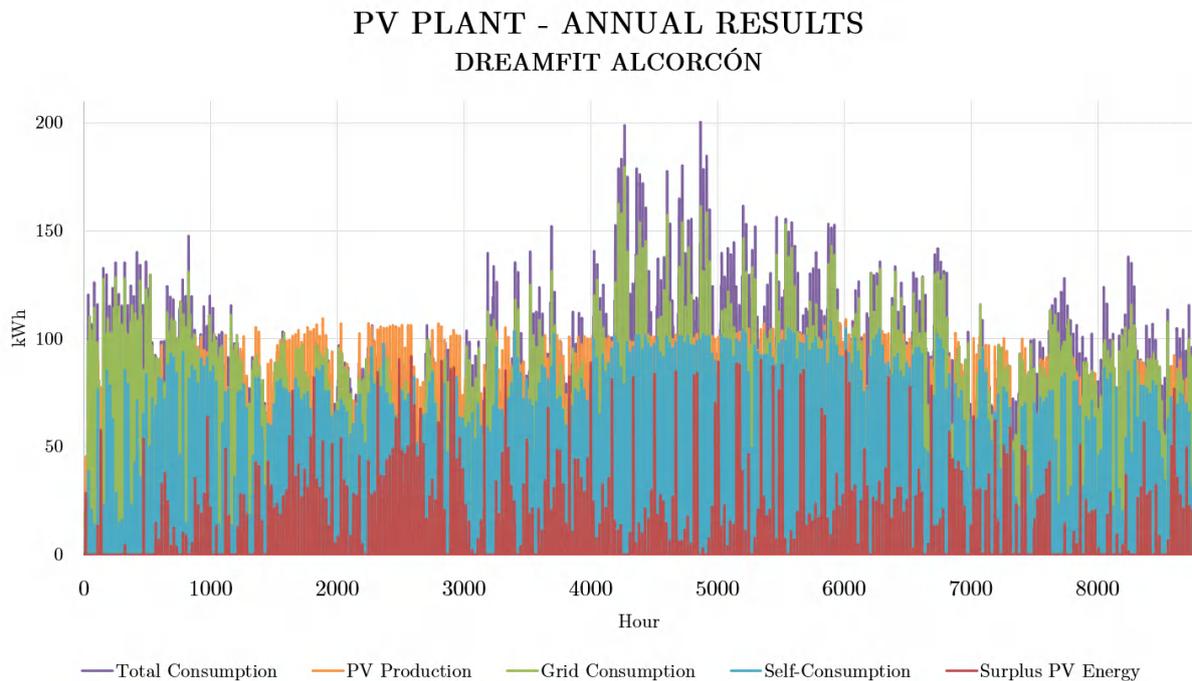


Figure 2.7. MATLAB - Annual results - PV production.

<sup>2</sup>The real-time PV power ( $kW$ ) cannot exceed the maximum AC active power withstood by the inverter under no circumstances, which in this case is 110  $kW$  according to the Inverter Data Sheet

## 2.3 Photovoltaic System

The PV system consists of two main components, the PV modules and the inverter. Then, taking into account that the optimal peak PV power is 111 kW and that the optimal rated power of the inverter is 100 kW, both elements have been selected:

Table 2.2. Description of the PV system.

PHOTOVOLTAIC SYSTEM	
PV Modules Manufacturer	
PV Modules Model	TSM-DE18M-(II)-505
N <sup>cr</sup> of PV Modules	220 PV modules
PV Module Peak Power	505 W <sub>p</sub>
PV System Peak Power	111.1 kW <sub>p</sub>
Inverter Manufacturer	
Inverter Model	SUN2000-100KTL-M1-400Vac
N <sup>cr</sup> of Inverters, Strings	1 inverter, 20 strings (10 MPPTs)
Inverter Rated Power	100 kW <sub>n</sub>
PV System Rated Power	100 kW <sub>n</sub>

In terms of the PV modules, the PV field power is equal to the optimal PV peak power:

$$220 \text{ PV modules} \cdot \frac{505 \text{ W}_p}{1 \text{ PV module}} = 111.1 \text{ kW} \checkmark \quad (2.8)$$

### 2.3.1 Photovoltaic Modules

The main characteristics of the monofacial PV modules are presented in table 2.3<sup>3</sup>:

Table 2.3. Main electrical features of every PV module.

PV MODULE FEATURES	
Peak Power	505 W <sub>p</sub>
Open-Circuit Voltage (V <sub>oc</sub> )	51.9 V
Maximum Power Point Voltage (V <sub>MPP</sub> )	43.0 V
Maximum Power Point Current (I <sub>MPP</sub> )	11.75 A
Short-Circuit Current (I <sub>sc</sub> )	12.35 A
Length	2.187 m
Width	1.102 m
Temperature Coefficient of P <sub>MAX</sub>	-0.34%/°C
Temperature Coefficient of V <sub>oc</sub>	-0.25%/°C
Temperature Coefficient of I <sub>sc</sub>	0.04%/°C

<sup>3</sup>Data under Standard Test Conditions: irradiance of 1,000/m<sup>2</sup>, cell temperature of 25°C and air mass AM1.5.

### 2.3.2 Inverter

The main characteristics of the inverter are presented in table 2.4:

Table 2.4. Main electrical features of the inverter.

INVERTER FEATURES	
Rated AC Output Active Power	100 kW
Rated AC Output Voltage, Frequency	400 V (3W+N+PE), 50 Hz
Maximum AC Output Current	160.4 A
Maximum DC Input Current per MPPT	26 A
Maximum Short-Circuit Current per MPPT	40A
Maximum Efficiency	98.6%
Minimum DC MPPT Operating Voltage	200 V
Maximum DC MPPT Operating Voltage	1,000 V
Maximum DC System Input Voltage	1,100 V
Number of MPP Trackers	10 MPPTs
Maximum Number of Strings per MPPT	2 strings

The PV modules as well as the inverter data sheets are included in the annexes.

### 2.3.3 Configuration of the Photovoltaic System

Considering that there are 10 MPPTs per inverter at which two different PV strings can be connected, twenty strings of PV panels can be connected to the same inverter. This is the reason why just one inverter is required to accomplish the expected performance in this project:

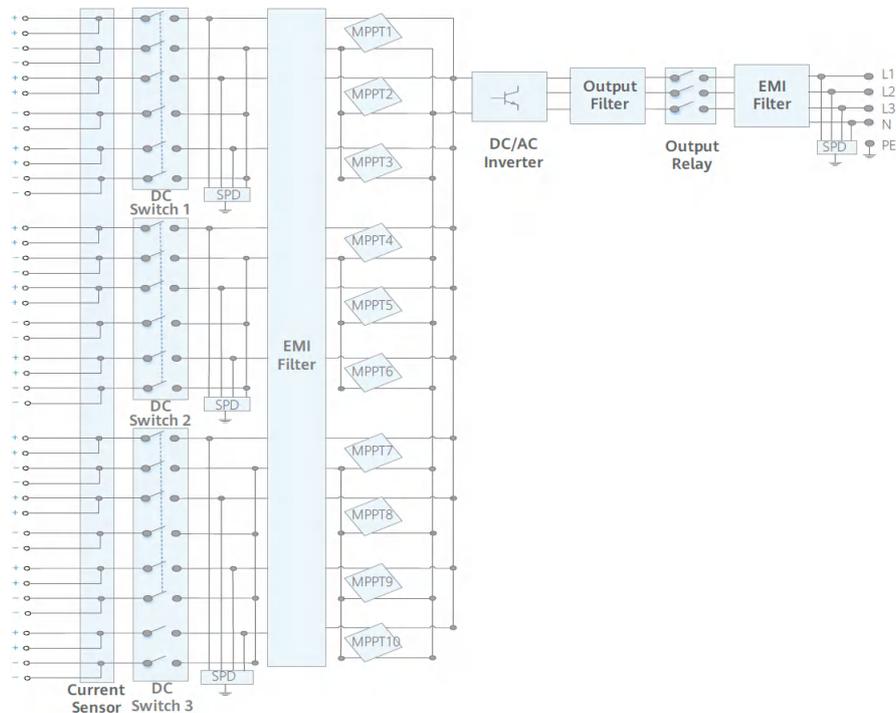


Figure 2.8. Circuit diagram of the inverter [38].

Once the inverter is selected, the PV modules have to be chosen too. The peak power per photovoltaic module should comply with two requirements:

- *Number of PV modules · Peak power per module = 111 kW.*
- *Remainder  $\left(\frac{\text{Number of PV modules}}{20 \text{ strings}}\right) = 0.$*

Therefore, 220 PV modules with a peak power of 505 W will be installed, having **11 PV panels connected in series per string and 2 parallel strings per MPPT**, id est, having 22 PV modules per MPPT in total. This PV configuration generates both an input voltage and current that never exceeds the inverter acceptable range regardless of the working conditions.

Although the operational temperature range of the PV modules is  $[-40^{\circ}\text{C}, 85^{\circ}\text{C}]$ , the PV system has been designed taking into account the official database of historical extreme temperatures of the closest meteorological station to Dreamfit Alcorcón [39].

Hence, the actual ambient range of temperatures analysed is  $[-12^{\circ}\text{C}, 41.6^{\circ}\text{C}]$ . So, now the temperature of the PV cells under limit conditions can be computed [40]:

$$T_c = T_{amb} + \frac{T_{NOC} - 20^{\circ}\text{C}}{800 \text{ W/m}^2} \cdot E \quad (2.9)$$

Where:

- $T_c \rightarrow$  Photovoltaic cells temperature under specific operating conditions  $[^{\circ}\text{C}]$ .
- $T_{amb} \in [-12^{\circ}\text{C}, 41.6^{\circ}\text{C}] \rightarrow$  Ambient temperature in the shade  $[^{\circ}\text{C}]$ .
- $E \rightarrow$  Solar irradiance  $[\text{W/m}^2]$ .
- $T_{NOC} \rightarrow$  Photovoltaic cells temperature under nominal operating conditions  $[^{\circ}\text{C}]$ .

According to the PV modules data sheet:  $T_{NOC} = 43^{\circ}\text{C}$ .

Then, the equation 2.9 is applied to obtain  $T_{c_{min}}$  for  $E = 100 \text{ W/m}^2$ :

$$T_{c_{min}} = -12^{\circ}\text{C} + \frac{43^{\circ}\text{C} - 20^{\circ}\text{C}}{800 \text{ W/m}^2} \cdot 100 \text{ W/m}^2 \longrightarrow \boxed{T_{c_{min}} = -9.13^{\circ}\text{C}} \quad (2.10)$$

Hereinafter, the equation 2.9 is applied to obtain  $T_{c_{max}}$  for  $E = 1,000 \text{ W/m}^2$ :

$$T_{c_{max}} = 41.6^{\circ}\text{C} + \frac{43^{\circ}\text{C} - 20^{\circ}\text{C}}{800 \text{ W/m}^2} \cdot 1,000 \text{ W/m}^2 \longrightarrow \boxed{T_{c_{max}} = 70.35^{\circ}\text{C}} \quad (2.11)$$

### 2.3.3.1 Maximum Power Point Conditions

Every Maximum Power Point Tracker (MPPT) will always try to maximise the PV production and therefore the efficiency of the system by means of working on the Maximum Power Point (MPP). Hence, the compliance with the inverter voltage limits under MPP conditions must be now verified regardless of the cells temperature to ensure a proper performance of the whole photovoltaic facility. Consequently:

- The maximum MPP voltage of the PV modules is reached for  $T_{c_{min}} \approx -10^{\circ}\text{C}$  since the voltage increases when the temperature decreases in crystalline cells.
- The minimum MPP voltage of the PV modules is registered for  $T_{c_{max}} \approx 70^{\circ}\text{C}$  since the voltage decreases when the temperature increases in crystalline cells.

Then, the requirements compliance under MPP conditions is justified below:

- **MPP upper limit condition.** Maximum voltage per MPPT under MPP conditions:

$$V_{max_{MPP_{PV}}} \overbrace{(-10^\circ C)}^{T_{c_{min}}} \leq V_{max_{MPP_{INVERTER}}} = \overbrace{1,000 V_{DC}}^{Table\ 2.4} \quad (2.12)$$

Remembering that there are 2 strings per MPPT of 11 PV modules connected in series:

$$V_{max_{MPP_{PV}}}(-10^\circ C) = \overbrace{11\ PV\ modules}^{Modules\ per\ string} \cdot \overbrace{43 \cdot V_{DC}}^{Table\ 2.3} \cdot [1 + \overbrace{(-0.0034^\circ C^{-1})}^{Table\ 2.3} \cdot \overbrace{(-35^\circ C)}^{\Delta T}] \quad (2.13)$$

Then, the upper limit condition is verified:

$$V_{max_{MPP_{PV}}}(-10^\circ C) = 529.29 V_{DC} \leq V_{max_{MPP_{INVERTER}}} = 1,000 V_{DC} \checkmark \quad (2.14)$$

- **MPP lower limit condition.** Minimum voltage per MPPT under MPP conditions:

$$V_{min_{MPP_{PV}}} \overbrace{(70^\circ C)}^{T_{c_{max}}} \geq V_{min_{MPP_{INVERTER}}} = \overbrace{200 V_{DC}}^{Table\ 2.4} \quad (2.15)$$

Remembering that there are 2 strings per MPPT of 11 PV modules connected in series:

$$V_{min_{MPP_{PV}}}(70^\circ C) = \overbrace{11\ PV\ modules}^{Modules\ per\ string} \cdot \overbrace{43 \cdot V_{DC}}^{Table\ 2.3} \cdot [1 + \overbrace{(-0.0034^\circ C^{-1})}^{Table\ 2.3} \cdot \overbrace{45^\circ C}^{\Delta T}] \quad (2.16)$$

Then, the lower limit condition is verified:

$$V_{min_{MPP_{PV}}}(-10^\circ C) = 400.63 V_{DC} \geq V_{min_{MPP_{INVERTER}}} = 200 V_{DC} \checkmark \quad (2.17)$$

Thus, it has been demonstrated that, when working under MPP conditions, the inverter will be able to withstand the maximum voltage per MPPT for the established PV configuration, as well as that the minimum voltage per MPPT will be greater than the inverter start voltage  $\checkmark$ .

### 2.3.3.2 Open-Circuit Conditions

In the same way, it must be checked that the inverter will withstand the maximum voltage per MPPT in case of working under Open-Circuit (OC) conditions. Nonetheless, the minimum voltage check is not required in this case since there would be no PV production in open-circuit conditions, so any start voltage needs to be exceeded. Once again:

- The maximum open-circuit voltage of the PV modules is reached for  $T_{c_{min}} \approx -10^\circ C$ .

Then, the upper limit requirement compliance under OC conditions is justified below:

- **OC upper limit condition.** Maximum voltage per MPPT under OC conditions:

$$V_{max_{OC_{PV}}} \overbrace{(-10^\circ C)}^{T_{c_{min}}} \leq V_{max_{OC_{INVERTER}}} = \overbrace{1,100 V_{DC}}^{Table\ 2.4} \quad (2.18)$$

Remembering that there are 2 strings per MPPT of 11 PV modules connected in series:

$$V_{maxOC_{PV}}(-10^{\circ}C) = \overbrace{11 \text{ PV modules}}^{\text{Modules per string}} \cdot \overbrace{51.9 V_{DC}}^{\text{Table 2.3}} \cdot [1 + \overbrace{(-0.0025^{\circ}C^{-1})}^{\text{Table 2.3}} \cdot \overbrace{(-35^{\circ}C)}^{\Delta T}] \quad (2.19)$$

Then, the upper limit condition is verified:

$$V_{maxOC_{PV}}(-10^{\circ}C) = 620.85 V_{DC} \leq V_{maxOC_{INVERTER}} = 1,100 V_{DC} \quad \checkmark \quad (2.20)$$

Once again, it has been demonstrated that, when working under open-circuit conditions, the inverter will be able to withstand the maximum voltage per MPPT for the established PV configuration  $\checkmark$ .

### 2.3.3.3 Short-Circuit Conditions

Similarly, it must be checked that the inverter will withstand the maximum current per MPPT in case of a Short-Circuit (SC). Nevertheless, the minimum inverter current check is not required since the danger related to a short-circuit is based on the high value reached by the currents. Accordingly, in this specific case:

- The maximum short-circuit current of the PV modules is reached for  $T_{c_{max}} \approx 70^{\circ}C$  since the current increases when the temperature increases in crystalline cells.

Then, the upper limit requirement compliance under SC conditions is justified below:

- **SC upper limit condition.** Maximum current per MPPT under SC conditions:

$$I_{maxSC_{PV}}(\overbrace{70^{\circ}C}^{T_{c_{max}}}) \leq I_{maxSC_{INVERTER}} = \overbrace{40 A_{DC}}^{\text{Table 2.4}} \quad (2.21)$$

Remembering that there are 2 strings per MPPT of 11 PV modules connected in series:

$$I_{maxSC_{PV}}(70^{\circ}C) = \overbrace{2 \text{ PV strings}}^{\text{Strings per MPPT}} \cdot \overbrace{12.35 A_{DC}}^{\text{Table 2.3}} \cdot [1 + \overbrace{(0.0004^{\circ}C^{-1})}^{\text{Table 2.3}} \cdot \overbrace{(45^{\circ}C)}^{\Delta T}] \quad (2.22)$$

Then, the upper limit condition is verified:

$$I_{maxSC_{PV}}(70^{\circ}C) = 25.14 A_{DC} \leq I_{maxSC_{INVERTER}} = 40 A_{DC} \quad \checkmark \quad (2.23)$$

Consequently, it has been demonstrated that, when working under short-circuit conditions, the inverter will be able to withstand the maximum current per MPPT for the established PV configuration  $\checkmark$ .

It is therefore demonstrated that the chosen inverter complies with the required operating specifications regardless of the working conditions.

## 2.4 Minimum Distance between Elements

The minimum distance between PV rows or between a row and an obstacle has been computed adapting the expression provided in the third annex of the Technical Specifications of Grid-Connected Facilities document. Then, with the aim of having at least four hours without shades between elements located right in front even in the worst-case scenario, id est, in the winter solstice, the distance between modules must be computed as follows [41]:

$$d \geq h \cdot k \Rightarrow d \geq h \cdot \frac{\overbrace{1}^k}{\tan(61^\circ - \phi)} \quad (2.24)$$

Where:

- $d$  → Minimum distance between elements measured horizontally [ $m$ ].
- $h$  → Height of an obstacle that project shadows [ $m$ ].
- $k$  → Dimensionless variable that depends on the location latitude [-].
- $\phi$  → Latitude of the location [ $^\circ$ ].

Graphically:

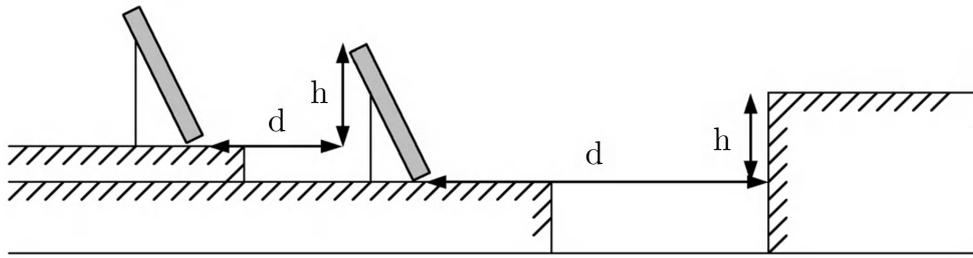


Figure 2.9. Minimum distance between elements [42].

Focusing on the triangle between the distance  $d$ , the height  $h$  and the sunlight:

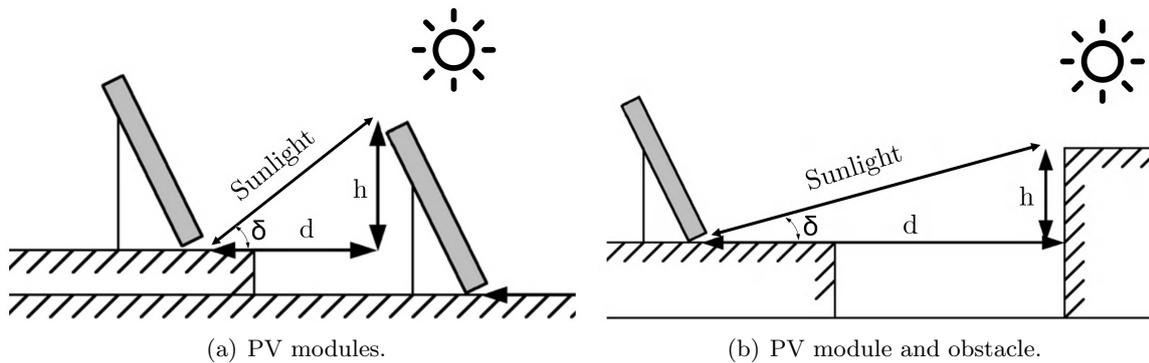


Figure 2.10. Solar elevation [42].

Where:

- $\delta$  → Solar elevation with respect to the horizontal plane [ $^\circ$ ].

Then, the solar elevation can be obtained by means of trigonometry:

$$\delta = \tan^{-1}(h/d) \quad (2.25)$$

Ideally, the required solar elevation to ensure no shades are created between elements located right in front is  $\delta = 0^\circ$ . Nonetheless, the distance between elements  $d$  should be infinite in that case. Taking into account that the latitude of Dreamfit Alcorcón is  $\phi = 40.33^\circ$ , the suggested solar elevation would be  $\delta = 20.67^\circ$  according to equation 2.24. Therefore, with the aim of being more restrictive than what the regulation imposes, it has been set a value of  $\delta = 14^\circ$ .

Then, imposing  $\delta = 14^\circ$  it can be observed through the sun path chart that even in the worst-case scenario, id est, in the winter solstice that takes place every twenty first of December, there will be more than six hours without shades between elements located right in front:

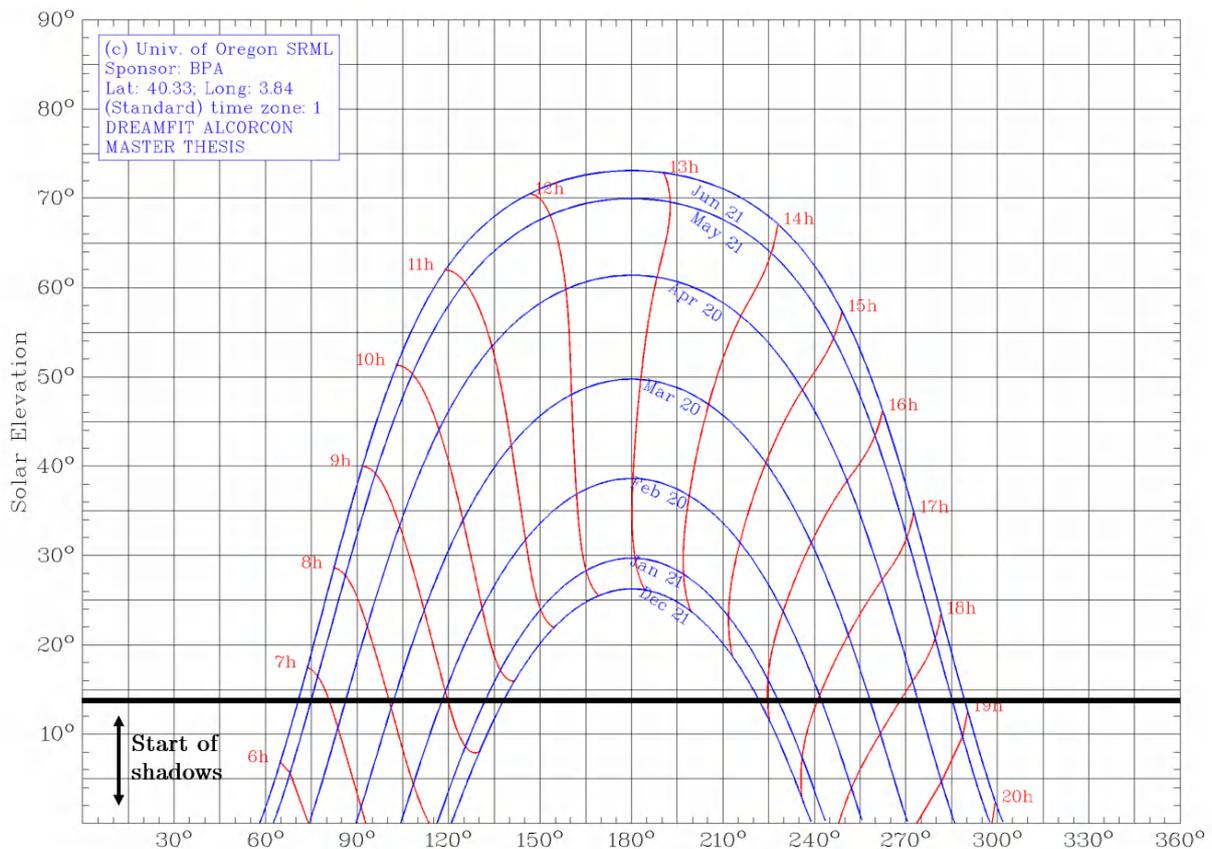


Figure 2.11. Sun path chart of Dreamfit Alcorcón [43].

Additionally, it must be taken into account that the previous plot has been developed in UTC+1 time, which corresponds to winter Spanish time. Therefore, regarding figure 2.11:

- **Early schedule:**

- **Winter.** The projected shadows affect only before 6:30h, when the gym is still no open and there is almost no sun ✓.
- **Summer.** The projected shadows affect only before 7:30h when the sunrise has not finished yet and the gym has just opened ✓.

- **Late schedule:**

- **Winter.** During winter months there is almost no sun after 19h, so shades essentially do not affect to the PV production ✓.
- **Summer.** During summer months, the projected shadows would start only after 20h, coinciding with the beginning of the sunset ✓.

Hence, the adjustment of the equation 2.24 for  $\delta = 14^\circ$  is included below:

$$d \geq h \cdot k \Rightarrow d \geq h \cdot \frac{\overbrace{1}^k}{\underbrace{\tan(14^\circ)}_\delta} \quad (2.26)$$

The expression 2.25 and therefore the expression 2.26 can be applied to obtain the minimum distance between PV rows if the azimuth angle of both the roof and the PV panels do not differ significantly from  $0^\circ$  [44]. Thus, in this case the mentioned equations can be implemented since the slope of the facility roof is just equal to 7% and the azimuth angle is  $0^\circ$  in both cases ✓.

The PV field is going to be deployed in such a way that the roof slope will not increase the projected shadows. Hence, the PV structure is going to be installed adjusting both the height and the tilt angle of each row. The aim consists of establishing in each PV row the required optimal tilt angle  $\beta = 33.5^\circ$  with the horizontal plane and a height difference of 0.3 m with respect to the perimeter wall. Then:

- The slope of the roof is equal to 7% and it is distributed in four different planes:
  - Two of these planes require a tilt angle  $\beta_{local_1} = 33.5^\circ + 4^\circ = 37.5^\circ$ .
  - The other two planes require a tilt angle  $\beta_{local_2} = 33.5^\circ - 4^\circ = 28.5^\circ$ .
  - The tilt angle with respect to the horizontal plane is in all cases  $\beta = 33.5^\circ$ .
- Although the building is a parallelepiped, the slope of the roof creates differences of height between the roof plane and the perimeter wall. This height varies between 0.3 m and 1.3 m, so, the PV rows will be installed adjusting the height:
  - In order to avoid shades issues between rows.
  - In order to avoid shades issues between modules and the perimeter wall as well.
  - The level of each row with respect to the ground plane will be therefore the same.

Evaluating the right triangle formed between the PV module, the horizontal plane and the projected vertical height of the PV panel itself:

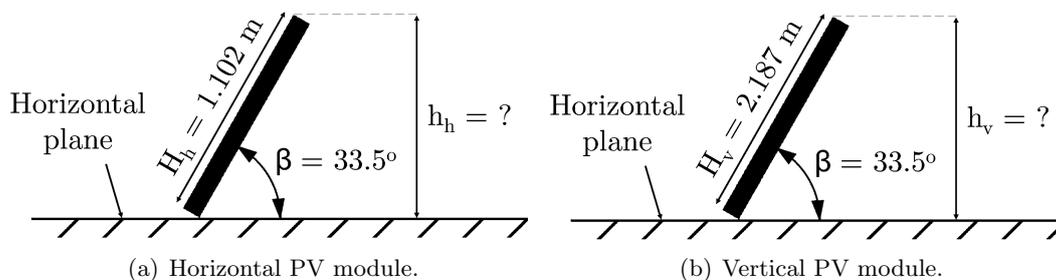


Figure 2.12. Projected vertical height of PV modules.

Then, the actual height of each PV panel, the tilt angle are and the latitude are, respectively:

- Height of a horizontal PV panel with respect to the horizontal plane  $\rightarrow H_h = 1.102 \text{ m}$ .
- Height of a vertical PV panel with respect to the horizontal plane  $\rightarrow H_v = 2.187 \text{ m}$ .
- Optimal tilt angle with respect to the horizontal plane  $\rightarrow \beta = 33.5^\circ$ .
- Latitude  $\rightarrow \phi = 40.33^\circ$ .

#### 2.4.1 Minimum Distance between the First and the Second PV Row

There are 18 thermal solar panels that are already located in the facility roof that has to be taken into account since these modules reduce the available space. Thus, the first row of PV modules will be placed horizontally to use the available space to a maximum.

Therefore, the height of the obstacle  $h_h$  according to figure 2.12(a) can be computed applying trigonometric identities:

$$h_h = \text{sen}(\beta) \cdot H_h \longrightarrow \boxed{h_h = 0.61 \text{ m}} \quad (2.27)$$

Substituting in equation 2.26 with  $h_h = 0.61 \text{ m}$ , the minimum distance between the first and the second PV row is included below:

$$d_h \geq h_h \cdot k \longrightarrow \boxed{d_h \geq 2.45 \text{ m}} \quad (2.28)$$

#### 2.4.2 Minimum Distance between the Rest of the PV Rows

Due to the existing thermal panels, the rest PV rows will be placed vertically to use the available space to a maximum.

Therefore, the height of the obstacle  $h_v$  according to figure 2.12(b) can be computed applying trigonometric identities:

$$h_v = \text{sen}(\beta) \cdot H_v \longrightarrow \boxed{h_v = 1.21 \text{ m}} \quad (2.29)$$

Substituting in equation 2.26 with  $h_v = 1.21 \text{ m}$ , the minimum distance between the rest PV rows is included below:

$$d_v \geq h_v \cdot k \longrightarrow \boxed{d_v \geq 4.85 \text{ m}} \quad (2.30)$$

#### 2.4.3 Minimum Distance between the First PV Row and the Perimeter Wall

The perimeter wall has a height of  $0.3 \text{ m}$  with respect to the horizontal plane:

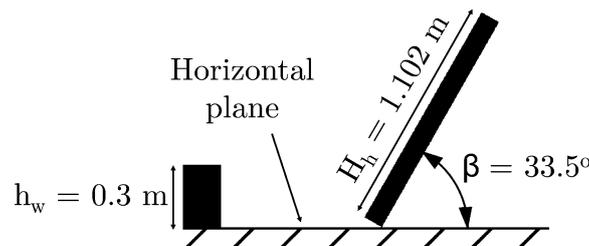


Figure 2.13. Height of the perimeter wall.

Substituting in equation 2.26 with  $h_w = 0.3 \text{ m}$ , the minimum distance between the perimeter wall and the first PV row is included below:

$$d_w \geq h_w \cdot k \longrightarrow \boxed{d_w \geq 1.20 \text{ m}} \quad (2.31)$$

## 2.5 Shades Analysis

The annual power losses due to shades between elements have been calculated according to the Technical Specifications of Grid-Connected Facilities. With the aim of analysing the worst-case scenario in term of power losses of the system, the six PV modules situated in the worst locations have been evaluated.

The procedure followed to compute the power losses due to shadows consists of 5 steps [45]:

1. Evaluation of the panels susceptible to a higher percentage of losses due to shadows.
2. Analysis of the profile of obstacles in each case.
3. Representation of every profile of obstacles in the sun path diagram.
4. Selection of the proper reference table depending on the tilt and azimuth angles.
5. Computation of the yearly power losses due to shadows in every module.

Once the surroundings of the PV field had been analysed, the panels susceptible to a higher percentage of losses due to shadows are highlighted in the next figure:

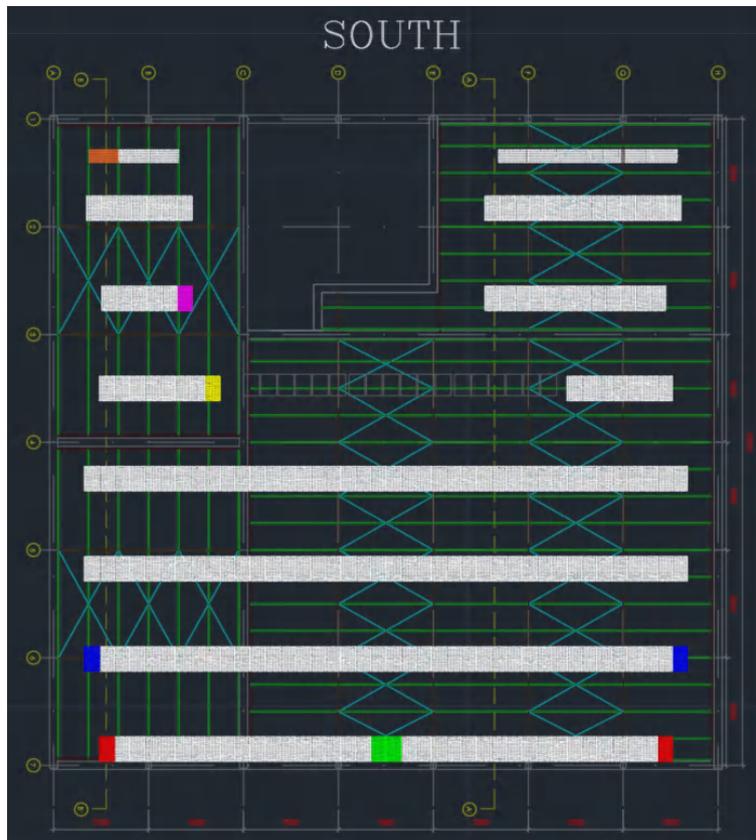
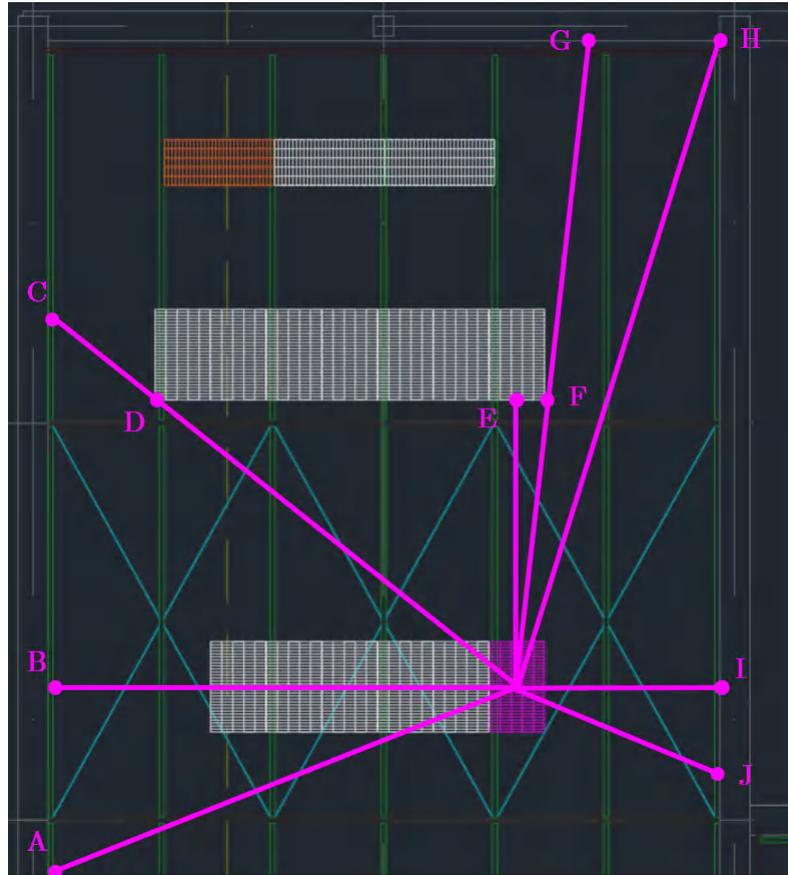


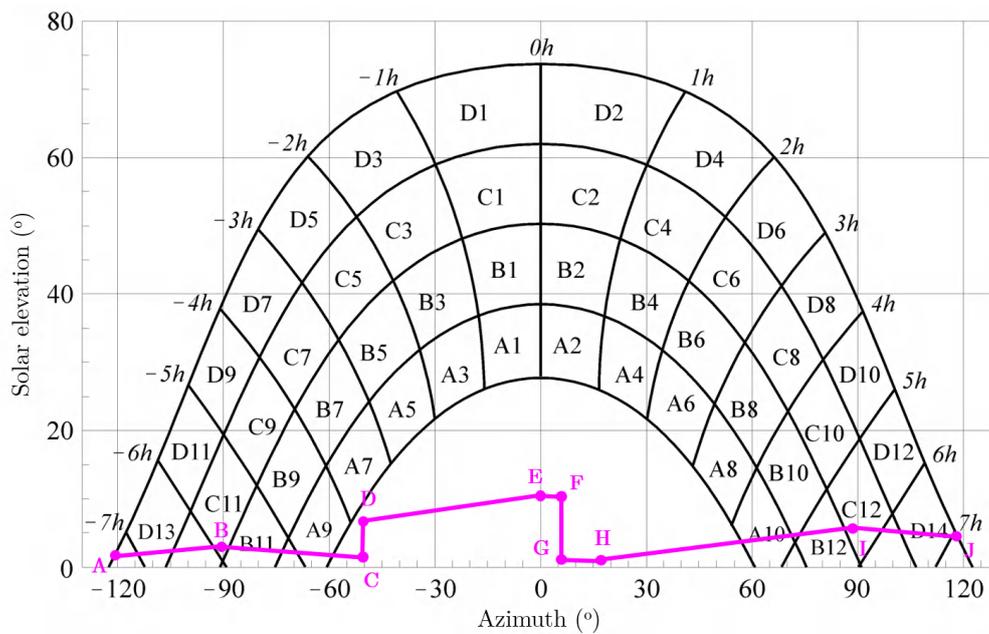
Figure 2.14. Modules susceptible to higher power losses due to shadows [46].



- Pink PV module:



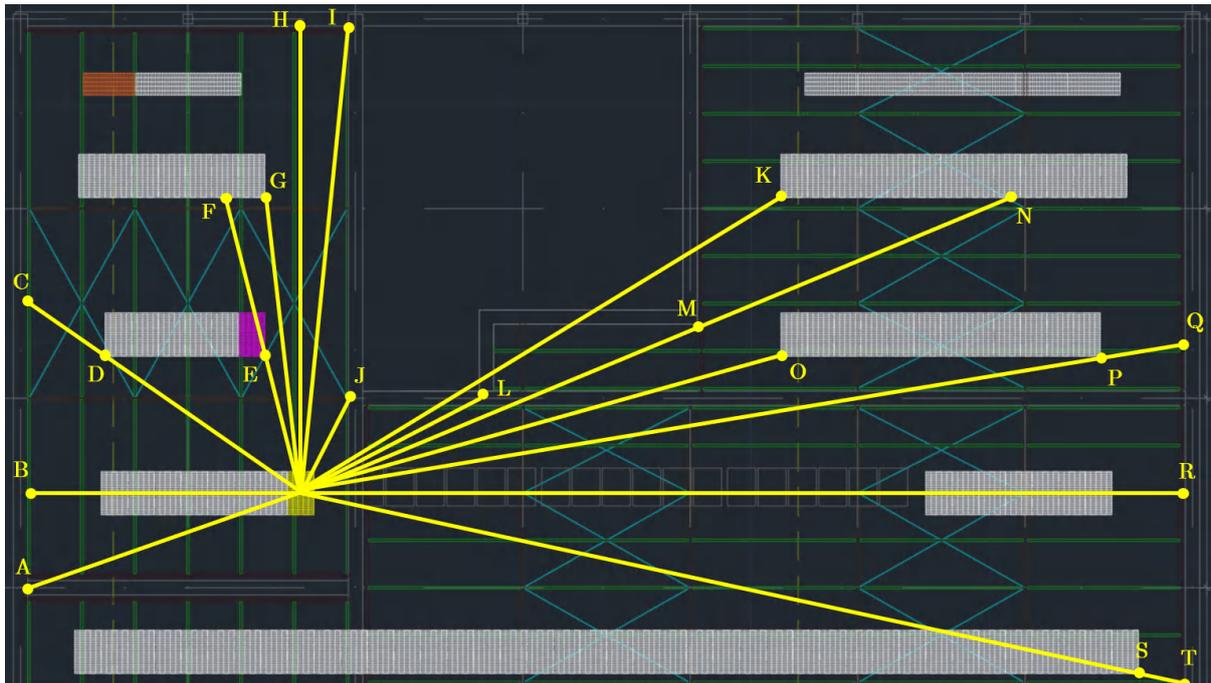
(a) Analysis of the profile of obstacles [46].



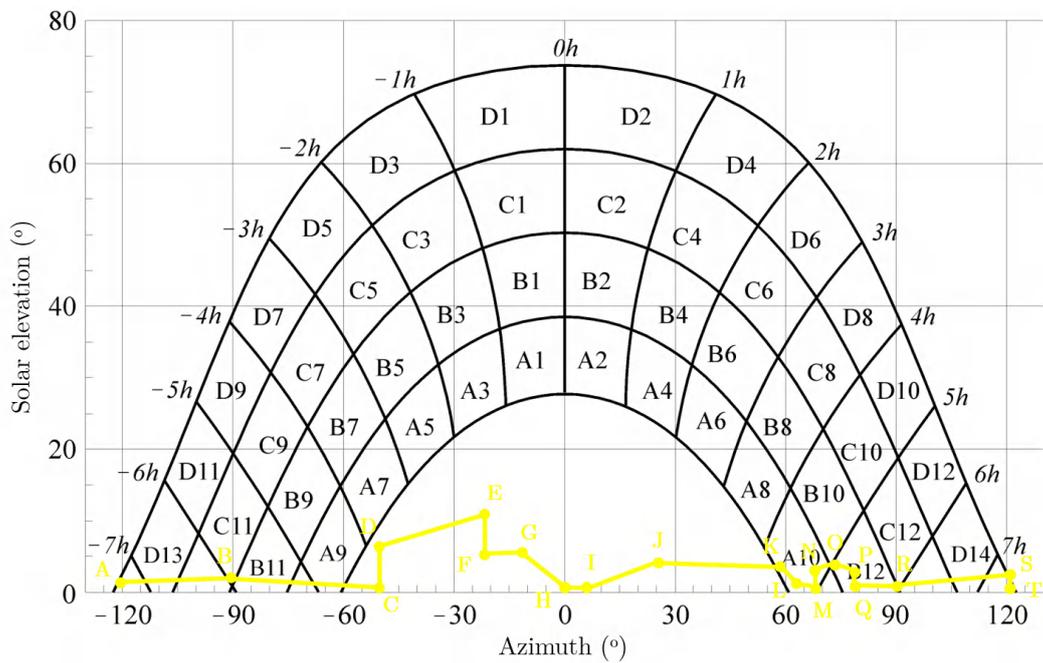
(b) Diagram of the profile of obstacles [47].

Figure 2.16. Profile of obstacles for the pink PV module.

• Yellow PV module:



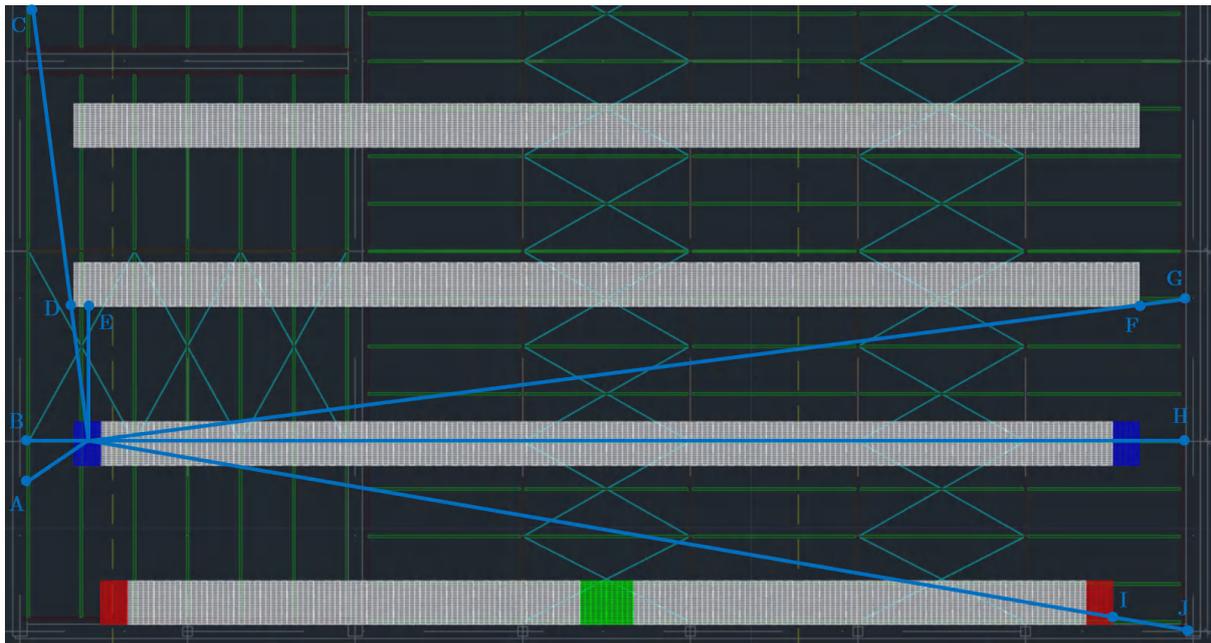
(a) Analysis of the profile of obstacles [46].



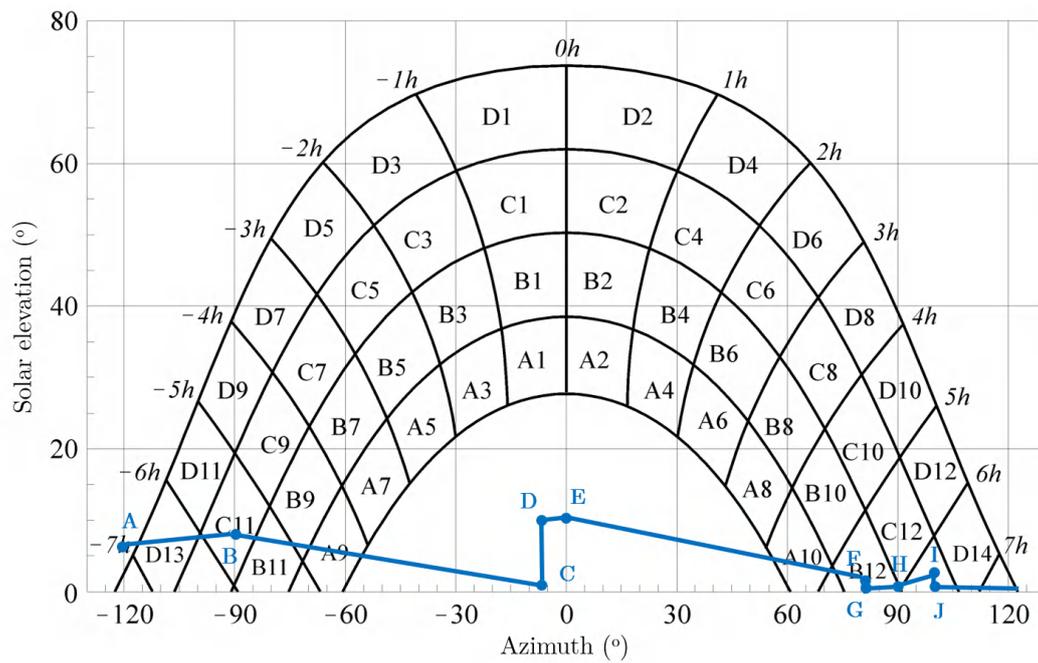
(b) Diagram of the profile of obstacles [47].

Figure 2.17. Profile of obstacles for the yellow PV module.

- Blue PV module<sup>4</sup>:



(a) Analysis of the profile of obstacles [46].

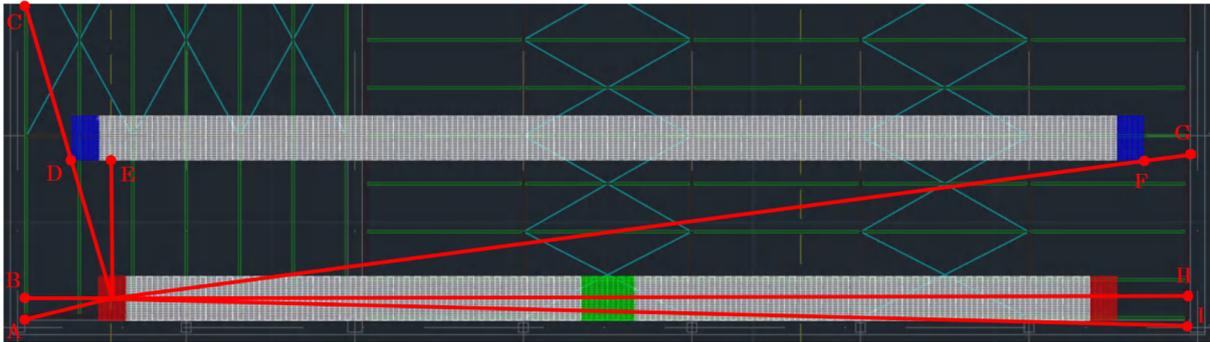


(b) Diagram of the profile of obstacles [47].

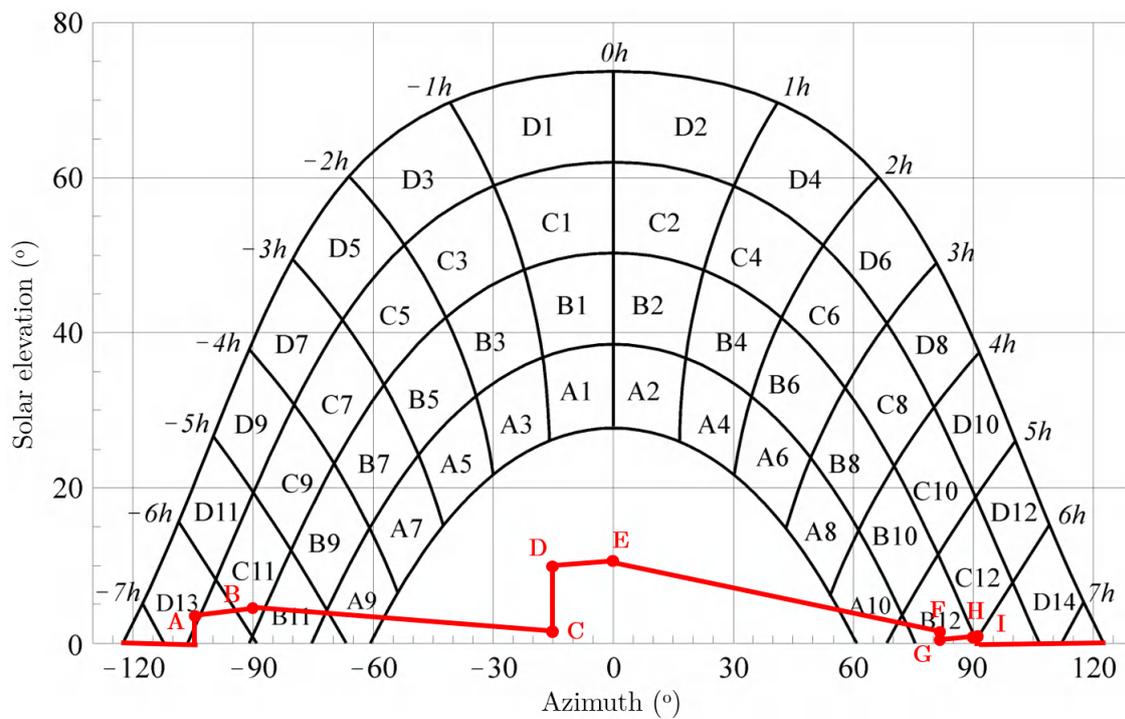
Figure 2.18. Profile of obstacles for the blue PV module.

<sup>4</sup>Figure 2.18 presents the results of the east-blue PV panel. The results for west-blue PV panel would be the same but changing the west for the east and vice versa in the diagram.

- Red PV module<sup>5</sup>:



(a) Analysis of the profile of obstacles [46].

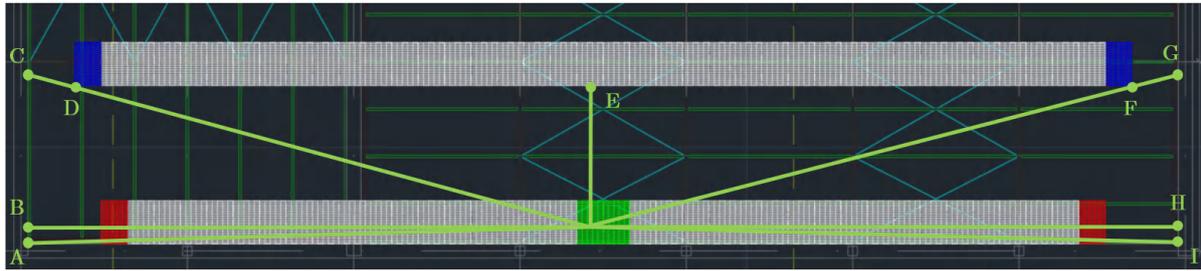


(b) Diagram of the profile of obstacles [47].

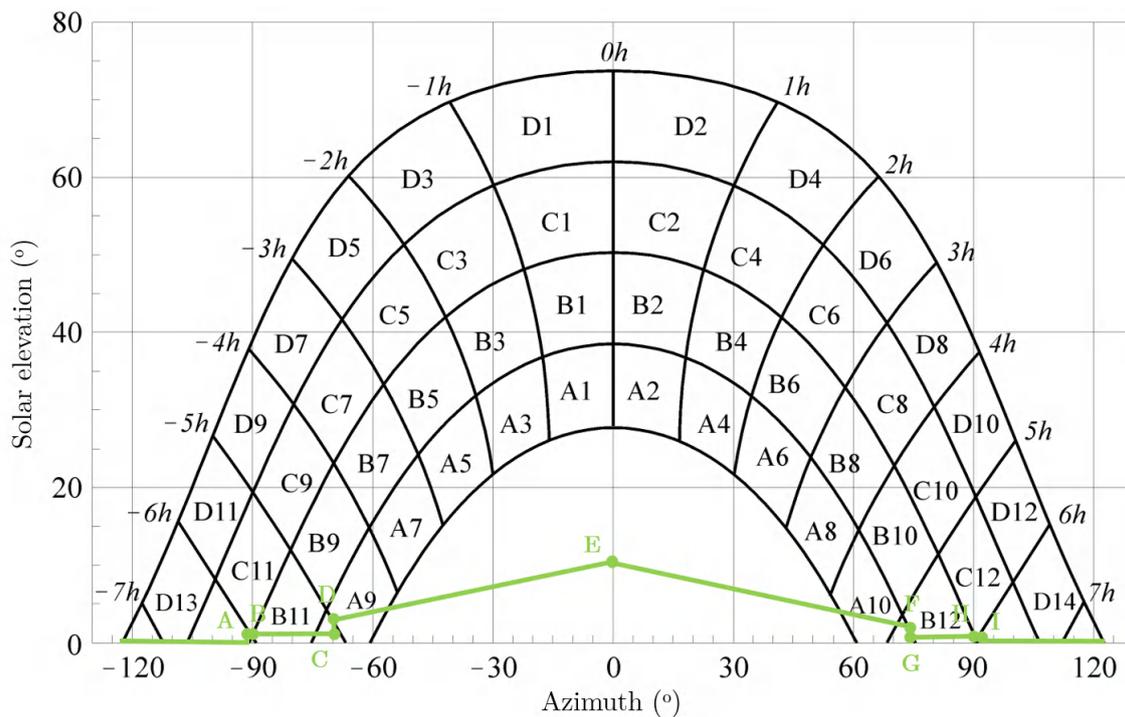
Figure 2.19. Profile of obstacles for the red PV module.

<sup>5</sup>Figure 2.19 presents the results of the east-red PV panel. The results for west-red PV panel would be the same but changing the west for the east and vice versa in the diagram.

- Green PV module<sup>6</sup>:



(a) Analysis of the profile of obstacles [46].



(b) Diagram of the profile of obstacles [47].

Figure 2.20. Profile of obstacles for the green PV module.

Next page includes the table 2.5 which contains detailed information required for the construction of the profile obstacle diagrams. Basically, it includes both the azimuth and the solar elevation angles of each point required for the development of the diagrams for every analysed PV module.

<sup>6</sup>Figure 2.20 presents the results of the east-green PV panel. The results for west-green PV panel would be the same but changing the west for the east and vice versa in the diagram.

Table 2.5. Angles required to construct the profile of obstacles.

ORANGE MODULE		
POINT	AZIMUTH (°)	SOLAR ELEVATION (°)
A	-120.00	4.37
B	-90.00	5.04
C	-53.13	4.03
D	0.00	6.71
E	75.74	1.62
F	90.00	1.71
G	120.00	1.48

PINK MODULE		
POINT	AZIMUTH (°)	SOLAR ELEVATION (°)
A	-120.00	1.59
B	-90.00	1.84
C	-50.34	1.42
D	-50.34	7.37
E	0.00	11.46
F	5.26	11.41
G	5.26	1.30
H	17.05	1.24
I	90.00	4.24
J	120.00	3.67

YELLOW MODULE		
POINT	AZIMUTH (°)	SOLAR ELEVATION (°)
A	-120.00	1.31
B	-90.00	1.51
C	-50.41	1.16
D	-50.41	7.36
E	-23.53	10.53
F	-23.53	5.01
G	-11.60	5.35
H	0.00	0.86
I	5.74	0.86
J	25.46	3.69
K	59.75	3.26
L	62.45	1.62
M	67.37	0.96
N	67.37	2.13
O	74.27	3.33
P	79.90	2.04
Q	79.90	0.46
R	90.00	0.47
S	120.00	1.93
T	120.00	0.40

BLUE MODULE		
POINT	AZIMUTH (°)	SOLAR ELEVATION (°)
A	-120.00	5.89
B	-90.00	6.80
C	-5.27	0.63
D	-5.27	11.41
E	0.00	11.46
F	82.26	1.56
G	82.26	0.37
H	90.00	0.37
I	99.63	1.60
J	99.63	0.37

RED MODULE		
POINT	AZIMUTH (°)	SOLAR ELEVATION (°)
A	-106.85	4.52
B	-90.00	4.72
C	-15.27	1.25
D	-15.27	11.06
E	0.00	11.46
F	82.07	1.60
G	82.07	0.38
H	90.00	0.39
I	91.41	0.38

GREEN MODULE		
POINT	AZIMUTH (°)	SOLAR ELEVATION (°)
A	-92.66	0.73
B	-90.00	0.73
C	-74.60	0.70
D	-74.60	3.08
E	0.00	11.46
F	75.97	2.81
G	75.97	0.67
H	90.00	0.69
I	-92.64	0.69

Each of the portions in figures 2.15(b), 2.16(b), 2.17(b), 2.18(b), 2.19(b) and 2.20(b) represent the path of the Sun in a certain period of time that constitutes one hour over several days. Therefore each portion has a certain contribution to the annual global solar irradiation that affects the analysed surface.

At this point, the proper reference table has to be selected depending on the tilt and the azimuth angles of the PV modules. In this particular case, the optimal angles where  $\beta_{opt} = 33.5^\circ$  and  $\alpha_{opt} = 0^\circ$ . Since there is not a reference table for the specific optimal parameters selected for the project, it has been selected the reference table for the closest values respecting the guidance provided within the Technical Specifications of Grid-Connected Facilities.

Then, the utilised reference table is presented below for  $\beta_{opt} = 35^\circ$  and  $\alpha_{opt} = 0^\circ$ , which are the available parameters more similar to the ones applied in this project. The table contains the annual percentage of losses in case the profile obstacle exceeds a particular portion identified by means of both a letter and a number:

Table 2.6. Reference table of solar irradiance losses due to shadows [48].

$\beta = 35^\circ$ $\alpha = 0^\circ$	A	B	C	D
13	0.00%	0.00%	0.00%	0.03%
11	0.00%	0.01%	0.12%	0.44%
9	0.13%	0.41%	0.62%	1.49%
7	1.00%	0.95%	1.27%	2.76%
5	1.84%	1.50%	1.83%	3.87%
3	2.70%	1.88%	2.21%	4.67%
1	3.15%	2.12%	2.43%	5.04%
2	3.17%	2.12%	2.33%	4.99%
4	2.70%	1.89%	2.01%	4.46%
6	1.79%	1.51%	1.65%	3.63%
8	0.98%	0.99%	1.08%	2.55%
10	0.11%	0.42%	0.52%	1.33%
12	0.00%	0.02%	0.10%	0.40%
14	0.00%	0.00%	0.00%	0.02%

Finally, the annual percentage of power losses has been computed for each PV panel taking into account the information provided by every profile obstacle diagram and the table 2.6. It must be taken into account that in case of partial concealment, the filling factor used has been the closest to the values: 0.25, 0.50, 0.75 or 1 [49].

- **Orange PV module:**

Table 2.7. Percentage of annual power losses due to shadows for the orange PV module.

<b>ORANGE MODULE</b>	
<b>FACTOR</b>	<b>LOSSES</b>
0.5 · D13	0.015%
0.25 · C11	0.030%
0.75 · B11	0.008%
0.25 · A9	0.033%
0.25 · A10	0.028%
0.25 · B12	0.005%
0.25 · D14	0.005%
<b>TOTAL</b>	<b>0.123%</b>

Then, the annual power losses due to shadows for the orange PV panel regarding figure 2.15(b) and table 2.6 are summarised below:

$$\boxed{Losses_{orange\ shadows} = 0.123\%} \quad (2.32)$$

- **Pink PV module:**

Table 2.8. Percentage of annual power losses due to shadows for the pink PV module.

<b>PINK MODULE</b>	
<b>FACTOR</b>	<b>LOSSES</b>
0.25 · D13	0.008%
0.25 · C11	0.030%
0.5 · B11	0.005%
0.25 · A9	0.033%
0.5 · A10	0.055%
0.75 · B12	0.015%
0.25 · C12	0.025%
0.5 · D14	0.010%
<b>TOTAL</b>	<b>0.180%</b>

Then, the annual power losses due to shadows for the pink PV panel regarding figure 2.16(b) and table 2.6 are summarised below:

$$\boxed{Losses_{pink\ shadows} = 0.180\%} \quad (2.33)$$

- **Yellow PV module:**

Table 2.9. Percentage of annual power losses due to shadows for the yellow PV module.

<b>YELLOW MODULE</b>	
<b>FACTOR</b>	<b>LOSSES</b>
0.25 · D13	0.008%
0.25 · B11	0.003%
0.25 · A9	0.033%
0.25 · A10	0.028%
0.25 · B12	0.005%
0.25 · D14	0.005%
<b>TOTAL</b>	<b>0.080%</b>

Then, the annual power losses due to shadows for the yellow PV panel regarding figure 2.17(b) and table 2.6 are summarised below:

$$\boxed{Losses_{yellow\ shadows} = 0.080\%} \quad (2.34)$$

- **Blue PV module:**

Table 2.10. Percentage of annual power losses due to shadows for the blue PV module.

<b>BLUE MODULE</b>	
<b>FACTOR</b>	<b>LOSSES</b>
0.75 · D13	0.023%
0.5 · C11	0.060%
0.75 · B11	0.008%
0.25 · B9	0.103%
0.50 · A9	0.065%
0.25 · A10	0.028%
0.25 · B12	0.005%
<b>TOTAL</b>	<b>0.290%</b>

Then, the annual power losses due to shadows for the blue PV panel regarding figure 2.18(b) and table 2.6 are summarised below:

$$\boxed{Losses_{blue\ shadows} = 0.290\%} \quad (2.35)$$

- **Red PV module:**

Table 2.11. Percentage of annual power losses due to shadows for the red PV module.

<b>RED MODULE</b>	
<b>FACTOR</b>	<b>LOSSES</b>
0.25 · C11	0.030%
0.50 · B11	0.005%
0.5 · A9	0.065%
0.25 · A10	0.028%
0.25 · B12	0.005%
<b>TOTAL</b>	<b>0.133%</b>

Then, the annual power losses due to shadows for the blue PV panel regarding figure 2.19(b) and table 2.6 are summarised below:

$$\boxed{Losses_{red\ shadows} = 0.133\%} \quad (2.36)$$

- **Green PV module:**

Table 2.12. Percentage of annual power losses due to shadows for the green PV module.

<b>GREEN MODULE</b>	
<b>FACTOR</b>	<b>LOSSES</b>
0.25 · B11	0.003%
0.25 · A9	0.033%
0.25 · A10	0.028%
0.25 · B12	0.005%
<b>TOTAL</b>	<b>0.068%</b>

Then, the annual power losses due to shadows for the blue PV panel regarding figure 2.20(b) and table 2.6 are summarised below:

$$\boxed{Losses_{green\ shadows} = 0.068\%} \quad (2.37)$$

Considering that the analysed modules are the six PV panels susceptible to a higher percentage of losses due to shadows, the results obtained in equations 2.32, 2.33, 2.34, 2.35, 2.36 and 2.37 confirm that in the worst-case scenario, the annual percentage of losses due to shadows will never exceed the 0.29% in any PV panel.

Taking into account that there are 220 modules and that the worst locations have been studied, the previous information justifies the assumption of having no shadow losses since they are negligible. Therefore, it has been demonstrated why power losses due to shades between elements have been ignored in this project.

## 2.6 Wiring Section

Establishing the distance between the inverter and the strings analysing the worst-case scenario (longest distance) is needed in order to compute the required section of the DC cables.

Then, the figure 2.21 identifies the distribution of the PV strings considering that:

- **20 strings** → There are 11 PV modules per string connected in series.
- **10 MPPTs** → There are 2 strings per MPPT connected in parallel.

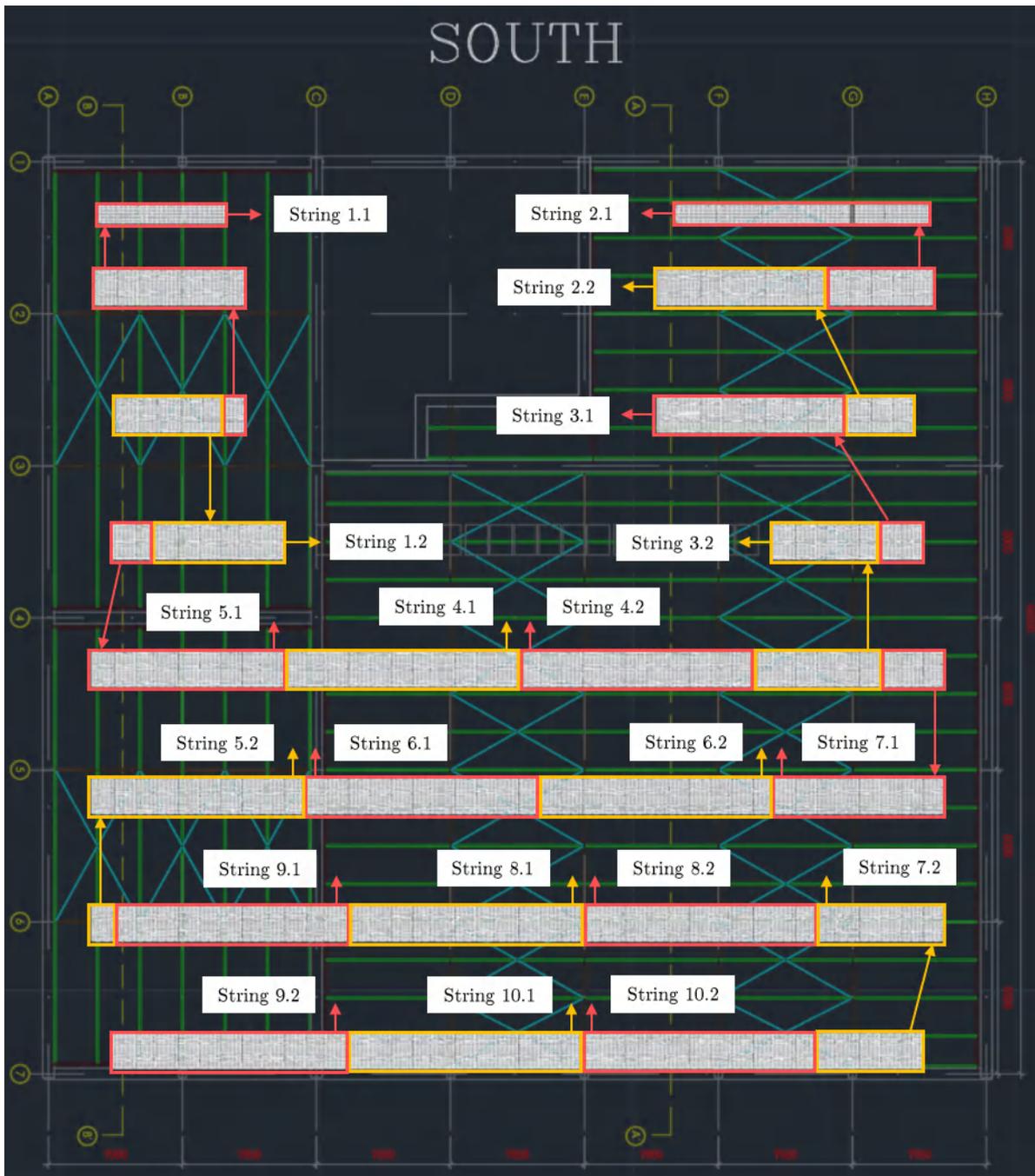


Figure 2.21. Physical distribution of the PV strings [46].

Once every string has been defined, the electrical canalisation has to be considered in order to establish the maximum distance between any PV string and the inverter, which will be located at the roof of the facility<sup>7</sup>:

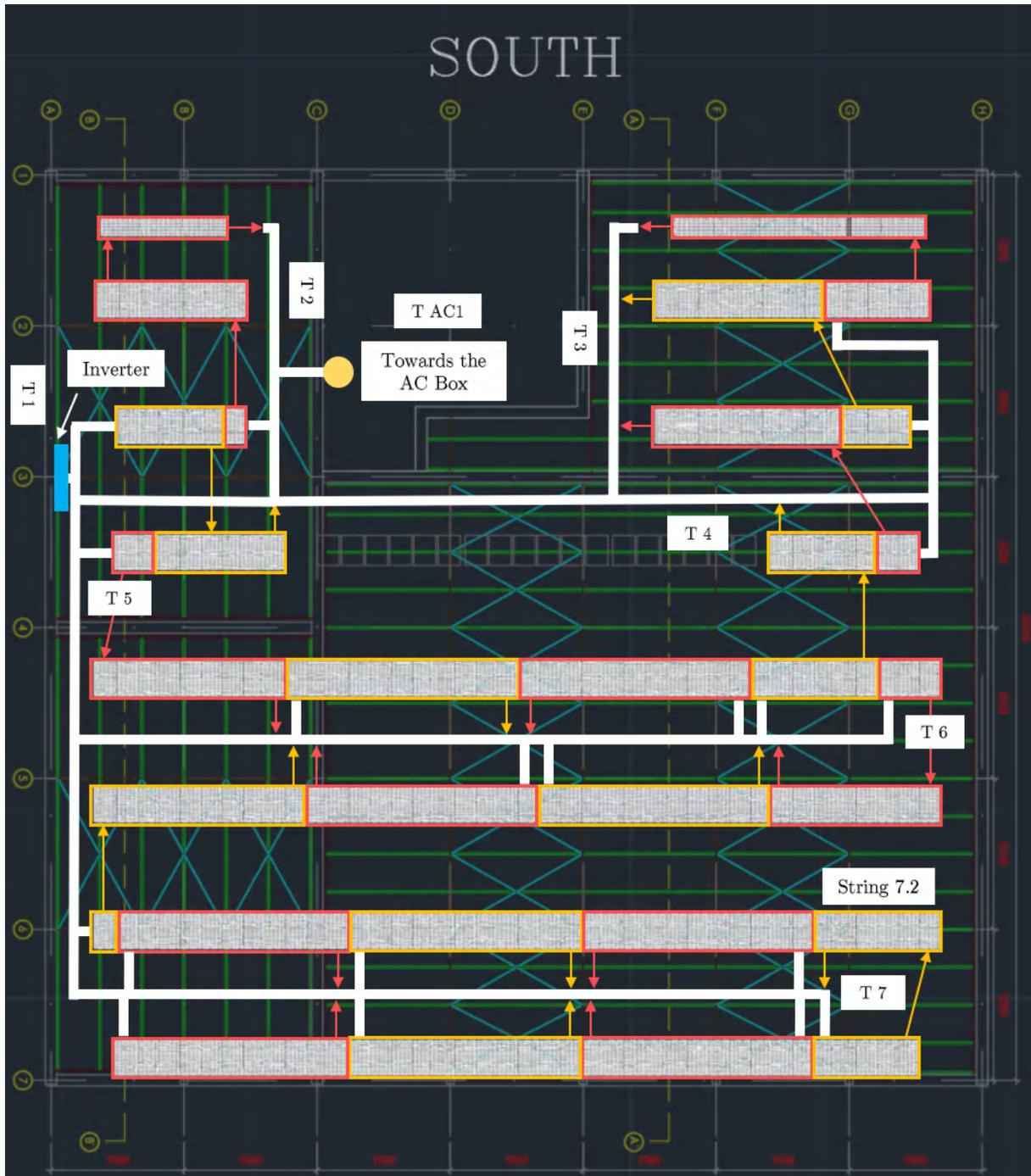


Figure 2.22. Electrical canalisation and inverter location [46].

In accordance with figure 2.22, it can be proved that the maximum distance and therefore the worst-case scenario is reached for the string 7.2. Consequently, the DC sections will be computed for the string 7.2 regarding the dimensions presented in the plans (document V).

<sup>7</sup>The elements T1-T7 in figure 2.22 identifies the canalisation tubes as presented in section 2.9.

Following the wiring path, the AC box will be located at the existing facilities zone in the upper level of the building. Next figure illustrates its location:

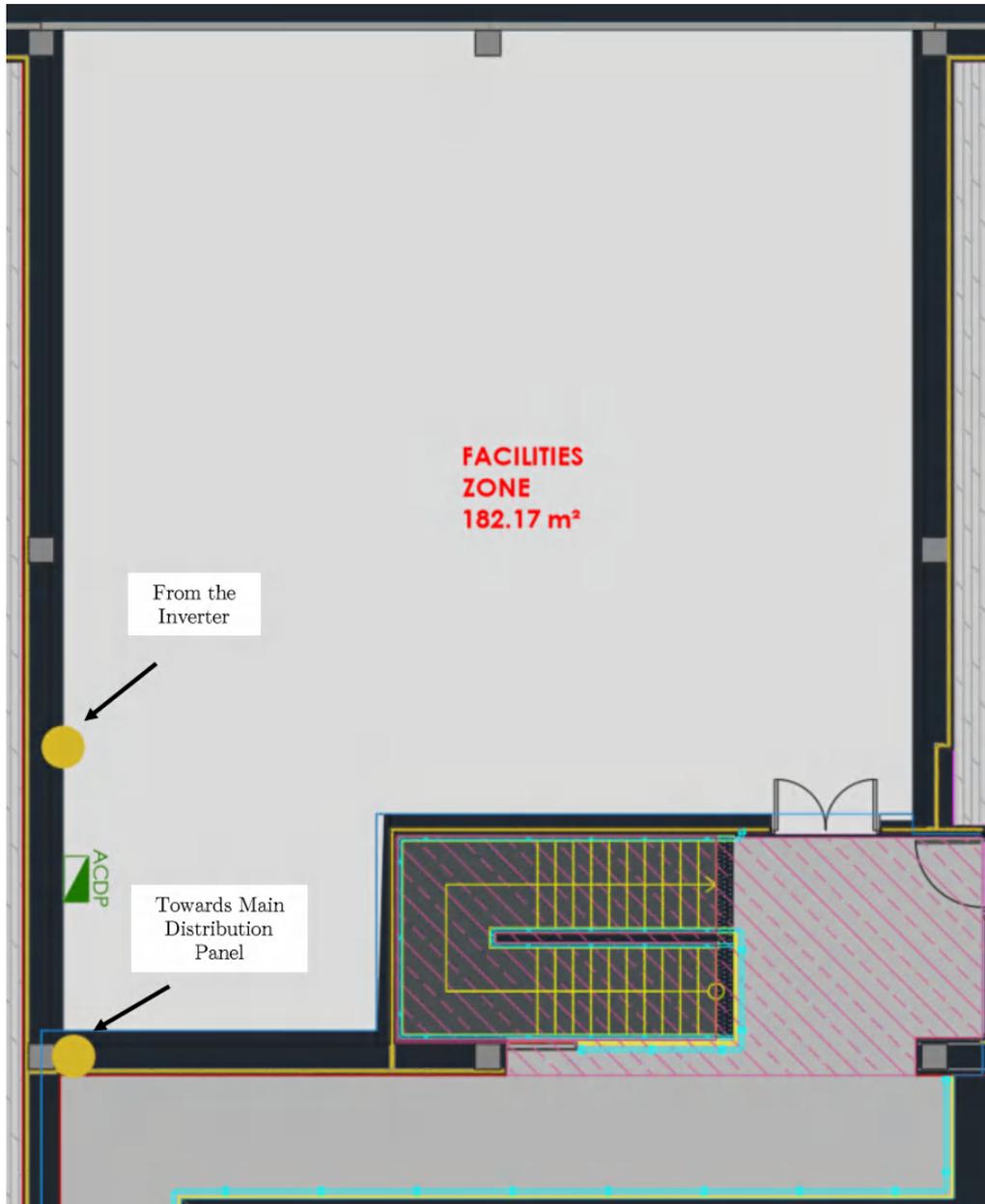


Figure 2.23. Location of the electrical AC box [46].

Regarding figures 2.22 and 2.23:

- The connection between the PV modules and the inverter as well as the connection between the inverter and the AC distribution panel will be done by means of outdoor cable tubes.
- The connection between the AC electrical distribution panel and the main electrical distribution panel of the gym will be done through the existing services raiser by means of an electrical cable tube too.

The final stage of the wiring path consists of traversing the false ceiling of the lower level by means of another cable tube in order to reach the main electrical distribution panel:

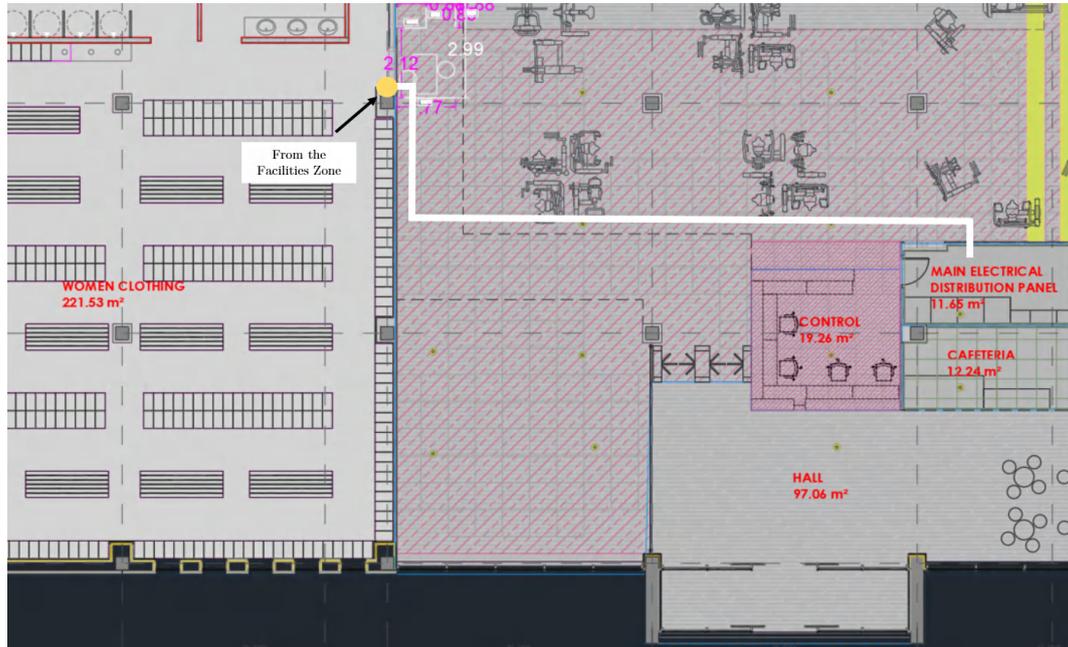
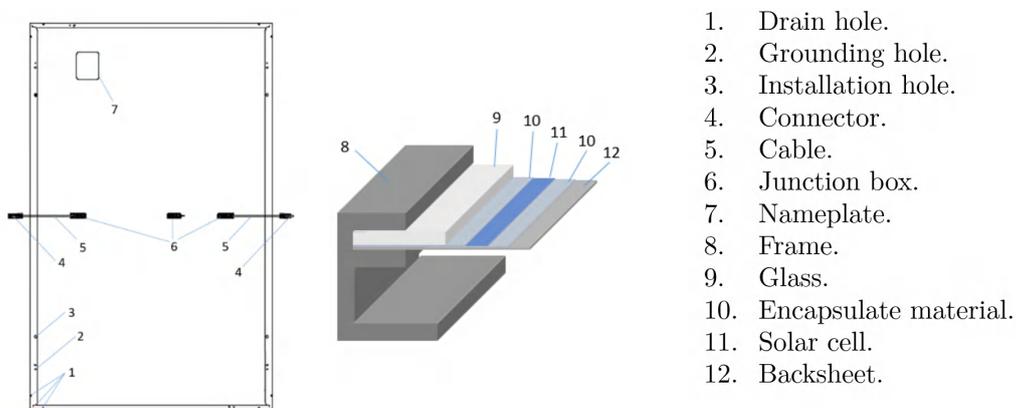
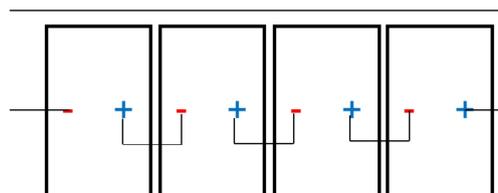


Figure 2.24. Cable tube between the facility zone and the main electrical distribution panel [46].

Additionally, the electrical connection of the PV modules has to be executed respecting the instructions provided by the manufacturer and making sure all connection polarity is correct:



(a) Mechanical drawing for monofacial modules.



(b) Linear wiring.

Figure 2.25. Electrical installation of the PV modules [22].

Then, the cable sections that have to be computed can be separated in three stretches:

- **DC cables** between every string and the inverter.
- **AC cables** between the inverter and the AC distribution panel of the PV plant.
- **AC cables** between the AC distribution panel and the gym's general distribution panel.

Cable sections have been computed following the ITC-BT-40 on low voltage generating facilities and the Technical Specifications of Grid-Connected Facilities. Thus:

- **DC Side.** Voltage drop between the PV modules and the inverter cannot exceed 1.5% according to point 5.5.2 of Technical Specifications of Grid-Connected Facilities.
- **AC Side.** Voltage drop between the inverter and the indoor facility interconnection point cannot exceed 1.5% according to section 5 of ITC-BT-40.
- **Sections.** Wires have to be sized for 125% of the generator maximum current.

The maximum admissible temperature of cables insulation in service will be considered to be 90°C in order to determine all the cable sections [19].

In conclusion, there are two criteria that have to be reviewed when designing cables:

- The **voltage drop** criteria.
- The **thermal** criteria.

### 2.6.1 Direct Current Wiring Section

The selected Direct Current cables will be unipolar copper wires with a rated voltage of 0.6/1 kV, class 5 (flexible), flame retardant, halogen free, normalised, specific for outdoor PV facilities and type ZZ-F(AS) [50, 51]. Then, for DC cables:

1. Voltage drop criteria for a cable section lower or equal to 120 mm<sup>2</sup>:

$$\Delta V(\%) = \frac{2 \cdot P \cdot L}{k \cdot S \cdot V^2} \cdot 125\% \quad (2.38)$$

Where:

- $\Delta V$  → Voltage drop [%].
- $P$  → Foreseen power per PV string for the generator maximum current [W].
- $L$  → Line length [m].
- $k$  → Copper conductivity ( $k_{cu} = 56 \frac{m}{\Omega \cdot mm^2}$ ) [m/(Ω · mm<sup>2</sup>)].
- $S$  → Cable section [mm<sup>2</sup>].
- $V$  → Foreseen voltage per PV string [mm<sup>2</sup>].

2. Thermal criteria:

$$T = 20^\circ C + (T_{max} - 20^\circ C) \cdot \left( \frac{I}{I_{adm}} \right)^2 \quad (2.39)$$

Where:

- $T$  → Operating temperature of the string cable [°C].
- $T_{max}$  → Maximum insulation temperature [°C].

- $I \rightarrow$  Foreseen maximum current of the string [A].
  - $I_{adm} \rightarrow$  Admissible current per string [A].
3. The conductor resistivity is computed for the actual operating temperature and then equation 2.38 is applied once again to verify the compliance with the voltage drop criteria.

### 2.6.1.1 Stretch 1 - Wiring between the PV Modules and the Inverter

Applying the three steps presented above and considering that, although there are 10 MPPTs at the inverter, the 20 strings are connected individually to the inverter:

1. **Voltage drop criteria** imposing  $\Delta V_{max} \leq 1.5\%$ .

Equation 2.38 is applied for the following values:

- $\Delta V = \Delta V_{max} = 1.5\%$ .
- $P = \text{Modules per string} \cdot V_{MPP} \cdot I_{SC} = 11 \text{ modules} \cdot \overbrace{43 \text{ V} \cdot 12.35 \text{ A}}^{\text{Table 2.3}} = 5,841.55 \text{ W}$ .
- $L = 70 \text{ m} \rightarrow$  String 7.2 according to figures 2.21 and 2.22 (worst-case scenario).
- $k = k_{cu} = 56 \text{ m}/(\Omega \cdot \text{mm}^2)$ .
- $V = \text{Modules per string} \cdot V_{MPP} = 11 \text{ modules} \cdot \overbrace{43 \text{ V}}^{\text{Table 2.3}} = 473 \text{ V}$ .
- Substituting in equation 2.38:  $S_{\Delta V_{theory}} = 5.43 \text{ mm}^2$

Nonetheless, according to ITC-BT-19 the first commercial section available greater than the required section is  $6 \text{ mm}^2$ .

$$\text{Then } \rightarrow \boxed{S_{\Delta V} = 6 \text{ mm}^2}$$

2. **Thermal criteria.**

Equation 2.39 is applied for the following values:

- $T_{max} = 90^\circ\text{C} \rightarrow$  Since the insulation is Halogen-Free Elastomer [19].
- $I = I_{SC} = \overbrace{12.35 \text{ A}}^{\text{Table 2.3}}$ .
- $I_{adm_{theory}} = 57 \text{ A} \rightarrow$  Since cables are deployed on vented tubes [19]. Nevertheless, the admissible current must be adjusted with the corresponding reduction factors according to ITC-BT-19:
  - 16/2 adjacent circuits of two charged conductors on the tube  $\rightarrow 0.7$ .
  - 2 layers of cables per tube  $\rightarrow 0.8$ .
  - Direct sun exposure  $\rightarrow 0.9$ .
- Thus  $\rightarrow I_{adm} = 57 \text{ A} \cdot 0.7 \cdot 0.8 \cdot 0.9 = 28.73 \text{ A} > I_{SC} = 12.35 \text{ A} \checkmark$ .
- Substituting in equation 2.39:  $T = 32.93^\circ\text{C} < T_{max} = 90^\circ\text{C} \checkmark$ .

$$\text{Then } \rightarrow \boxed{S_T = S_{\Delta V} = 6 \text{ mm}^2 \checkmark}$$

3. **Resistivity at the operating temperature of the cable.**

The new resistivity is computed considering the variation coefficient of the resistance with respect to the temperature ( $\alpha$ ):

$$\rho_{cuT} = \frac{1}{k_{cu}} \cdot \overbrace{[1 + \alpha_{cu} \cdot (T - 20^\circ\text{C})]}^{\alpha_{cu}=0.00392^\circ\text{C}^{-1}} \rightarrow \boxed{\rho_{cuT} = 0.01876 \Omega \cdot \text{mm}^2/\text{m}} \quad (2.40)$$

Finally, equation 2.38 is applied to verify the compliance with the voltage drop criteria for the new resistivity. In this case there are two details that must be taken into account:

- $\Delta V$  is computed for  $S = 6 \text{ mm}^2$
- $k_{cuT} = 1/\rho_{cuT} = 53.30 \text{ m}/(\Omega \cdot \text{mm}^2)$ .
- Substituting in equation 2.38:  $\Delta V = 1.43\% < 1.5\% \checkmark$

In conclusion, for the first stretch between the PV modules and the Inverter:

$$\boxed{S_1 = 6 \text{ mm}^2} \quad \boxed{\Delta V_1 = 1.43\%} \quad (2.41)$$

All in all, the total voltage drop at the DC side is computed below:

$$\Delta V_{DC} = \Delta V_1 = 1.43\% \longrightarrow \boxed{\Delta V_{DC} = 1.43\% < 1.5\% \checkmark} \quad (2.42)$$

### 2.6.2 Alternating Current Wiring Section

The selected Alternating Current cables will be unipolar copper wires with a rated voltage of 0.6/1 kV, flame retardant, halogen free, normalised and type RZ1-K(AS) complying with the norm UNE-HD 603-0:2007. Then, for AC cables:

1. Voltage drop criteria for a cable section lower or equal to 120  $\text{mm}^2$ :

$$\Delta V(\%) = \frac{P \cdot L}{k \cdot S \cdot V^2} \cdot 125\% \quad (2.43)$$

Where:

- $\Delta V \rightarrow$  Voltage drop [%].
- $P \rightarrow$  Foreseen output power for the generator maximum current [W].
- $L \rightarrow$  Line length [m].
- $k \rightarrow$  Copper conductivity ( $k_{cu} = 56 \frac{\text{m}}{\Omega \cdot \text{mm}^2}$ ) [ $\text{m}/(\Omega \cdot \text{mm}^2)$ ].
- $S \rightarrow$  Cable section [ $\text{mm}^2$ ].
- $V \rightarrow$  Foreseen output line voltage [ $\text{mm}^2$ ].

2. Thermal criteria:

$$T = 20^\circ\text{C} + (T_{max} - 20^\circ\text{C}) \cdot \left( \frac{I}{I_{adm}} \right)^2 \quad (2.44)$$

Where:

- $T \rightarrow$  Operating temperature of the AC phase cable [ $^\circ\text{C}$ ].
- $T_{max} \rightarrow$  Maximum insulation temperature [ $^\circ\text{C}$ ].
- $I \rightarrow$  Foreseen maximum current of the AC phase cable [A].
- $I_{adm} \rightarrow$  Admissible current per AC phase cable [A].

3. The conductor resistivity is computed for the actual operating temperature and then equation 2.43 is applied once again to verify the compliance with the voltage drop criteria.

### 2.6.2.1 Stretch 2 - Wiring between the Inverter and the AC Box

Applying the three steps presented above and considering that there is one cable per phase and an additional neutral wire:

1. **Voltage drop criteria** imposing  $\Delta V_{max} \leq 0.75\%$ . The limit is 1.5% for the AC side, so the 1.5% is allocated proportionally to the two stretches.

Equation 2.43 is applied for the following values:

- $\Delta V = \Delta V_{max} = 0.75\%$ .
- $P = \sqrt{3} \cdot V_{out} \cdot I_{out_{max}} \cdot \cos(\varphi) = \sqrt{3} \cdot \overbrace{400 \text{ V} \cdot 160.4 \text{ A}}^{\text{Table 2.4}} \cdot 1 = 111,128.38 \text{ W}$ .
- $\cos(\varphi) = 1 \rightarrow$  The power factor is adjustable between 0.8 leading and 0.8 lagging in accordance with the inverter data sheet.
- $L = 25 \text{ m} \rightarrow$  Distance between the inverter and the AC distribution panel.
- $k = k_{cu} = 56 \text{ m}/(\Omega \cdot \text{mm}^2)$ .
- $V = 400 \text{ V}$ .
- Substituting in equation 2.43:  $S_{\Delta V_{theory}} = 51.68 \text{ mm}^2$

Nonetheless, according to ITC-BT-19 the first commercial section available greater than the required section is  $70 \text{ mm}^2$ .

$$\text{Then } \rightarrow \boxed{S_{\Delta V} = 70 \text{ mm}^2}$$

#### 2. Thermal criteria.

Equation 2.44 is applied for the following values:

- $T_{max} = 90^\circ\text{C} \rightarrow$  Since the insulation is XLPE [19].
- $I = I_{out_{max}} = \overbrace{160.4 \text{ A}}^{\text{Table 2.4}}$ .
- $I_{adm_{theory}} = 223 \text{ A} \rightarrow$  Since cables are deployed on vented tubes [19]. Nevertheless, the admissible current must be adjusted with the corresponding reduction factors according to ITC-BT-19:
  - 1 circuit of three-phase conductors on the tube  $\rightarrow 1$ .
  - 1 layer of cables per tube  $\rightarrow 1$ .
  - Direct sun exposure  $\rightarrow 0.9$ .
- Thus  $\rightarrow I_{adm} = 223 \text{ A} \cdot 1 \cdot 1 \cdot 0.9 = 200.7 \text{ A} > I_{out_{max}} = 160.4 \text{ A} \checkmark$ .
- Substituting in equation 2.44:  $T = 64.71^\circ\text{C} < T_{max} = 90^\circ\text{C} \checkmark$ .

$$\text{Then } \rightarrow \boxed{S_T = 70 \text{ mm}^2}$$

#### 3. Resistivity at the operating temperature of the cable.

The new resistivity is computed considering the variation coefficient of the resistance with respect to the temperature ( $\alpha$ ):

$$\rho_{cu_T} = \frac{1}{k_{cu}} \cdot \left[ 1 + \overbrace{\alpha_{cu} \cdot (T - 20^\circ\text{C})}^{\alpha_{cu}=0.00392^\circ\text{C}^{-1}} \right] \rightarrow \boxed{\rho_{cu_T} = 0.02099 \Omega \cdot \text{mm}^2/\text{m}} \quad (2.45)$$

Finally, equation 2.43 is applied to verify the compliance with the voltage drop criteria for the new resistivity. In this case there are two details that must be taken into account:

- $\Delta V$  is computed for  $S = 70 \text{ mm}^2$
- $k_{cu_T} = 1/\rho_{cu_T} = 47.64 \text{ m}/(\Omega \cdot \text{mm}^2)$ .
- Substituting in equation 2.43:  $\Delta V = 0.65\% < 0.75\% \checkmark$

In conclusion, for the second stretch between the inverter and the AC distribution panel:

$$\boxed{S_2 = 3 \text{ phase} \cdot 70 \text{ mm}^2 + 1 \text{ neutral} \cdot 70 \text{ mm}^2} \quad \boxed{\Delta V_2 = 0.65\%} \quad (2.46)$$

### 2.6.2.2 Stretch 3 - Wiring between the AC Box and the Main Panel

Applying the three steps presented above and considering that there is one cable per phase and an additional neutral wire:

1. **Voltage drop criteria** imposing  $\Delta V_{max} \leq (1.5\% - 0.65\%) = 0.85\%$ .

Equation 2.43 is applied for the following values:

- $\Delta V = \Delta V_{max} = 0.85\%$ .
- $P = \sqrt{3} \cdot V_{out} \cdot I_{out_{max}} \cdot \cos(\varphi) = \sqrt{3} \cdot \overbrace{400 \text{ V} \cdot 160.4 \text{ A}}^{\text{Table 2.4}} \cdot 1 = 111,128.38 \text{ W}$ .
- $\cos(\varphi) = 1 \rightarrow$  The power factor is adjustable between 0.8 leading and 0.8 lagging in accordance with the inverter data sheet.
- $L = 35 \text{ m} \rightarrow$  Distance between the inverter and the AC distribution panel.
- $k = k_{cu} = 56 \text{ m}/(\Omega \cdot \text{mm}^2)$ .
- $V = 400 \text{ V}$ .
- Substituting in equation 2.43:  $S_{\Delta V_{theory}} = 63.84 \text{ mm}^2$

Nonetheless, according to ITC-BT-19 the first commercial section available greater than the required section is  $70 \text{ mm}^2$ .

$$\text{Then } \rightarrow \boxed{S_{\Delta V} = 70 \text{ mm}^2}$$

2. **Thermal criteria.**

Equation 2.44 is applied for the following values:

- $T_{max} = 90^\circ \text{C} \rightarrow$  Since the insulation is XLPE [19].
- $I = I_{out_{max}} = \overbrace{160.4 \text{ A}}^{\text{Table 2.4}}$ .
- $I_{adm_{theory}} = 272 \text{ A} \rightarrow$  Since cables are deployed on no-vented tubes through the false ceiling [19]. Nevertheless, the admissible current must be adjusted with the corresponding reduction factors according to ITC-BT-19:
  - 3 circuits of 3-phase conductors close to the 1<sup>st</sup> stretch of the tube  $\rightarrow 0.8$ .
  - 1 layer of cables per tube  $\rightarrow 1$ .
  - No direct sun exposure  $\rightarrow 1$ .
- Thus  $\rightarrow I_{adm} = 272 \text{ A} \cdot 0.8 \cdot 1 \cdot 1 = 217.6 \text{ A} > I_{out_{max}} = 160.4 \text{ A} \checkmark$ .
- Substituting in equation 2.44:  $T = 57.84^\circ \text{C} < T_{max} = 90^\circ \text{C} \checkmark$ .

$$\text{Then } \rightarrow \boxed{S_T = 120 \text{ mm}^2}$$

### 3. Resistivity at the operating temperature of the cable.

The new resistivity is computed considering the variation coefficient of the resistance with respect to the temperature ( $\alpha$ ):

$$\rho_{cu_T} = \frac{1}{k_{cu}} \cdot \overbrace{[1 + \alpha_{cu} \cdot (T - 20^\circ C)]}^{\alpha_{cu}=0.00392^\circ C^{-1}} \longrightarrow \boxed{\rho_{cu_T} = 0.02051 \Omega \cdot mm^2/m} \quad (2.47)$$

Finally, equation 2.43 is applied to verify the compliance with the voltage drop criteria for the new resistivity. In this case there are two details that must be taken into account:

- $\Delta V$  is computed for  $S = 120 \text{ mm}^2$
- $k_{cu_T} = 1/\rho_{cu_T} = 48.76 \text{ m}/(\Omega \cdot mm^2)$ .
- Substituting in equation 2.43:  $\Delta V = 0.52\% < 0.85\% \checkmark$

In conclusion, for the third stretch between the AC panel and the interconnection point between generation and consumption:

$$\boxed{S_3 = 3 \text{ phase} \cdot 120 \text{ mm}^2 + 1 \text{ neutral} \cdot 120 \text{ mm}^2} \quad \boxed{\Delta V_3 = 0.52\%} \quad (2.48)$$

All in all, the total voltage drop at the AC side is computed below:

$$\Delta V_{AC} = \Delta V_2 + \Delta V_3 = 0.65\% + 0.52\% \longrightarrow \boxed{\Delta V_{AC} = 1.17\% < 1.5\% \checkmark} \quad (2.49)$$

The total voltage drop between the PV generator and the national grid connection point is lower than 3% as it is stated on the Technical Specifications of Grid-Connected Facilities and the technical instruction ITC-BT-40:

$$\Delta V_{TOTAL} = \Delta V_{DC} + \Delta V_{AC} = 1.43\% + 1.17\% \longrightarrow \boxed{\Delta V_{TOTAL} = 2.60\% < 3\% \checkmark} \quad (2.50)$$

### 2.6.3 Wiring Summary

The table 2.13 presents all the parameters that enables the identification of all the electrical circuits required for the project<sup>8</sup>:

- Line code  $\rightarrow$  To identify the line.
- From & To  $\rightarrow$  To highlight the elements connected by the line.
- Type  $\rightarrow$  To specify if it is a DC or an AC line.
- Cable  $\rightarrow$  To define core and insulation materials.
- Installation type  $\rightarrow$  A canalisation tube in all cases.
- Section  $\rightarrow$  To clarify the required section for each cable.
- Active poles  $\rightarrow$  2 for DC (+, -) and 4 for AC (3 phases + neutral).
- Temperature  $\rightarrow$  Operating temperature of each cable.
- Voltage drop  $\rightarrow$  The computed voltage drop per line.
- Length  $\rightarrow$  Length for a single active pole.
- Total length  $\rightarrow$  Whole length taking into account all active poles.

<sup>8</sup>Sections at the DC side have been computed considering the worst-case scenario, id est, the longest distance between a PV string and the inverter. This is the string highlighted in red in table 2.13.

Table 2.13. Voltage drop and operating temperature per line.

LINE CODE	FROM	TO	TYPE	CABLE	INSTALLATION TYPE	SECTION (mm <sup>2</sup> )	ACTIVE POLES	TEMPERATURE (°C)	VOLTAGE DROP (%)	LENGTH (m)	TOTAL LENGTH (m)
DC 1.1	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	28	56
DC 1.2	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	12	24
DC 2.1	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	46	92
DC 2.2	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	48	96
DC 3.1	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	48	96
DC 3.2	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	60	120
DC 4.1	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	39	78
DC 4.2	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	50	100
DC 5.1	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	28	56
DC 5.2	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	28	56
DC 6.1	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	39	78
DC 6.2	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	50	100
DC 7.1	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	60	120
DC 7.2	String	Inverter	DC	Cu XLPE	Vented tube	6	2	32.93	1.43	70	140
DC 8.1	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	56	112
DC 8.2	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	68	136
DC 9.1	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	42	84
DC 9.2	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	42	84
DC 10.1	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	56	112
DC 10.2	String	Inverter	DC	Cu XLPE	Vented tube	6	2	<32.93	<1.43	68	136
AC 1	Inverter	AC Box	AC	Cu XLPE	Vented tube	70	3+N	64.71	0.65	25	100
AC 2	AC Box	Main AC Box	AC	Cu XLPE	Vented tube	120	3+N	57.84	0.52	35	140
<b>SYSTEM LENGTH</b>										<b>2,116</b>	

## 2.7 Protections

The electrical protections of the PV plant have been designed according to Royal Decree 1663/2000 and Royal Decree 1699/2011, related to the connection of PV facilities to the low voltage grid. Then, the protection requirements for the photovoltaic plant are presented below:

- **General Manual Circuit Breaker.** It is a circuit breaker with a short circuit current greater than the required by the distribution company. It has to be an accessible breaker for the DSO in order to enable the manual disconnection of the PV plant if needed. This manual circuit breaker is already deployed and therefore not extra computation is required, since according to the connection scheme of the PV plant, the DSO would disconnect the PV plant when shutting the power supply off.
- **Automatic Residual Current Circuit Breaker.** With the purpose of protecting people in the event of an electrical shunt.
- **Automatic Circuit Breaker.** To ensure the automatic shutdown of the photovoltaic plant in case of losing the network voltage or the network frequency as well as in case of any over-current.
- **Voltage and Frequency Control.** Protection for the interconnection of maximum and minimum frequency (50.5 Hz and 48 Hz respectively), and protection for the maximum and minimum voltage ( $1.15 \cdot V_m$  and  $0.85 \cdot V_m$  respectively). These protective devices are not computed since they are integrated in the PV inverter [16].

### 2.7.1 DC Protections

According to the inverter data sheet as well as to the inverter user manual, the DC side of the PV plant does not require fuses nor over-voltage protection since all these protective devices are incorporated in the inverter.

Specifically, the inverter counts with 3 different automatic DC switches that protect against short-circuits and 3 DC surge protective devices type II against over-voltages.

#### 2.7.1.1 DC Switches

In this subsection, the proper operation of the DC switches is checked in order to ensure its right performance for the parameters of the facility.

The rated current of the inverter is 26 A per MPPT, while the breaking capacity is 40 A per MPPT. Then, according to ITC-BT-22, DC switches must comply with two conditions:

- **Overloads:**

- $I_{MPP} \leq I_N \leq I_{adm}$ .
- $1.6 \cdot I_N \leq 1.45 \cdot I_{adm}$ .

- **Short-circuits:**

- $I_c \geq I_{SC}$ .
- $t_c \leq t_{T_{max} adm} \Rightarrow \sqrt{t_{T_{max} adm}} = k \cdot \frac{S}{I_{SC}}$ .

Where:

- $I_{MPP}$  → Maximum power point current [A].
- $I_N$  → Rated current of the protective device [A].
- $I_{adm}$  → Computed admissible current of the cable [A].
  
- $I_c$  → Breaking capacity of the protective device [A].
- $I_{SC}$  → Short-circuit current [A].
- $t_c$  → Short-circuit breaking time [s].
- $t_{T_{max} adm}$  → Time a cable takes to reach its admissible temperature [s].
- $k$  → Constant that depends on the insulation cable material [-].
- $S$  → Conductive section [ $mm^2$ ].

In this particular case, taking into account that there are two PV strings per MPPT:

- **Overloads:**

$$2 \cdot 11.75 \text{ A} \leq 26 \text{ A} \leq 28.73 \text{ A} \longrightarrow \boxed{23.50 \text{ A} \leq 26 \text{ A} \leq 28.73 \text{ A} \checkmark} \quad (2.51)$$

$$1.6 \cdot 26 \text{ A} \leq 1.45 \cdot 28.73 \text{ A} \longrightarrow \boxed{41.60 \text{ A} \leq 41.66 \text{ A} \checkmark} \quad (2.52)$$

- **Short-circuits:**

$$40 \text{ A} \geq 2 \cdot 12.35 \text{ A} \longrightarrow \boxed{40 \text{ A} \geq 24.7 \text{ A} \checkmark} \quad (2.53)$$

The second short-circuit condition which is related to the short-circuit breaking time does not need to be reviewed since the DC sections have been designed for the maximum current that can flow through the electrical conductor, id est, for the short-circuit current. Therefore, the short-circuit breaking time is necessarily lower than the time required by the conductive material to reach its admissible temperature  $\checkmark$ .

Consequently, the DC switches that are embedded to the PV inverter are appropriate to protect the DC side of the PV facility, not requiring any extra fuse.

### 2.7.1.2 Over-Voltage Protection

The embedded Direct Current Surge Protection Devices (DC SPDs) that exist within the inverter have thresholds values that can be adjusted, complying with Royal Decree 1663/2000 and with Royal Decree 1699/2011. Therefore, no extra calculation is needed since the SPD devices are accurate enough to meet the aforementioned requirements  $\checkmark$ .

### 2.7.2 AC Protections

In accordance with the current regulation, only the automatic residual current circuit breaker and the automatic circuit breaker are required since the general manual circuit breaker is already deployed at the Distribution System Operator side of the circuit, which would be triggered when shutting the power supply off.

### 2.7.2.1 Automatic Circuit Breakers

Since the distance between the inverter and the main electrical distribution panel of the facility is greater than 50 metres, two automatic circuit breakers have been considered for the AC side of the PV plant. This is the reason why an intermediate AC box has been included at the facilities zone of the building. Then, according to ITC-BT-22, automatic circuit breakers must comply with the following conditions:

- **Overloads - Thermal protection:**

- $I_{out_{max}} \leq I_N \leq I_{adm}$ .
- $1.3 \cdot I_N \leq 1.45 \cdot I_{adm}$ .

- **Short-circuits - Magnetic protection:**

- $I_c \geq I_{SC_{max}}$ .
- $I_{SC_{min}} > I_m$ .

Where:

- $I_{out_{max}}$  → Maximum output current of the inverter [A].
- $I_N$  → Rated current of the protective device [A].
- $I_{adm}$  → Computed admissible current of the cable [A].
- $I_c$  → Breaking capacity of the protective device [A].
- $I_{SC_{max}}$  → Maximum short-circuit current [A].
- $I_{SC_{min}}$  → Minimum short-circuit current [A].
- $I_m$  → Minimum current that ensures the magnetic activation of the breaker [A].

In the specific case of three-phase supply:

- **Maximum short-circuit current.** The one produced between the three phases:

$$I_{SC_{max}} = \frac{400 V}{\sqrt{3} \cdot \sum Z_P} \quad (2.54)$$

- **Minimum short-circuit current.** The produced between a phase and the neutral wire:

$$I_{SC_{min}} = \frac{230 V}{\sum(Z_P + Z_N)} \quad (2.55)$$

Where:

- $Z_P$  → Phase impedance [ $\Omega$ ].
- $Z_N$  → Neutral impedance [ $\Omega$ ].
- Summation since impedance between the DSO transformer including the general feeding line and the short-circuit point have to be considered.

Then, taking into account that the conductive material is copper:

$$Z^2 = R^2 + X^2 = (\rho_{cuT} \cdot \frac{L}{S})^2 + \overbrace{(8 \cdot 10^{-5} \Omega/m \cdot L)^2}^{UNE-HD60364} \quad (2.56)$$

Where:

- $R \rightarrow$  Resistance  $[\Omega]$ .
- $X \rightarrow$  Reactance  $[\Omega]$ .
- $\rho_{cuT} \rightarrow$  Resistivity at the operating temperature of the cable  $[\Omega \cdot mm^2/m]$ .
- $L \rightarrow$  Length of the cable  $[m]$ .
- $S \rightarrow$  Conductive section  $[mm^2]$ .

It is assumed that the DSO transformer impedance as well as the general feeding line impedance is  $0 \Omega$  in order to analyse the worst-case scenario.

Then, distinguishing between the two AC stretches defined in subsection 2.6.2:

- Wire impedance between the inverter and the AC box:
  - $\rho_{cuT} = 0.02099 \Omega \cdot mm^2/m$  (equation 2.45).
  - $L = 25 m$  (table 2.13).
  - $S = 70 mm^2$  (table 2.13).
  - Then, applying equation 2.56  $\rightarrow Z_{stretch\ AC1} = 7.76 \cdot 10^{-3} \Omega$
- Wire impedance between the AC box and the main distribution panel:
  - $\rho_{cuT} = 0.02051 \Omega \cdot mm^2/m$  (equation 2.45).
  - $L = 35 m$  (table 2.13).
  - $S = 120 mm^2$  (table 2.13).
  - Then, applying equation 2.56  $\rightarrow Z_{stretch\ AC2} = 6.60 \cdot 10^{-3} \Omega$

It must be taken into account that the section of the neutral wire is equal to the phase section for this project, id est, in all cases  $Z = Z_P = Z_N$ .

Now, the two circuit breakers of the AC side are computed:

- **Circuit breaker at the AC box.**

- **Overloads - Thermal protection:**

$$\overbrace{160.4 A}^{Table\ 2.4} \leq I_N \leq 200.7 A \quad (2.57)$$

$$1.3 \cdot I_N \leq 291.015 A \quad (2.58)$$

- **Short-circuits - Magnetic protection:**

Computing the required summation of impedance for this AC stretch:

$$* \sum Z_P = Z_{stretch\ AC1} + Z_{stretch\ AC2} \rightarrow \sum Z_P = 14.36 \cdot 10^{-3} \Omega$$

$$* \text{Then, applying equation 2.54} \rightarrow I_{SC_{max}} = 16.08 kA$$

$$* \sum (Z_P + Z_N) = 2 \cdot (Z_{stretch\ AC1} + Z_{stretch\ AC2}) \rightarrow \sum Z_P = 28.72 \cdot 10^{-3} \Omega$$

$$* \text{Then, applying equation 2.55} \rightarrow I_{SC_{min}} = 8.01 kA$$

Consequently:

$$I_c \geq 16.08 \text{ kA} \quad (2.59)$$

$$8.01 \text{ kA} > I_m \quad (2.60)$$

All in all, an automatic circuit breaker with a rated current of 200 A and a short-circuit breaking capacity of 36 kA would be enough to comply with the previously mentioned requirements at the AC box ✓.

- **Circuit breaker at the main electrical distribution panel of the gym.**

- **Overloads:**

$$\overbrace{160.4 \text{ A}}^{\text{Table 2.4}} \leq I_N \leq 217.6 \text{ A} \quad (2.61)$$

$$1.3 \cdot I_N \leq 315.52 \text{ A} \quad (2.62)$$

- **Short-circuits:**

Computing the required summation of impedance for this AC stretch:

$$* \sum Z_P = Z_{stretch \ AC2} \longrightarrow \boxed{\sum Z_P = 6.60 \cdot 10^{-3} \ \Omega}$$

$$* \text{ Then, applying equation 2.54 } \longrightarrow \boxed{I_{SC_{max}} = 34.99 \text{ kA}}$$

$$* \sum (Z_P + Z_N) = 2 \cdot Z_{stretch \ AC2} \longrightarrow \boxed{\sum Z_P = 13.2 \cdot 10^{-3} \ \Omega}$$

$$* \text{ Then, applying equation 2.55 } \longrightarrow \boxed{I_{SC_{min}} = 17.42 \text{ kA}}$$

Consequently:

$$I_c \geq 34.99 \text{ kA} \quad (2.63)$$

$$17.42 \text{ kA} > I_m \quad (2.64)$$

Once again, an automatic circuit breaker with a rated current of 200 A and a short-circuit breaking capacity of 36 kA would be enough to comply with the previously mentioned requirements at the main electrical distribution panel of Dreamfit Alcorcón ✓.

Although both automatic circuit breakers have equal rated current, discrimination between them can be ensured if the aforementioned currents  $I_N$  and  $I_m$  are adjustable ✓.

### 2.7.2.2 Automatic Residual Current Circuit Breaker

A residual current circuit breaker is included at the main electrical distribution panel of the facility, which has to have a sensitivity ( $I_{\Delta n}$ ) of 30 mA according to ITC-BT-18.

Additionally, the rated current of the residual current device must be at least equal to the rated current of the automatic circuit breaker with which it is connected, id est, the rated current of the residual current device must be at least 200 A.

Then, the proposed device consists of a residual current relay with a rated current greater than 200 A, a sensitivity of 30 mA and a toroid with enough diameter for the three 120 mm<sup>2</sup> phases and the neutral wire, id est, with an inside section greater than 480 mm<sup>2</sup> ✓.

### 2.7.2.3 Voltage and Frequency Control

The SUN2000-100KTL-M1 Smart String Inverter counts with a system to control both the AC output voltage and the AC output frequency:

- **Frequency Control.** The inverter includes a frequency control system that enables adjusting an upper and a lower limit of the frequency with respect to the rated frequency ( $F_N = 50 \text{ Hz}$ ) to shut down the system in case of fault. Specifically, the threshold frequencies can be adjusted:
  - **Lower frequency limit** between  $0.8 \cdot F_N$  and  $1.0 \cdot F_N$ .
  - **Upper frequency limit** between  $1.0 \cdot F_N$  and  $1.2 \cdot F_N$ .

Therefore, no extra devices are required in terms of frequency control ✓.

- **Voltage Control.** The inverter includes a voltage control system that enables adjusting an upper and a lower limit of the voltage with respect to the rated voltage ( $V_N = 400 \text{ Hz}$ ) to shut down the system in case of fault. Specifically, the threshold voltages can be adjusted:
  - **Lower voltage limit** between  $0.45 \cdot V_N$  and  $1.0 \cdot V_N$ .
  - **Upper voltage limit** between  $1.0 \cdot F_N$  and  $1.36 \cdot F_N$ .

Therefore, no extra devices are required in terms of AC voltage control ✓.

### 2.7.2.4 General Manual Circuit Breaker

In accordance with the third article within the second chapter of the Royal Decree 244/2019 which regulates self-consumption in Spain, grid-connected facilities can now be connected at the main electrical distribution panel of the consumer, id est, sharing the connection infrastructure with the consumer supply line.

Then, connecting the PV plant directly to the DSO or TSO grid is not required anymore, since the distribution company can disconnect the PV plant when shutting the whole consumer power supply off. Consequently, the PV plant will be connected at the indoor main electrical panel of the gym with the aforementioned circuit breakers and the residual current device at the AC side, not requiring any extra general manual circuit breaker ✓.

## 2.8 Earthing System

The designed earthing system has to coexist with the residual current device selected, ensuring a proper combination between both elements to reach an optimal operation of the PV plant in terms of safety. Additionally, the existing earthing net composed by 8 ground spikes at Dreamfit Alcorcón is going to be leveraged. In this sense, creating a new grounding network for the PV plant in parallel with the already deployed could compromise people safety since differences in electrical potential could be created.

Therefore, the existing grounding system of the building will be used both for the DC and the AC side of the PV facility, thus ensuring the equipotentiality of the installation. The schema followed by the already deployed grounding system of the gym is TT according to ITC-BT-08. Then, the new grounding wires of the PV plant will be connected in accordance with this schema.

The earthing is going to be carried out unifying the earth of all the metallic elements that make up the photovoltaic facility: the PV structure and modules, the inverter and both electrical distribution panels.

The existing grounding system of Dreamfit Alcorcón building consists of:

- **Copper bare conductor buried horizontally:** 450 *m* of length and 35 *mm*<sup>2</sup> of section.
- **Four copper ground spikes buried vertically:** 2 *m* of length and 14.3 *mm* of diameter.

Hence, according to ITC-BT-18, the resistance of the earthing system is computed as follows:

- **Copper bare conductor buried horizontally:**

$$R_{cond} = 2 \cdot \frac{\rho}{L} \quad (2.65)$$

- **Copper ground spikes buried vertically:**

$$R_{spikes} = \frac{\rho}{N \cdot L} \quad (2.66)$$

Where:

- $R_{cond}$  → Resistance of the copper bare conductor buried horizontally [ $\Omega$ ].
- $R_{spikes}$  → Resistance of the copper ground spikes buried vertically [ $\Omega$ ].
- $\rho$  → Soil resistivity [ $\Omega \cdot m$ ].
- $L$  → Length of the electrode [*m*].
- $N$  → Number of equal spikes (parallel association of the conductivity resistances) [–].

The soil of Dreamfit Alcorcón is a low fertile arable land, so according to ITC-BT-18, the average value of its resistivity is typically of 500  $\Omega \cdot m$ .

Thus, for the copper bare conductor buried horizontally:

- $\rho = 500 \Omega \cdot m$ .
- $L = 450 m$ .
- Then, applying equation 2.65 →  $R_{cond} = 2.22 \Omega$

Analogously, for the four copper ground spikes buried vertically:

- $\rho = 500 \Omega \cdot m$ .
- $N = 4$ .
- $L = 2 m$ .
- Then, applying equation 2.66 →  $R_{spikes} = 62.5 \Omega$

The whole resistance of the earthing system is the result of the parallel association of both the conductor and the spikes resistances according once again to ITC-BT-18:

$$R_{earth} = \frac{R_{cond} \cdot R_{spikes}}{R_{cond} + R_{spikes}} = \frac{2.22 \Omega \cdot 62.5 \Omega}{2.22 \Omega + 62.5 \Omega} \rightarrow R_{earth} = 2.14 \Omega \quad (2.67)$$

At this point, the resistance of the earthing system must be compared with the resistance of the receiver for which the earthing system must operate regarding the sensitivity of the residual current device. In this case the residual current is  $I_{\Delta n} = 0.03 \text{ A}$ . Then, taking into account the ITC-BT-18 requirements:

$$R_{earth} < \frac{U_c}{I_{\Delta n}} \quad (2.68)$$

Where the only one parameter which has not been mentioned previously is  $U_c$ :

- $U_c = 50 \text{ V} \rightarrow$  Contact voltage for general facilities [V].
- Then, applying equation 2.68  $\rightarrow$   $R_{earth} = 2.14 \text{ ohm} < 1,666.67 \Omega \checkmark$

The value of  $R_{earth}$  is not only lower than the division between the contact voltage and the sensitivity current, but also is lower than the human body resistance under standard conditions ( $\approx 2,500 \Omega$ ) [52]. Thus, the proper operation of the earthing system is ensured even before the activation of the residual device protection  $\checkmark$ .

Hence, the design of the protection wiring has to respect the minimum section requirements:

Table 2.14. Section required for protection wires [53].

PHASE WIRES SECTION $S \text{ (mm}^2\text{)}$	PROTECTION WIRES MINIMUM SECTION $S_p \text{ (mm}^2\text{)}$
$S \leq 16$	$S_p = S$
$16 < S \leq 35$	$S_p = 16$
$S > 35$	$S_p = S/2$

Then, in accordance with the wiring sections and lengths presented in table 2.13:

- **DC side.** The earthing system that connects the PV modules, the structure and all the conductive parts consists of a circuit of coated copper of  $6 \text{ mm}^2 \checkmark$ .
- **AC side.** The earthing system that connects the inverter, the AC box and any conductive part consists of a circuit of coated copper with section:
  - **Stretch between the inverter and the AC box.**  $35 \text{ mm}^2 \checkmark$ .
  - **Stretch between the AC box and the main distribution panel.**  $60 \text{ mm}^2 \checkmark$ .

Table 2.15. Protection wire length requirements.

LINE CODE	PROTECTION WIRE SECTION $\text{(mm}^2\text{)}$	TOTAL LENGTH $\text{(m)}$
DC 1.1 - (...) - DC 10.2	6	950
AC 1	35	30
AC 2	60	40

## 2.9 Electrical Canalisation

The electrical canalisation is based on halogen free conduits prepared to be used outdoors and with a high UV resistance. The design has been done regarding the strings distribution as well as the section of both the DC and the AC wires.

According to ITC-BT-21, in case of having several wires with the same section within tubes, the required internal diameter of tubes have to computed applying the following equation:

$$\varnothing_{int. tube} = \varnothing_{ext. tube} \cdot \sqrt{n \cdot f} \quad (2.69)$$

Where:

- $\varnothing_{int. tube}$  → Required internal diameter of the tube [mm].
- $\varnothing_{ext. cond}$  → External diameter of the conductor<sup>9</sup> [mm].
- $n$  → Number of cables with equal section [ $\Omega \cdot m$ ].
- $f$  → Reduction factor defined in ITC-BT-19 that depends on the type of deployment [–].

Thus, the reduction factors for the worst-case scenarios analysed in the wiring section:

- **DC Side:**  $n = 0.7 \cdot 0.8 \cdot 0.9 = 0.504$  according to subsection 2.6.1.1.
- **AC Side:**
  - **Inverter - AC Box:**  $n = 0.9$  according to subsection 2.6.2.1.
  - **AC Box - Main Distribution Panel:**  $n = 0.8$  according to subsection 2.6.2.2.

Then, respecting the identification codes for every canalisation tube presented in figure 2.22 and considering Pemsas RLH1250 tubes for unipolar cables, the electrical canalisation results applying equation 2.69 are included in table 2.16:

Table 2.16. Dimensions of the canalisation tubes.

CABLE TUBE CODE	FROM	TO	TYPE	CABLES SECTION & NUMBER	MINIMUM INTERNAL DIAMETER (mm <sup>2</sup> )	INTERNAL TUBE DIAMETER (mm)	INTERNAL TUBE SECTION (mm <sup>2</sup> )	EXTERNAL TUBE DIAMETER (mm)	TOTAL LENGTH (m)
T 1	String	Inverter	DC	1·[1·6 mm <sup>2</sup> + 1·TT·6 mm <sup>2</sup> ]	5.92	21.6	366	25	5
T 2	String	Inverter	DC	1·[3·6 mm <sup>2</sup> + 1·TT·6 mm <sup>2</sup> ]	8.38	21.6	366	25	30
T3	String	Inverter	DC	1·[3·6 mm <sup>2</sup> + 0·TT·6 mm <sup>2</sup> ]	7.25	21.6	366	25	40
T4	String	Inverter	DC	1·[4·6 mm <sup>2</sup> + 3·TT·6 mm <sup>2</sup> ]	11.08	21.6	366	25	70
T5	String	Inverter	DC	1·[1·6 mm <sup>2</sup> + 1·TT·6 mm <sup>2</sup> ]	5.92	21.6	366	25	7
T6	String	Inverter	DC	1·[13·6 mm <sup>2</sup> + 6·TT·6 mm <sup>2</sup> ]	18.26	28	616	32	65
T7	String	Inverter	DC	1·[15·6 mm <sup>2</sup> + 8·TT·6 mm <sup>2</sup> ]	12.57	28	616	32	75
T AC1	Inverter	AC Box	AC	1·[4·70 mm <sup>2</sup> + 1·TT·35 mm <sup>2</sup> ]	31.93	45.2	1605	50	30
T AC2	AC Box	Main AC Box	AC	1·[4·120 mm <sup>2</sup> + 1·TT·60 mm <sup>2</sup> ]	38.80	45.2	1605	50	40

Where:

- Cable tube code → To identify the canalisation tube.
- From - To → To highlight the elements connected by the canalisation tube.
- Type → To specify if it is a DC or an AC line tube.
- Cables section & number → To define the number and the section of lines within the tube.

<sup>9</sup>Table 2.16 minimum sections have been computed with ZZ-F Topsolar DC Cables and RV-K RCT AC Cables.

- Minimum internal diameter → Required internal tube diameter applying equation 2.69.
- Internal tube diameter → Internal diameter of the selected tube commercially available.
- Internal tube section → Internal section of the selected tube commercially available.
- External tube diameter → External diameter of the selected tube commercially available.
- Total length → Total length of tube required.

## 2.10 Photovoltaic Mounting Structure

The photovoltaic modules will be mounted on a structure based on rails able to withstand the loads derived from the facility itself and that provides the proper tilt and azimuth angles. In fact, the structure will be installed in accordance with the installation instructions specified in the user manual to comply with the IEC certification [54].

The weight and the surface of every PV module is required as input data to design the photovoltaic structure and can be obtained from the PV Modules Data Sheet:

- $W = 26.5 \text{ kg}$  → Weight per module.
- $A = 2.187 \text{ m} \cdot 1.102 \text{ m} = 2.41 \text{ m}^2$  → Surface area per module.

Additionally, the structure should be a modular system made of extruded aluminium profiles. Selecting the aluminium structural profiles of Solarstem® [55] and analysing the worst-case scenario, id est, picking the profile with highest section from its data sheet:

- $\rho = 2,700 \text{ kg/m}^3$  → Density of the aluminium profile EN AW-6082-T6 PS-401 [ $\text{kg/m}^3$ ].
- $S = 7.46 \text{ cm}^2$  → Section of the PS-401 profile [ $\text{cm}^2$ ].

Moreover, next figure includes a section view of the PV modules in order to highlight the PV structure, the tilt angles, the 8 rows of PV panels that were initially presented in figure 2.14, and the 3 stretches in which the roof of Dreamfit Alcorcón is divided to evacuate rainwater:

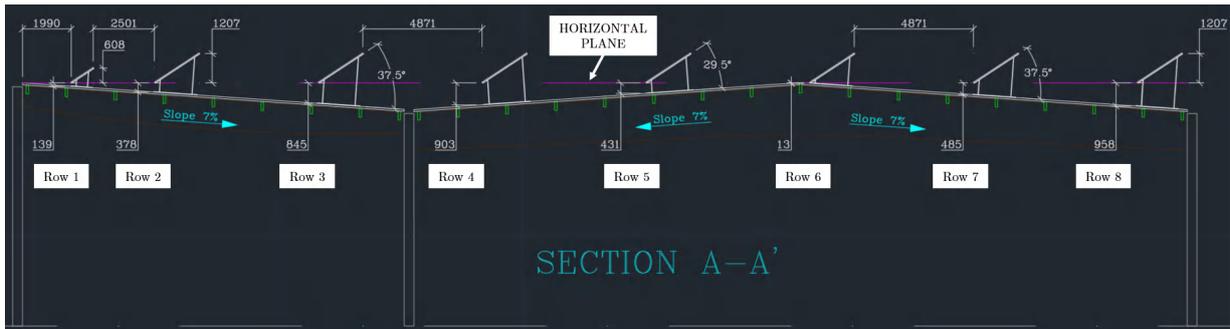


Figure 2.26. Section view of the PV modules structure [46].

As it can be observed in the previous figure 2.26, the tilt angle of every row with respect to the roof of Dreamfit Alcorcón differs since it has a  $\pm 7\%$  of slope, id est,  $\pm 4^\circ$  divided in three different stretches. However, according to the information provided in section 2.1, the tilt angle of every row is measured with respect to the horizontal plane, so it is actually  $\beta = 33.5^\circ \checkmark$ .

Additionally, every PV module will be installed at the same height with respect to ground regardless of the slope of the roof to avoid shadow issues as it was stated in section 2.5.

Hence, the tilt angle with respect to the building roof has been adjusted in every stretch:

- **Stretch 1 of the Roof** - Downward Slope  $\rightarrow \beta + 4^\circ$ .
  - **Stretch 2 of the Roof** - Upward Slope  $\rightarrow \beta - 4^\circ$ .
  - **Stretch 3 of the Roof** - Downward Slope  $\rightarrow \beta + 4^\circ$ .
- Nonetheless,  $\beta = \beta_{opt} = 33.5^\circ$  with respect to the horizontal plane in the 3 stretches ✓.

Analysing figure 2.26, the worst-case scenario occurs at row 8 since these PV modules require a bigger structure of aluminium profiles. In fact, even considering that a strut system is needed, the maximum length of aluminium profiles per PV module at row 8 would be:

- $L_{max} = 14 \text{ m}$   $\rightarrow$  Maximum length of aluminium profile per PV module [m].

Taking into account the information provided above, the maximum load per square meter added to the roof of Dreamfit Alcorcón can be now computed:

$$Load_{added_{max}} = \frac{\rho \cdot S \cdot L + W}{A} \rightarrow \boxed{Load_{added_{max}} = 22.70 \text{ kg/m}^2} \quad (2.70)$$

Now, the assumptions considered for the design of the roof in the original project of the sports centre are detailed below [56]:

- Metallic roof sandwich panel  $\rightarrow 25 \text{ kg/m}^2$ .
- Facilities and other  $\rightarrow 25 \text{ kg/m}^2$ .
- Snow (zone 4  $h \approx 700 \text{ m}$ )  $\rightarrow 65 \text{ kg/m}^2$ .
- Wind (dynamic pressure zone A)  $\rightarrow 42 \text{ kg/m}^2$ .
- Usage (not simultaneous usage in case of wind or snow)  $\rightarrow 40 \text{ kg/m}^2$

All in all, it can be concluded that:

- PV modules will be placed at a roof area without any facilities nor any other kind of load.
- Regarding the result obtained in equation 2.70  $\rightarrow Load_{added_{max}} = 22.70 \text{ kg/m}^2$ .
- The roof of Dreamfit Alcorcón was designed assuming a load for facilities of  $25 \text{ kg/m}^2$ .

$$Load_{added_{max}} = 22.7 \text{ kg/m}^2 < 25 \text{ kg/m}^2 = Load_{design_{facilities}} \quad \checkmark \quad (2.71)$$

Then, it has been demonstrated even for the worst-case scenario that no structural reinforcement is required to install the PV plant at the roof of the sports centre since the architect forecast a possible future usage of this area in the original project of the gym. Consequently, the PV structure can be directly screwed to the roof.

Although the total weight of the inverter including the mounting plate is  $90 \text{ kg}$ , it will be anchored to the concrete perimeter wall of the roof where the structural pillars of the building are located. Therefore, there will be no roof load issues related to the inverter either.



## Section 3

# Production and Economic Study

### Contents

---

3.1	Production Study . . . . .	<b>100</b>
3.1.1	Input and Output Data . . . . .	100
3.1.2	System Yield and Losses . . . . .	100
3.1.2.1	Mismatch or Coupling Losses . . . . .	101
3.1.2.2	Losses due to Dust or Dirt at the PV Modules . . . . .	101
3.1.2.3	Array Incidence Losses - Incidence Angle Modifier . . . . .	101
3.1.2.4	Losses with respect to the Rated Power . . . . .	102
3.1.2.5	PV Modules Efficiency and Temperature Relation . . . . .	102
3.1.2.6	Ohmic Losses in DC and AC Wiring . . . . .	103
3.1.2.7	Errors while Tracking the Maximum Power Point . . . . .	103
3.1.2.8	Inverter Energy Efficiency . . . . .	103
3.1.2.9	Losses due to Generator Layout and Shading . . . . .	103
3.1.3	Performance Ratio . . . . .	103
3.1.4	Results of the Production Study . . . . .	104
3.2	Economic Study . . . . .	<b>113</b>
3.2.1	Electricity Tariff 3.0TD . . . . .	113
3.2.1.1	Seasons and Periods of Tariff 3.0TD . . . . .	113
3.2.1.2	Power Fixed Term of Tariff 3.0TD . . . . .	115
3.2.1.3	Excessive Power Penalty of Tariff 3.0TD . . . . .	116
3.2.1.4	Energy Term of Tariff 3.0TD . . . . .	116
3.2.1.5	Reactive Energy Penalty of Tariff 3.0TD . . . . .	116
3.2.2	Simplified Compensation Mechanism . . . . .	118
3.2.3	Economic Study Algorithm Explanation - <i>economic.m</i> . . . . .	119
3.2.4	Results of the Economic Study . . . . .	120

---

### 3.1 Production Study

The PV production study of Dreamfit Alcorcón has been carried out in two different ways:

1. **MATLAB®**. Function *tfm.m* presented in section 2.2. The algorithm computes not only the optimal PV peak power to install, but also the performance of the generation plant for that peak power.
2. **PVsyst®**. Professional PV software utilised to replicate the system with the same hypothesis and assumptions in order to assess the accuracy of the production analysis developed in MATLAB.

This section presents the results obtained through the MATLAB programming function, whereas the PVsyst analysis results have been included at the annexes.

#### 3.1.1 Input and Output Data

Although it has been explained more elaborately in section 2.2, the most important input data used by the algorithm *tfm.m* to establish the performance of the plant are presented below:

- **Global In-Plane Irradiance per Hour** ( $G(i)$  [ $W/m^2$ ]). Vector of global irradiance obtained through PVGIS® TMY Tool considering both the optimal tilt and azimuth angles, which in this case are  $\beta_{opt} = 33.5^\circ$  and  $\alpha_{opt} = 0^\circ$  respectively [30].
- **Hourly Consumption of Dreamfit Alcorcón** ( $E_c(i)$  [ $kWh$ ]). Vector of consumption data obtained through the Circutor® power analyser of Dreamfit Alcorcón [35]. Consumption data from year 2020 cannot be used due to COVID-19 lockdown, so the most recent and representative consumption data available corresponds to the year 2019. This is the reason why data from year 2019 has been utilised.

Once the code is executed, the optimal PV peak to install is returned by the *tfm.m* function. Additionally, the optimisation vectors presented in section 2.2 are exported to a Microsoft Excel file where data per hour, day, week, month and year can be analysed:

- **PSH**. The Peak Solar Hours available [ $h$ ].
- **PV Production**. Energy generated by the Distributed Energy Resource [ $kWh$ ].
- **Total Consumption**. Energy supplied to the user either through the PV plant or through the DSO network [ $kWh$ ].
- **Self-Consumption**. Energy produced by the plant and self-consumed by the user [ $kWh$ ].
- **Surplus PV Energy**. Excessive energy produced injected into the DSO grid [ $kWh$ ].
- **Grid Consumption**. Energy supplied to the consumer from the DSO grid [ $kWh$ ].

#### 3.1.2 System Yield and Losses

The transformation of solar energy into electrical energy through the photovoltaic cells is carried out with a yield represented by the Performance Ratio (PR), which was initially introduced in section 2.2. The PR includes all energy losses in the Low Voltage grid up to the DSO power meter, but it does not include the degradation of the PV modules nor of any other electromechanical component of the facility [37].

The PR encompasses a series of energy losses:

- Some of them depend on the design of the facility and the equipment.
- Others are directly related to the instantaneous weather conditions of the site.

Then, the following losses have to be taken into account in order to determine the PR [57]:

- Mismatch or Coupling Losses.
- Losses due to Dust or Dirt at the PV Modules.
- Array Incidence Losses (Incidence Angle Modifier).
- Losses with respect to the Rated Power.
- Relation between the PV Modules Efficiency and the Temperature.
- Ohmic Losses in DC and AC Wiring.
- Losses due to Errors while Tracking the Maximum Power Point (MPPT).
- Inverter Energy Efficiency.
- Losses due to Generator Layout and Shading.

### 3.1.2.1 Mismatch or Coupling Losses

Mismatch losses are caused by the connection of several PV modules working under slightly different electrical parameters to form a PV string. This phenomenon has special importance since each module produces individually a low voltage around 40 V at the MPP. These modules are grouped in series, so voltages are summed to reach the inverter voltage threshold.

On the one hand, the PV module with lower output current per series limits the current of the entire PV string. On the other hand, all PV series or strings connected in parallel to the same MPPT will work with the same voltage.

In this project, mismatch losses are reduced since the Huawei SUN2000-100KTL-M1 inverter counts with 10 MPPTs and there are only 20 strings of 11 PV modules.

Mismatch Losses =  $-2.10\%$   $\rightarrow$  In accordance with PVsyst Simulation Results.

### 3.1.2.2 Losses due to Dust or Dirt at the PV Modules

The deposition of dust and dirt on the surface of PV modules reduces its generation capacity, reducing the amount of solar energy captured. Dust losses vary between 0% after a rainy day or after a cleaning day and can reach 8% if modules are considerably dirty. These losses depend on the inclination of the panels, on the distance to areas such as farms, roads, etc.

Dust Losses  $\approx 0.00\%$   $\rightarrow$  Since a regular professional cleaning will be included by maintenance.

### 3.1.2.3 Array Incidence Losses - Incidence Angle Modifier

The PV peak power of a module is measured under Standard Test Conditions, id est, with an irradiance of  $1,000/m^2$ , a cell temperature of  $25^\circ C$  and an air mass spectra of AM1.5G. Nonetheless, there are losses due to irradiance reflexion under normal operation conditions, as well as losses due to the spectrum, which is not standard during the whole operating time.

Particularly, the incidence effect (IAM) corresponds to the decrease of the irradiance that actually reaches the PV cells' surface, with respect to irradiance under normal incidence. This decrease is mainly due to reflexions on the glass cover, which increases with the incidence angle.

In principle, the IAM effect obeys the Fresnel's Law<sup>1</sup>:

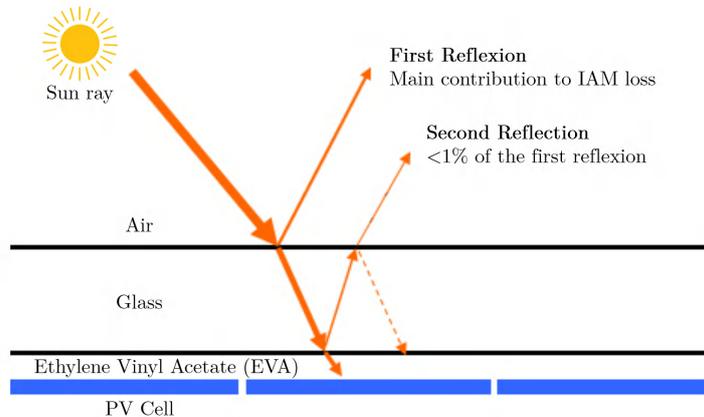


Figure 3.1. Incidence Angle Modifier (IAM) [58].

In this project, the PV modules are placed on a static mounting structure, what increases array incidence losses.

Array Incidence Losses =  $-2.01\%$   $\rightarrow$  In accordance with PVsyst Simulation Results.

### 3.1.2.4 Losses with respect to the Rated Power

PV modules are obtained from an industrial manufacturing process, so differences among them can appear due to tolerance percentages. Then, it is possible that once installed, the actual PV field power does not coincide with the sum of the catalogue powers of each module.

Losses with respect to Rated Power =  $\pm 3.00\%$   $\rightarrow$  According to PV Modules Data Sheet.

### 3.1.2.5 PV Modules Efficiency and Temperature Relation

PV modules experience losses when its temperature is greater than the Standard Test Conditions, which require  $25^{\circ}\text{C}$  according to the PV modules data sheet. Additionally, the Standard Test Conditions imply an irradiance of  $1,000/m^2$  and an air mass spectra of AM1.5G. These laboratory conditions are barely reproducible at the daily operation of the PV plant.

The solar cell temperature is normally  $20^{\circ}\text{C}$  above the ambient temperature, thus the overheating of the modules worsen its performance and reduces its generating capabilities.

Temperature Losses =  $-4.56\%$   $\rightarrow$  In accordance with PVsyst Simulation Results.

<sup>1</sup>Cross-linkable Ethylene Vinyl Acetate (EVA) is the most common encapsulation system in the solar industry, which helps preventing humidity and dirt penetrating the solar panels as well as softening shocks and vibrations.

### 3.1.2.6 Ohmic Losses in DC and AC Wiring

There are losses caused by voltage drops in the conductors both in the DC side and AC side of the facility. In the specific case of Spain, as explained in section 2.6, the DC voltage drop cannot exceed 1.5%, as well as the AC voltage drop, which cannot exceed 1.5% neither. The configuration and the design of the PV plant have been done in order to ensure enough wiring section to avoid exceeding these voltage drop limits.

Ohmic Losses in DC and AC Wiring =  $\pm 1.12\%$   $\rightarrow$  According to PVsyst Simulation Results.

### 3.1.2.7 Errors while Tracking the Maximum Power Point

The solar inverter has an electronic device to monitor and track the maximum power point of the photovoltaic generator. The controller algorithm of inverters may vary among models and manufacturers, and therefore an error following the Maximum Power Point implies a loss in the generated energy.

Ohmic Losses in DC and AC Wiring =  $0.00\%$   $\rightarrow$  According to PVsyst Simulation Results.

### 3.1.2.8 Inverter Energy Efficiency

The inverter is the electronic device that transforms the DC energy from the PV field into AC energy to supply the electrical loads. The inverter establishes parameters such as voltage and frequency to make the output AC energy compatible with the supply power grid.

Therefore, the inverter has a specific yield. In fact, the simple Joule effect causes power losses during the mentioned DC/AC transformation process.

Inverter Losses =  $-2.32\%$   $\rightarrow$  In accordance with PVsyst Simulation Results.

### 3.1.2.9 Losses due to Generator Layout and Shading

Once the location of the building in which the PV modules will be mounted is known, both the tilt and the azimuth angles must be determined. Then, depending on the orientation of the PV field, power losses can arise.

Additionally, possible shades created among modules and obstacles must be taken into account and minimised as much as possible during the design phase to maximise production. Shadows generate power losses and an early module degradation.

Shading Losses =  $\approx 0.00\%$   $\rightarrow$  In accordance with mathematical demonstration of section 2.5.

## 3.1.3 Performance Ratio

All in all, the value of the performance ratio has been computed through a PVsyst simulation considering the location, the components and all the power losses mentioned above. Therefore:

$$\boxed{PR = 88.7\%} \quad (3.1)$$

### 3.1.4 Results of the Production Study

This section includes the highlights of the production study developed in MATLAB for a performance ratio of 88.7% and an optimal PV field power of 111 *kW*:

- **TOTAL CONSUMPTION:** 447,567.75 *kWh/year*.
- **PV PRODUCTION:** 198,897.59 *kWh/year*.
- **SURPLUS PV ENERGY:** 29,733.28 *kWh/year*.
- **GRID CONSUMPTION:** 278,403.45 *kWh/year*.
- **SELF-CONSUMPTION:** 169,164.30 *kWh/year*.

Then, the technical data of Dreamfit Alcorcón PV Plant are presented in the next table:

Table 3.1. Technical hypothesis for Dreamfit Alcorcón PV plant.

<b>HYPOTHESIS - PV PLANT TECHNICAL DATA</b>	
Location	DREAMFIT ALCORCÓN
Azimuth and Tilt Angles	SOUTH, 33.5°
PV Modules	220 modules, 505 $W_p$
PV Modules Annual Power Attenuation	0.55%/year
Facility Useful Life	> 25 years
PV Plant Rated Power	100 kW
PV Plant Peak Power	111.1 kW
Expected Production	198,897.59 kWh/year
Self-Consumption Rate	85.05%
Autarky Rate	37.80%

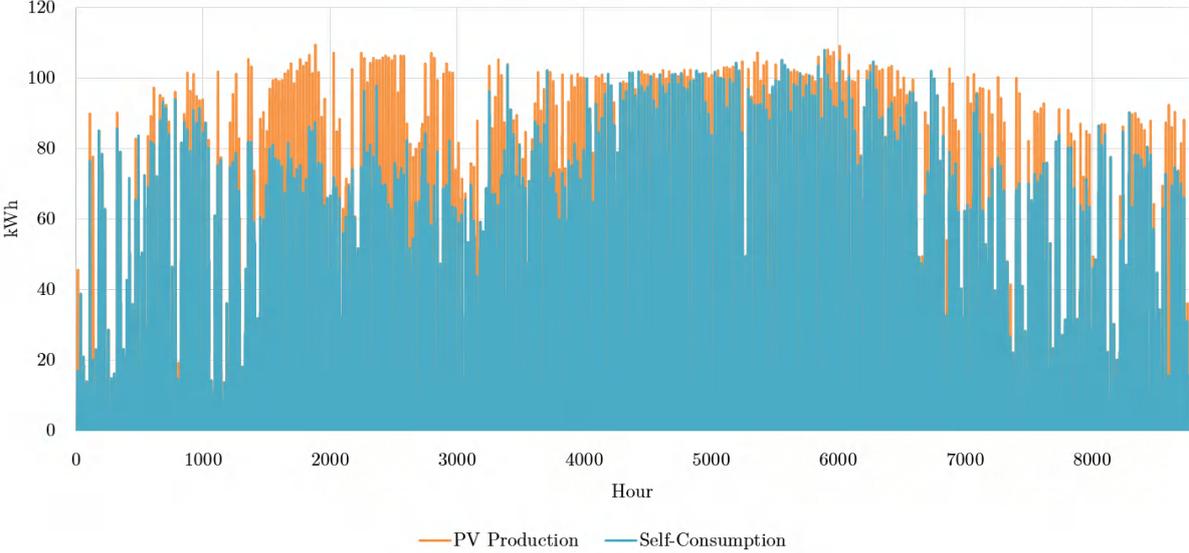
Regarding table 3.1:

- **Self-Consumption Rate.** More than 85% of the energy generated by the PV plant will be self-consumed by the sports facility ✓.
- **Autarky Rate.** Almost 38% of the total energy consumed by Dreamfit Alcorcón per year will be generated through the PV plant ✓.

Next page includes two subfigures that represent graphically the self-consumption rate as well as the autarky rate along the 8,760h of the year. As it can be seen in figure 3.2, the results exposed in table 3.1 match with the graphic representation.

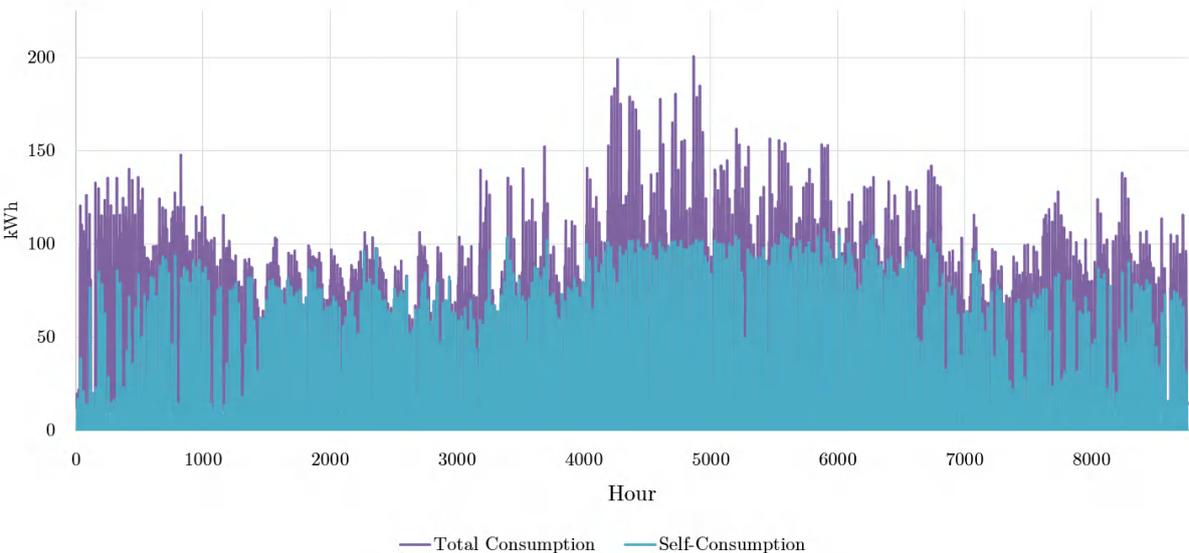
Although subfigure 3.2(a) shows that the PV production exceeds in some hours 100 *kW*, it must be taken into account that the maximum output power of the inverter is 110 *kW*. Consequently, the produced energy can sporadically exceed the rated power of the inverter. Nonetheless, the rated power of the inverter and therefore the rated power of the generation PV plant of Dreamfit Alcorcón is 100 *kW*.

PV PLANT - ANNUAL RESULTS  
SELF-CONSUMPTION RATE  
DREAMFIT ALCORCÓN



(a) Self-Consumption rate.

PV PLANT - ANNUAL RESULTS  
AUTARKY RATE  
DREAMFIT ALCORCÓN



(b) Autarky rate.

Figure 3.2. Evolution of self-consumption and autarky rates along the 8,760h of the year.

Although the self-consumption rate is 85.05%, the weekend opening hours of Dreamfit Alcorcón differ considerably if compared with working days opening hours. Therefore, an analysis of the average self-consumption rate has been developed per day of week and month:

Table 3.2. Self-consumption rate analysis per day of week and month.

SELF-CONSUMPTION RATE							
MONTH	DAY OF WEEK						
	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY	SUNDAY
JANUARY	96.55%	96.40%	99.26%	98.41%	99.07%	90.64%	61.48%
FEBRUARY	96.90%	94.25%	88.76%	90.96%	91.27%	88.47%	80.11%
MARCH	88.83%	84.52%	86.33%	86.54%	86.75%	74.37%	64.82%
APRIL	80.14%	91.47%	84.04%	73.26%	77.76%	72.54%	49.77%
MAY	89.27%	93.59%	84.26%	84.58%	91.57%	80.52%	59.52%
JUNE	96.68%	92.23%	85.93%	88.39%	90.11%	88.58%	56.11%
JULY	98.09%	96.41%	97.42%	96.59%	96.82%	75.19%	55.68%
AUGUST	94.92%	97.02%	92.64%	87.43%	95.94%	64.91%	57.50%
SEPTEMBER	89.07%	93.16%	90.24%	93.04%	90.39%	84.19%	63.29%
OCTOBER	88.35%	88.90%	88.50%	90.44%	91.29%	87.71%	62.59%
NOVEMBER	96.37%	87.22%	84.04%	92.30%	87.75%	97.15%	80.64%
DECEMBER	92.07%	86.39%	73.39%	92.56%	92.34%	90.53%	79.48%
AVERAGE	92.27%	91.80%	87.90%	89.54%	90.92%	82.90%	64.25%

Analysing the opening hours of Dreamfit Alcorcón:

- **Mondays to Fridays.** 7h-23h.
- **Saturdays.** 9h-21h.
- **Sundays and Bank Holidays.** 9h-15h.

Then, delving into table 3.2 and regarding Dreamfit opening hours, there is a significant difference in the self-consumption percentage from Mondays to Fridays (and even on Saturdays) if compared with Sundays. However, this fact is consistent with the results obtained since there are several sunny hours on Sundays where the sports centre remains closed ✓.

As it can be deduced from table 3.2, installing a storage system would only be interesting for leveraging the surplus energy generated on Sundays and bank holidays. Nevertheless, including a BESS would affect considerably to the payback period of the project since the technology has still not reached its maturity. This is the reason why Dreamfit Alcorcón will compensate the surplus energy injected into the grid respecting the current Spanish regulation.

Moreover, the month in which less PV energy is generated is January, whereas the month in which more PV energy is generated is July. Thus, next two pages include table 3.3 and figure 3.3 in which an average working day of both months is analysed. The considered variables are once again the photovoltaic production, the total consumption, the self-consumption, the surplus PV energy and the grid consumption, but applied to a single average day of these two most representative months.

Additionally, figure 3.4 presents a monthly summary of the five analysed variables along the first year of the project, where it can be confirmed that the surplus energy is minimum during winter months and maximum during summer months.

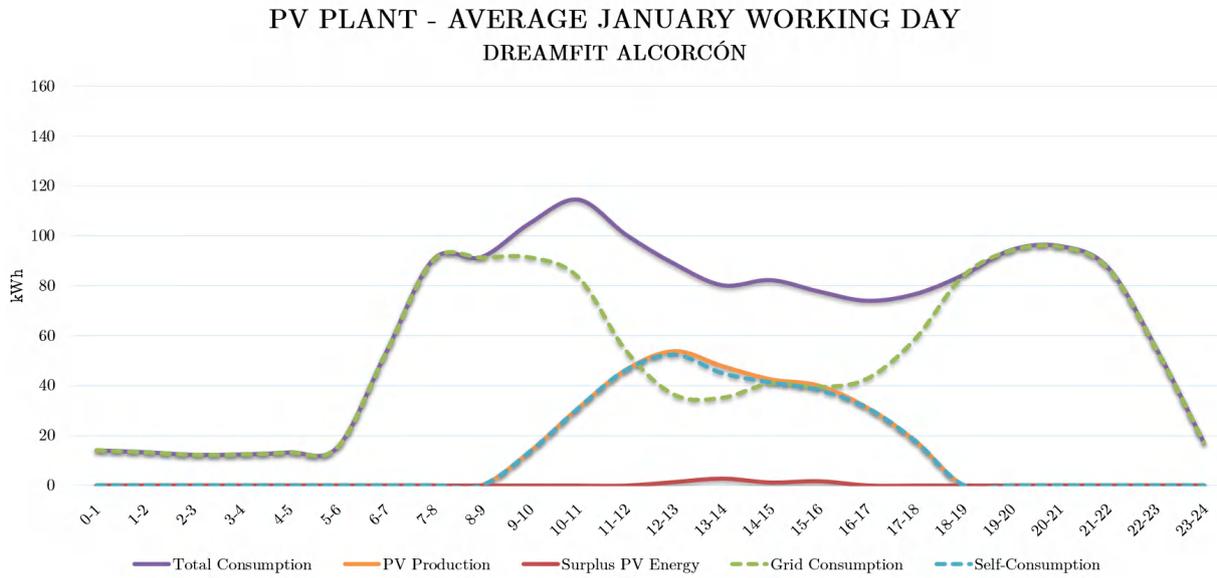
Table 3.3. PV plant performance - Most sunny versus most cloudy day.

(a) Average January working day.

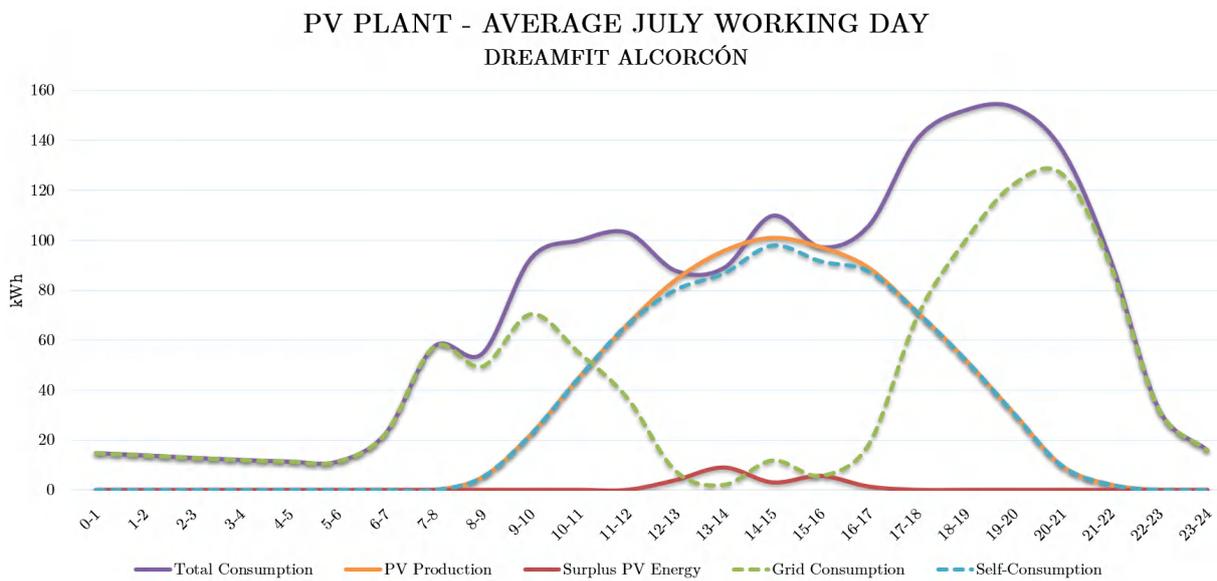
AVERAGE JANUARY WORKING DAY					
HOURL	PV PRODUCTION (kWh)	TOTAL CONSUMPTION (kWh)	SELF-CONSUMPTION (kWh)	SURPLUS PV ENERGY (kWh)	GRID CONSUMPTION (kWh)
0-1	0.00	14.05	0.00	0.00	14.05
1-2	0.00	13.31	0.00	0.00	13.31
2-3	0.00	12.26	0.00	0.00	12.26
3-4	0.00	12.38	0.00	0.00	12.38
4-5	0.00	13.20	0.00	0.00	13.20
5-6	0.00	15.20	0.00	0.00	15.20
6-7	0.00	52.72	0.00	0.00	52.72
7-8	0.00	90.59	0.00	0.00	90.59
8-9	0.00	91.41	0.00	0.00	91.41
9-10	13.53	105.00	13.53	0.00	91.47
10-11	30.81	114.40	30.81	0.00	83.59
11-12	46.32	100.27	46.32	0.00	53.95
12-13	53.72	88.70	52.35	1.38	36.35
13-14	47.70	80.11	44.94	2.76	35.17
14-15	42.43	82.20	41.24	1.20	40.96
15-16	39.90	77.64	38.17	1.73	39.47
16-17	31.17	73.92	31.12	0.05	42.80
17-18	17.85	76.59	17.85	0.00	58.74
18-19	0.13	84.24	0.13	0.00	84.10
19-20	0.00	94.29	0.00	0.00	94.29
20-21	0.00	95.84	0.00	0.00	95.84
21-22	0.00	87.34	0.00	0.00	87.34
22-23	0.00	55.12	0.00	0.00	55.12
23-24	0.00	17.09	0.00	0.00	17.09
<b>TOTAL</b>	<b>323.57</b>	<b>1,547.87</b>	<b>316.46</b>	<b>7.11</b>	<b>1,231.41</b>

(b) Average July working day.

AVERAGE JULY WORKING DAY					
HOURL	PV PRODUCTION (kWh)	TOTAL CONSUMPTION (kWh)	SELF-CONSUMPTION (kWh)	SURPLUS PV ENERGY (kWh)	GRID CONSUMPTION (kWh)
0-1	0.00	14.90	0.00	0.00	14.90
1-2	0.00	14.01	0.00	0.00	14.01
2-3	0.00	12.99	0.00	0.00	12.99
3-4	0.00	12.17	0.00	0.00	12.17
4-5	0.00	11.52	0.00	0.00	11.52
5-6	0.00	11.47	0.00	0.00	11.47
6-7	0.00	22.86	0.00	0.00	22.86
7-8	0.04	57.59	0.04	0.00	57.56
8-9	5.16	54.80	5.16	0.00	49.64
9-10	22.24	92.78	22.24	0.00	70.54
10-11	45.06	100.06	45.06	0.00	55.00
11-12	66.28	103.14	66.28	0.00	36.86
12-13	84.08	87.86	80.18	3.90	7.68
13-14	95.71	89.05	86.81	8.90	2.24
14-15	100.88	109.92	97.92	2.96	11.99
15-16	97.15	97.36	91.56	5.59	5.80
16-17	88.80	106.05	87.52	1.28	18.54
17-18	71.14	140.72	71.14	0.00	69.58
18-19	52.06	152.23	52.06	0.00	100.17
19-20	30.62	153.30	30.62	0.00	122.68
20-21	9.59	136.16	9.59	0.00	126.56
21-22	2.20	92.16	2.20	0.00	89.96
22-23	0.00	32.33	0.00	0.00	32.33
23-24	0.00	16.03	0.00	0.00	16.03
<b>TOTAL</b>	<b>771.01</b>	<b>1,721.46</b>	<b>748.38</b>	<b>22.63</b>	<b>973.08</b>



(a) Average January working day.



(b) Average July working day.

Figure 3.3. PV plant performance - Most sunny versus most cloudy day.

## PV PLANT - MONTHLY RESULTS DREAMFIT ALCORCÓN

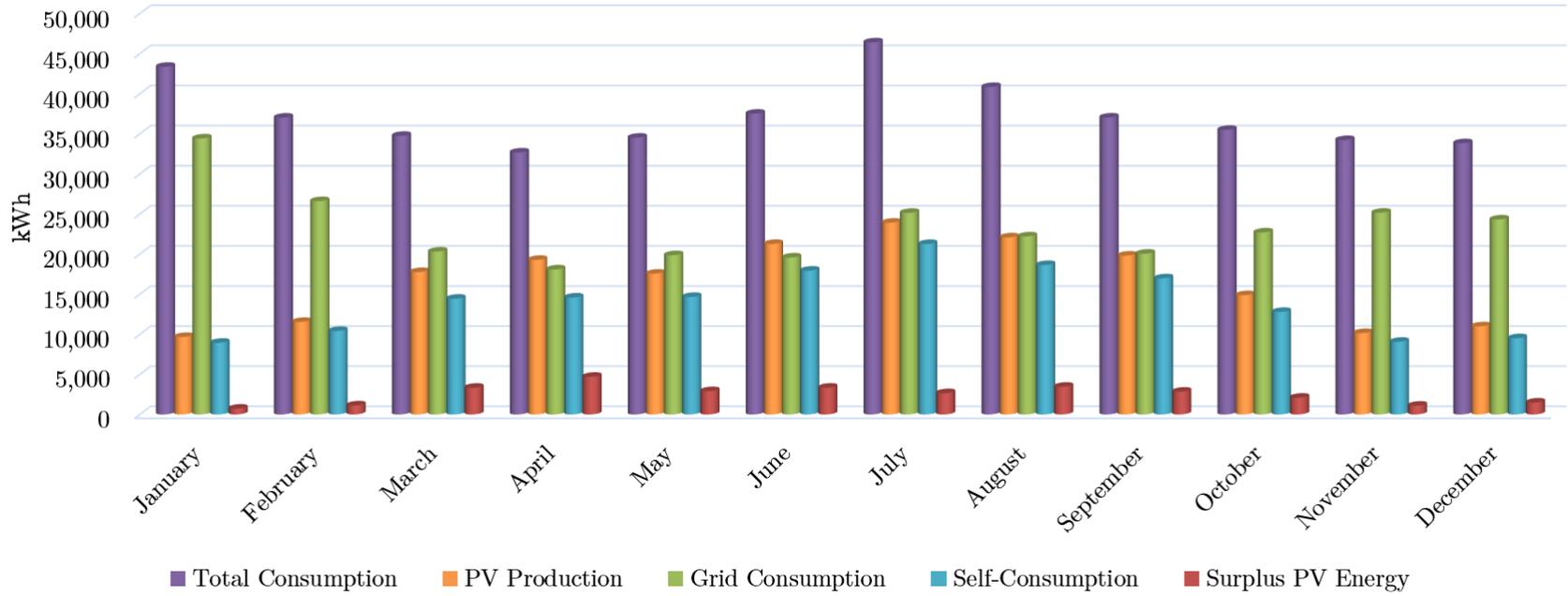


Figure 3.4. Monthly performance results of Dreamfit Alcorcón PV plant.

Analysing figure 3.3, there is an inverse relationship between the energy consumed from the grid and the photovoltaic production:

- **Average January Working Day.** It can be observed how during sunny hours the grid consumption gets visibly reduced. Additionally, almost no surplus energy is injected into the grid, since during working days Dreamfit opens from 7h to 23h and January is the month in which there are less Peak Sun Hours (PSH) according to the analysis.
- **Average July Working Day.** It can be observed how during sunny hours the grid consumption is almost null. A little bit more of surplus energy can be observed if compared with the average January working day, but it is consistent since July is the month in which there are more Peak Sun Hours (PSH) according to the analysis.

Delving into figure 3.4, it can be confirmed how there is a direct relationship between the PSH and the PV production. Additionally, the surplus energy is also greater during summer months, but it has to be remembered that most of the excessive energy is concentrated in Sundays due to Dreamfit opening hours, exactly as demonstrated in table 3.2.

The PV production study has been focused on the first year performance of the PV plant. Nonetheless, according to its data sheet, the PV modules experience a yearly power attenuation of 0.55%/year due to degradation over time. Although this fact has been considered in the economic assessment, a summary graphic of the PV production study is included taking into account the power attenuation. Basically, figure 3.5 compares monthly self-consumed energy in three representative years of the 25 years PV plant useful life.

Finally, table 3.4 is included as a main results overview, representing a numerical summary of the production study for the first year of the project. The table 3.4 is configured similarly to the *Balances and main results* table of the fourth page of the PVsyst Simulation Report in order to assess the accuracy of the production study developed with MATLAB. Then:

- **PSH.** Peak Sun Hours per month and year.
- **PV Production.** The energy produced by the PV plant corresponds partially with the *EArray* variable in the PVsyst report. The difference between them is that the PV Production considers all losses mentioned in subsection 3.1.2, whereas the *EArray* has not considered yet the solar inverter losses.
- **Total Consumption.** The total energy supplied to the user corresponds with the variable *E.User* in the PVsyst report.
- **Self-Consumption.** The self-consumed energy corresponds with *E.Solar* variable in the PVsyst report.
- **Surplus PV Energy.** The excessive energy injected into the grid corresponds with the *E.Grid* variable in the PVsyst report.
- **Grid Consumption.** The energy consumed from the DSO grid corresponds with the *EFrGrid* variable in the PVsyst report.

All in all, comparing table 3.4 with the *Balances and main results* table of the PVsyst Simulation Report, the analysis performed through MATLAB can be validated and therefore extrapolated to future Dreamfit PV projects ✓.

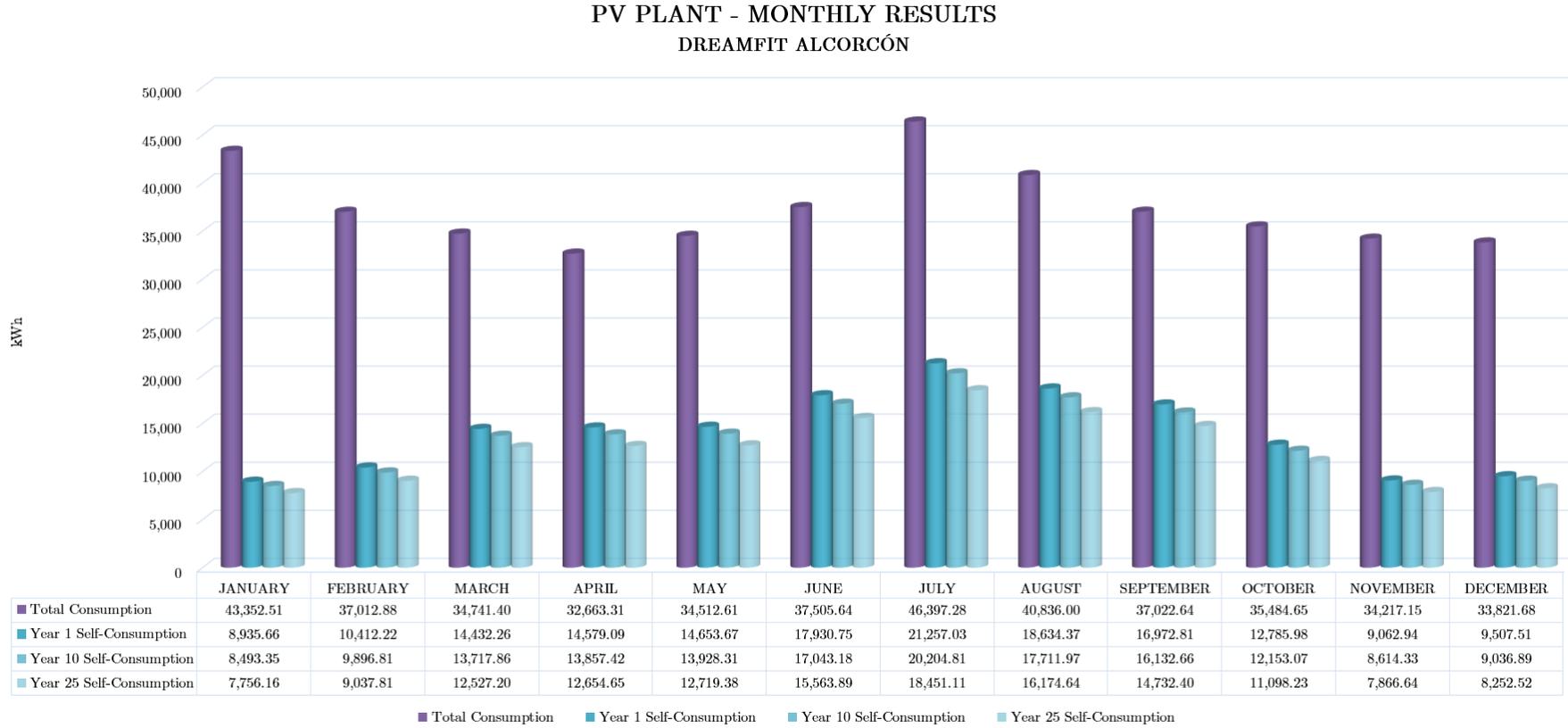


Figure 3.5. Production study - Balances and main results along the useful life of the project.

Table 3.4. Production study - Balances and main results.

<b>PV PRODUCTION STUDY - YEAR 1</b>						
<b>MONTH</b>	<b>PSH (h)</b>	<b>PV PRODUCTION <i>E</i>Array* (kWh)</b>	<b>TOTAL CONSUMPTION <i>E</i>_User (kWh)</b>	<b>SELF-CONSUMPTION <i>E</i>_Solar (kWh)</b>	<b>SURPLUS PV ENERGY <i>E</i>_Grid (kWh)</b>	<b>GRID CONSUMPTION <i>E</i>FrGrid (kWh)</b>
JANUARY	98.14	9,662.73	43,352.51	8,935.66	727.07	34,416.85
FEBRUARY	117.20	11,538.99	37,012.88	10,412.22	1,126.77	26,600.66
MARCH	180.40	17,761.94	34,741.40	14,432.26	3,329.68	20,309.14
APRIL	195.81	19,278.55	32,663.31	14,579.09	4,699.46	18,084.22
MAY	178.32	17,556.79	34,512.61	14,653.67	2,903.12	19,858.95
JUNE	216.00	21,266.38	37,505.64	17,930.75	3,335.63	19,574.89
JULY	242.88	23,912.75	46,397.28	21,257.03	2,655.71	25,140.24
AUGUST	224.32	22,085.82	40,836.00	18,634.37	3,451.44	22,201.63
SEPTEMBER	201.23	19,812.73	37,022.64	16,972.81	2,839.92	20,049.83
OCTOBER	151.10	14,877.22	35,484.65	12,785.98	2,091.24	22,698.67
NOVEMBER	103.13	10,153.56	34,217.15	9,062.94	1,090.61	25,154.20
DECEMBER	111.62	10,990.14	33,821.68	9,507.51	1,482.63	24,314.16
<b>YEAR</b>	<b>2,020.15</b>	<b>198,897.59</b>	<b>447,567.75</b>	<b>169,164.30</b>	<b>29,733.28</b>	<b>278,403.45</b>

\*EArray in PVSyst does not consider the solar inverter losses, while PV Production column represents actual available energy downstream the inverter.

## 3.2 Economic Study

The economic study of Dreamfit Alcorcón has also been carried out in two different ways:

1. **MATLAB®**. Function *economic.m* that assesses CAPEX and OPEX expenditures and evaluates the profitability of the project.
2. **PVsyst®**. Professional PV software utilised to replicate the system with the same hypothesis and assumptions in order to assess the accuracy of the economic analysis developed in MATLAB.

This section presents the results obtained through the MATLAB programming function, whereas the PVsyst analysis results have been included at the annexes.

### 3.2.1 Electricity Tariff 3.0TD

First of all, the electricity tariff of the facility has to be analysed in order to perform an economic study. Dreamfit Alcorcón has an electricity tariff 3.0TD since 1<sup>st</sup> June 2021 according to the last update of the Spanish regulation [59].

Electricity tariffs in Spain have two main items:

- **Fixed Term** based on the contracted power (kW) and including a possible overrun due to excess demanded power.
- **Variable Term** related to the actual consumed energy (kWh) and including a possible overrun due to reactive energy.

The main features of the Spanish 3.0TD electricity tariff are exposed below:

- Electricity tariff with six pricing periods and six contracted powers.
- The supplied voltage is lower than 1 kV.
- The contracted power is greater than 15 kW at least in the sixth period.
- The contracted powers have to verify equation 3.2 [60]:

$$P_1 \leq P_2 \leq P_3 \leq P_4 \leq P_5 \leq P_6 \quad (3.2)$$

#### 3.2.1.1 Seasons and Periods of Tariff 3.0TD

The electricity tariff 3.0TD counts with four seasons and six pricing periods [59]:

- **High Season.** January, February, July and December:
  - **P1** → 9 hours per day // **P2** → 7 hours per day // **P6** → 8 hours per day.
- **Medium-High Season.** March and November:
  - **P2** → 9 hours per day // **P3** → 7 hours per day // **P6** → 8 hours per day.
- **Medium Season.** June, August and September:
  - **P3** → 9 hours per day // **P4** → 7 hours per day // **P6** → 8 hours per day.
- **Low Season.** April, May and October:
  - **P4** → 9 hours per day // **P5** → 7 hours per day // **P6** → 8 hours per day.

Graphically, the distribution of periods along the 24 hours of a day in tariffs 3.0TD depending on the season are presented in figure 3.6:

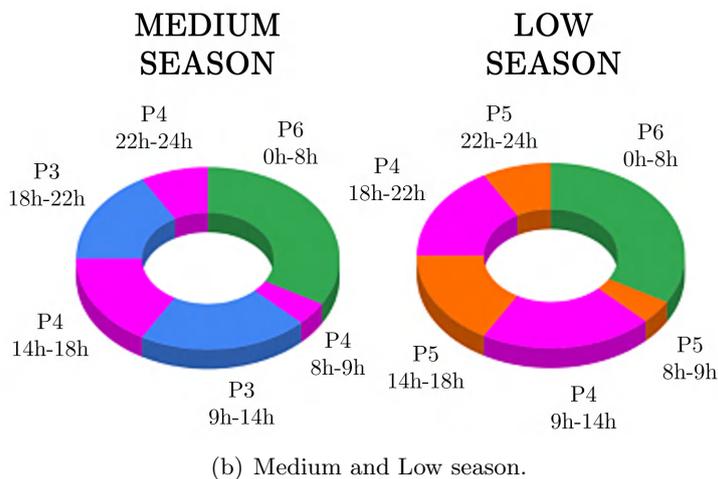
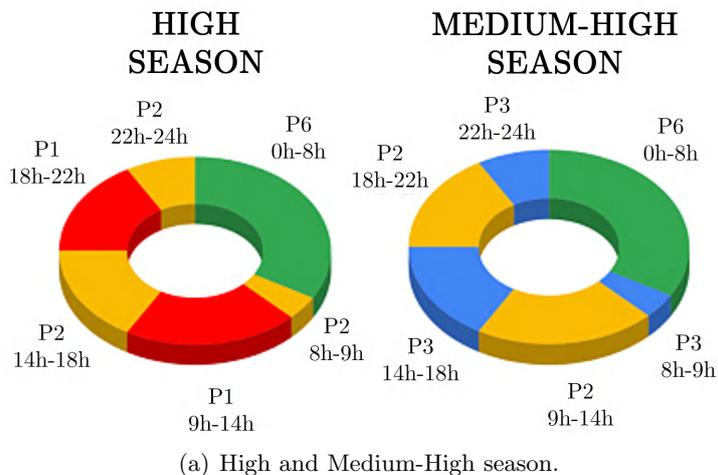


Figure 3.6. Electricity tariff 3.0TD seasons and pricing periods.

In terms of power cost, P1 is the most expensive period and P6 is the cheapest period. In fact, on Saturdays, Sundays and national bank holidays there are 24 hours per day of P6:



Figure 3.7. Electricity tariff 3.0TD at weekends and national bank holidays.

The programming function *economic.m* developed for the CAPEX & OPEX study of the project assesses grid consumption, self-consumption and energy surpluses hour by hour and month by month. Then, next table classifies tariff 3.0TD periods per hour and month:

Table 3.5. Monthly distribution of periods in electricity tariff 3.0TD.

ELECTRICITY TARIFF 3.0TD													
HOOR	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER	WEEKENDS BANK HOLIDAYS
0h-1h	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
1h-2h	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
2h-3h	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
3h-4h	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
4h-5h	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
5h-6h	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
6h-7h	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
7h-8h	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
8h-9h	P2	P2	P3	P5	P5	P4	P2	P4	P4	P5	P3	P2	P6
9h-10h	P1	P1	P2	P4	P4	P3	P1	P3	P3	P4	P2	P1	P6
10h-11h	P1	P1	P2	P4	P4	P3	P1	P3	P3	P4	P2	P1	P6
11h-12h	P1	P1	P2	P4	P4	P3	P1	P3	P3	P4	P2	P1	P6
12h-13h	P1	P1	P2	P4	P4	P3	P1	P3	P3	P4	P2	P1	P6
13h-14h	P1	P1	P2	P4	P4	P3	P1	P3	P3	P4	P2	P1	P6
14h-15h	P2	P2	P3	P5	P5	P4	P2	P4	P4	P5	P3	P2	P6
15h-16h	P2	P2	P3	P5	P5	P4	P2	P4	P4	P5	P3	P2	P6
16h-17h	P2	P2	P3	P5	P5	P4	P2	P4	P4	P5	P3	P2	P6
17h-18h	P2	P2	P3	P5	P5	P4	P2	P4	P4	P5	P3	P2	P6
18h-19h	P1	P1	P2	P4	P4	P3	P1	P3	P3	P4	P2	P1	P6
19h-20h	P1	P1	P2	P4	P4	P3	P1	P3	P3	P4	P2	P1	P6
20h-21h	P1	P1	P2	P4	P4	P3	P1	P3	P3	P4	P2	P1	P6
21h-22h	P1	P1	P2	P4	P4	P3	P1	P3	P3	P4	P2	P1	P6
22h-23h	P2	P2	P3	P5	P5	P4	P2	P4	P4	P5	P3	P2	P6
23h-24h	P2	P2	P3	P5	P5	P4	P2	P4	P4	P5	P3	P2	P6

In conclusion, it can be observed that there are four type of months along the year which coincide with the four predefined seasons. Additionally, there are at least eight P6 hours per day with the cheapest power-term prices independently of the season.

### 3.2.1.2 Power Fixed Term of Tariff 3.0TD

The fixed power term is charged monthly depending on the contracted power per period and the fixed price per period settled with the energy supplier regarding table 3.5. In this particular case, hypothetical power prices have been consulted to a professional Spanish company devoted to energy services, electrical engineering and renewable energies: Symelec Renovables® [61].

Then, the hypothetical power prices per period for the economic study are presented below:

- **P1 Power Price.** 0.053690 €/kW-day.
- **P2 Power Price.** 0.037759 €/kW-day.
- **P3 Power Price.** 0.019193 €/kW-day.
- **P4 Power Price.** 0.016729 €/kW-day.
- **P5 Power Price.** 0.012053 €/kW-day.
- **P6 Power Price.** 0.007225 €/kW-day.

Currently, the contracted powers in Dreamfit Alcorcón are:

- $P_1 = 143 \text{ kW}$ .
- $P_2 = P_3 = P_4 = P_5 = P_6 = 155 \text{ kW}$ .

Then, the current contracted powers of Dreamfit Alcorcón verify equation 3.2 ✓.

### 3.2.1.3 Excessive Power Penalty of Tariff 3.0TD

As the maximum contracted power is greater than 50 kW, the demanded power per period is assessed on a 15-minutes basis and charged monthly in case of exceeding the contracted power evaluating the so-called power load profile of the consumer.

Then, the excessive power is charged according to the following equation:

$$F_{EP} = \sum_{i=1}^6 K_i \cdot 1.406368 \cdot \sqrt{\sum_{j=1}^n (P_{d_j} - P_{C_i})^2} \quad (3.3)$$

Where:

- $F_{EP}$  → Monthly excessive demanded power charge [€].
- $K_i$  → Pricing coefficient per period  $i$  [€/kW]:
  - **P1.** 1 €/kW.
  - **P2.** 0.873773 €/kW.
  - **P3.** 0.35234 €/kW.
  - **P4.** 0.267883 €/kW.
  - **P5.** 0.107572 €/kW.
  - **P6.** 0.107572 €/kW.
- $P_{d_j}$  → Demanded power at the  $n$  15-minutes intervals in which the demanded power of the period  $i$  has exceeded the contracted power of that period [kW].
- $P_{C_i}$  → Contracted power in the period  $i$  [kW].

### 3.2.1.4 Energy Term of Tariff 3.0TD

The variable energy term is charged monthly depending on the active energy consumption per period and the price per kilowatt-hour settled with the energy supplier regarding table 3.5. Once again, hypothetical energy prices have been consulted to a professional company devoted to energy services, electrical engineering and renewable energies: Symelec Renovables® [61].

Then, the hypothetical energy prices per period for the economic study are presented below:

- **P1 Energy Price.** 0.207797 €/kWh.
- **P2 Energy Price.** 0.184083 €/kWh.
- **P3 Energy Price.** 0.153379 €/kWh.
- **P4 Energy Price.** 0.130097 €/kWh.
- **P5 Energy Price.** 0.108142 €/kWh.
- **P6 Energy Price.** 0.110010 €/kWh.

### 3.2.1.5 Reactive Energy Penalty of Tariff 3.0TD

There is a penalty if excessive reactive-inductive energy is consumed in periods P1 to P5. Specifically, there is an economic extra charge if the monthly reactive-inductive energy consumed exceeds the 33% of the active energy consumption, id est, reactive energy will be charged monthly if the power factor is lower than 0.95.

Graphically:

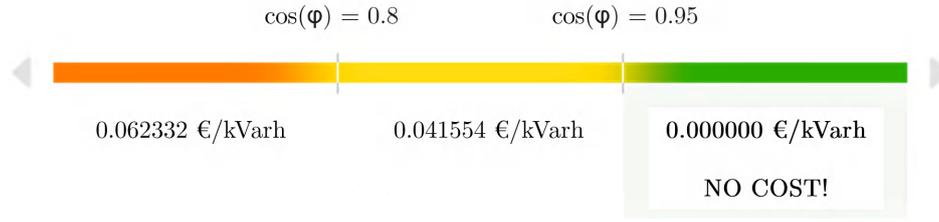


Figure 3.8. Reactive energy penalty for electricity tariff 3.0TD.

The reactive energy is computed applying the following equation:

$$\cos(\phi) = \frac{E_a}{\sqrt{E_a^2 + E_r^2}} \quad (3.4)$$

Where:

- $\cos(\phi) \rightarrow$  Power factor  $\in [0, 1]$  [-].
- $E_a \rightarrow$  Active energy consumption [kWh].
- $E_r \rightarrow$  Reactive-inductive energy consumption [kWh].

Analysing the thresholds showed in figure 3.8 for which reactive energy is charged:

- $\cos(\phi) = 0.95 \iff E_r > 0.33 \cdot E_a$ .
- $\cos(\phi) = 0.8 \iff E_r > 0.75 \cdot E_a$ .

Thus, the excessive reactive-inductive energy is charged through the following expression<sup>2</sup>:

$$ER = \sum_{i=1}^5 [E_{R_i} - 0.33 \cdot E_{A_i}] \cdot t_{ER} \quad (3.5)$$

Where:

- $ER \rightarrow$  Excessive reactive-inductive energy charge of the six periods [€].
- $E_{R_i} \rightarrow$  Reactive-inductive energy actually consumed in the period  $i$  [kVarh].
- $E_{A_i} \rightarrow$  Active energy actually consumed in the period  $i$  [kWh].
- $t_{ER} \rightarrow$  Price of the excessive reactive-inductive energy [€/kVarh]:
  - $t_{ER} = 0$ , if  $\cos(\phi) \geq 0.95$ .
  - $t_{ER} = 0.041554$  €/kVarh, if  $\cos(\phi) \in [0.80, 0.95)$ .
  - $t_{ER} = 0.062332$  €/kVarh, if  $\cos(\phi) < 0.80$ .

According to Spanish regulation, there is no penalty at all for the reactive-capacitive energy in the 3.0TD electricity tariff, as well as there is no penalty for any kind of reactive energy in the sixth period. Nonetheless, Dreamfit Alcorcón has not reactive energy penalties due to the existence of shunt capacitive compensation.

Additionally, the solar inverter SUN2000-100KTL-M1 includes mechanisms to govern the power factor of the generated energy, ensuring that reactive power remains controlled. Therefore, it has been demonstrated why the reactive energy does not need to be considered at the economic analysis of Dreamfit Alcorcón PV plant.

<sup>2</sup>The summation in equation 3.5 does not consider P6 since there are no reactive penalties in the sixth period.

### 3.2.2 Simplified Compensation Mechanism

Dreamfit Alcorcón PV plant will inject surplus energy into the distribution network. In Spain, the Royal Decree 244/2019 regulates the surplus energy simplified compensation mechanism for self-consumption purposes:

- The energy source must be renewable ✓.
- The rated power of the generation plant cannot exceed 100 kW ✓.

The surplus energy is injected into the DSO grid and assessed hour by hour. Then, energy consumed from the grid as well as the energy injected into the grid are balanced hourly:

- **Hourly Net Balance.** If the difference between grid injection and grid consumption is negative, this difference is considered as grid consumption and charged normally.
- **Simplified Compensation.** If the difference between grid injection and consumption is positive, this difference is considered as surplus energy and economically compensated.

Graphically, being  $E_h(i)$  the Energy Injected into the Grid,  $E_h(c)$  the Energy Consumed from the Grid and  $E_h(b) = E_h(i) - E_h(c)$  the Grid Balance between injection and consumption:

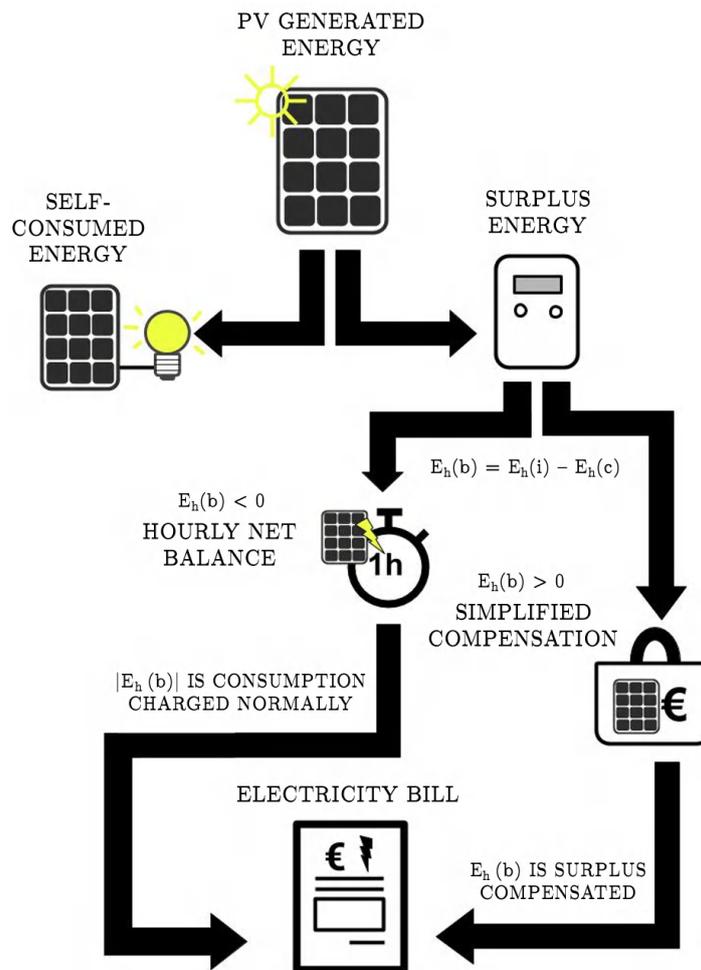


Figure 3.9. Simplified Energy Compensation Mechanism [62].

In case of energy surpluses, the compensation mechanism works as follows:

- The compensation process takes place monthly and it is not cumulative.
- The **economic value** of the surplus energy is discounted from the **economic value** of the grid consumption energy.
- The maximum economic value compensated cannot exceed the economic value of the grid consumption. Hence, if the economic value of the compensated energy is greater than the economic value of the grid consumption, the actual energy economic charge will be 0€.
- The compensation cost per *kWh* injected into the grid is agreed between the supplier company and the prosumer.

### 3.2.3 Economic Study Algorithm Explanation - *economic.m*

The profitability of the project PV plant has been analysed by means of the programming function *economic.m*, which determines the payback period of the plant as well as the optimal powers to contract at the six periods once the PV modules are installed.

The algorithm has been developed programming in MATLAB® [29] and uses as input the same *data* matrix required for function *tfm.m* explained in subsection 2.2. The program also requires as input data the performance ratio of the PV plant and the PV peak power installed, which is obtained as an output of the *tfm.m* function mentioned above.

The function requires also hypothetical economical data as input: the initial investment cost of the project, the energy and power costs per period for the tariff 3.0TD, the annual maintenance cost of the DER as well as the Consumer Price Index (CPI) and the annual power attenuation rate of the modules.

The operating procedure followed by the function *economic.m* is explained below:

1. **Weekday Computation.** Once the code is executed, the function asks the programmer to enter the weekday of the 1st of January of the analysed year. Then, the program assigns the corresponding number between 1 (Monday) to 7 (Sunday) to the 8,760 rows of the *data* matrix, id est, each hour of the analysed year is assigned to its weekday.
2. **Consumption Distribution.** The program allocates per period and month the total energy demanded by the gym, the energy surpluses, the PV production as well as the energy consumed from the grid. Thus, a loop is executed distinguishing among months, weekdays and bank holidays based on the information provided in table 3.5 (tariff 3.0TD).
3. **Optimal Power per Period.** The function determines the six optimal contracted powers when the PV plant is included. Hence, the algorithm takes into account the assumptions done in terms of power prices for the fixed part and the equation 3.3 for the power penalty part. Consequently, the function computes a vector of six powers that makes the annual cost of the total power term minimum, id est, the powers that minimise the sum of the two terms presented in subsections 3.2.1.2 and 3.2.1.3 for a 3.0TD tariff:

$$power_{opt} = [p1, \dots, p6] \iff \min(\text{Power Term Total Cost}) \quad (3.6)$$

4. **Power Penalty Cost.** The month by month cost of the penalty cost due to power excesses having and not having the PV plant are computed. Data for 25 years is obtained since the useful life of modules are 25 years according to its data sheet.

5. **Energy Term Total Cost.** The month by month cost of the energy consumed from the grid having and not having the PV plant as well as the energy surpluses are computed. Hence, the algorithm takes into account the assumptions done in terms of energy prices. Once again, data for the useful 25 years of the facility is gathered.
6. **Power Term Total Cost.** The month by month fixed power cost is established having and not having the PV plant for the following 25 years. The results obtained are added to the power penalty cost in order to compute the total power cost per year.
7. **Payback Period Computation.** Considering all the economic information mentioned above, the electrical tax which in Spain takes a value of 5.11% and the maintenance cost as well as the initial investment, the payback period of the project is obtained.

The inclusion of a PV plant for self-consumption at the roof of Dreamfit Alcorcón has direct consequences in terms of the contracted powers. Although the 15-minutes power load profile of Dreamfit Alcorcón have been requested to the distribution company, the data has not been received before the deadline of the Master Thesis submission. Thus, the optimal contracted powers have been established utilising the hourly consumption curve of the facility.

In this sense, the hourly consumption of Dreamfit Alcorcón has been allocated at the corresponding quarter to analyse the demanded power. Nonetheless, in order to minimise possible errors due to the usage of this approximation, a 20% security factor has been applied, id est, the hourly grid consumption has been multiplied by 1.2 to be treated as 15-minutes power data.

### 3.2.4 Results of the Economic Study

This section includes the highlights of the economic study developed in MATLAB for Dreamfit Alcorcón PV plant. Then, the hypothetical economical data used to perform the CAPEX & OPEX analysis are presented below:

Table 3.6. Economical hypothesis for Dreamfit Alcorcón PV plant.

HYPOTHESIS - PV PLANT ECONOMICAL DATA	
Location	DREAMFIT ALCORCÓN
Facility Useful Life	> 25 years
PV Plant Peak Power	111.1 kW
Initial Investment (VAT not included)	100,395.22 €
Annual O&M Cost	5,000 €/year
Expected Production	198,897.59 kWh/year
CPI Overrun	2.02%/year
PV Modules Power Attenuation	0.55%/year
Surplus Compensated Energy Price	0.05 €/kWh
Surplus Depreciation Rate	1.5%/year
Payback Period	4 years

As prices always rise, Consumer Price Index has been considered to perform the economic analysis. Since the useful life of the PV plant are 25 years, the CPI included in table 3.6 is the average Consumer Price Index of the last 25 years in Spain [63].

The PV power attenuation presented in table 3.6 has been obtained from the PV modules data sheet. Exactly as power and energy prices per period, the hypothetical price paid per  $kWh$  compensated as well as its depreciation rate showed in table 3.6 have been consulted to a professional company devoted to energy services, electrical engineering and renewable energies: Symelec Renovables® [61].

After running the algorithm, the optimal contracted powers per period as well as the payback period returned by the programming function *economic.m* are presented below:

MATLAB Command Window

```
>> [power_opt, payback_period] = economic()
Enter the PV peak power installed at the photovoltaic field: 111
Enter the week day of the 1st of January of the analysed year
if MONDAY = 1 and SUNDAY = 7: 2

power_opt =

    135    135    135    135    135    155

payback_period =

     4

>>
```

Figure 3.10. Optimal contracted powers and payback period returned by MATLAB.

Then, it can be seen that the payback period is actually 4 years as stated in table 3.6. Delving into the contracted powers, the PV plant enables a slightly reduction in the five first periods. Nonetheless, if the actual power load curves were available, optimal contracted powers would be lower, but as explained in subsection 3.2.3, a security coefficient has been applied since consumption has been treated as power to perform the economic analysis.

Moreover, the sixth period power has been forced to be 155  $kW$  in order to preserve the so-called *extent right* since P6 is the cheapest power period [64]:

Table 3.7. Contracted powers with and without PV plant.

CONTRACTED POWERS		
PERIOD	CURRENT POWERS WITHOUT PV PLANT	OPTIMISED POWERS WITH PV PLANT
P1	143 kW	135 kW
P2	155 kW	135 kW
P3	155 kW	135 kW
P4	155 kW	135 kW
P5	155 kW	135 kW
P6	155 kW	155 kW

Next figure presents the annual allocation of total consumption, PV production, grid consumption, self-consumption and surpluses per period provided by the *economic.m* function<sup>3</sup>:

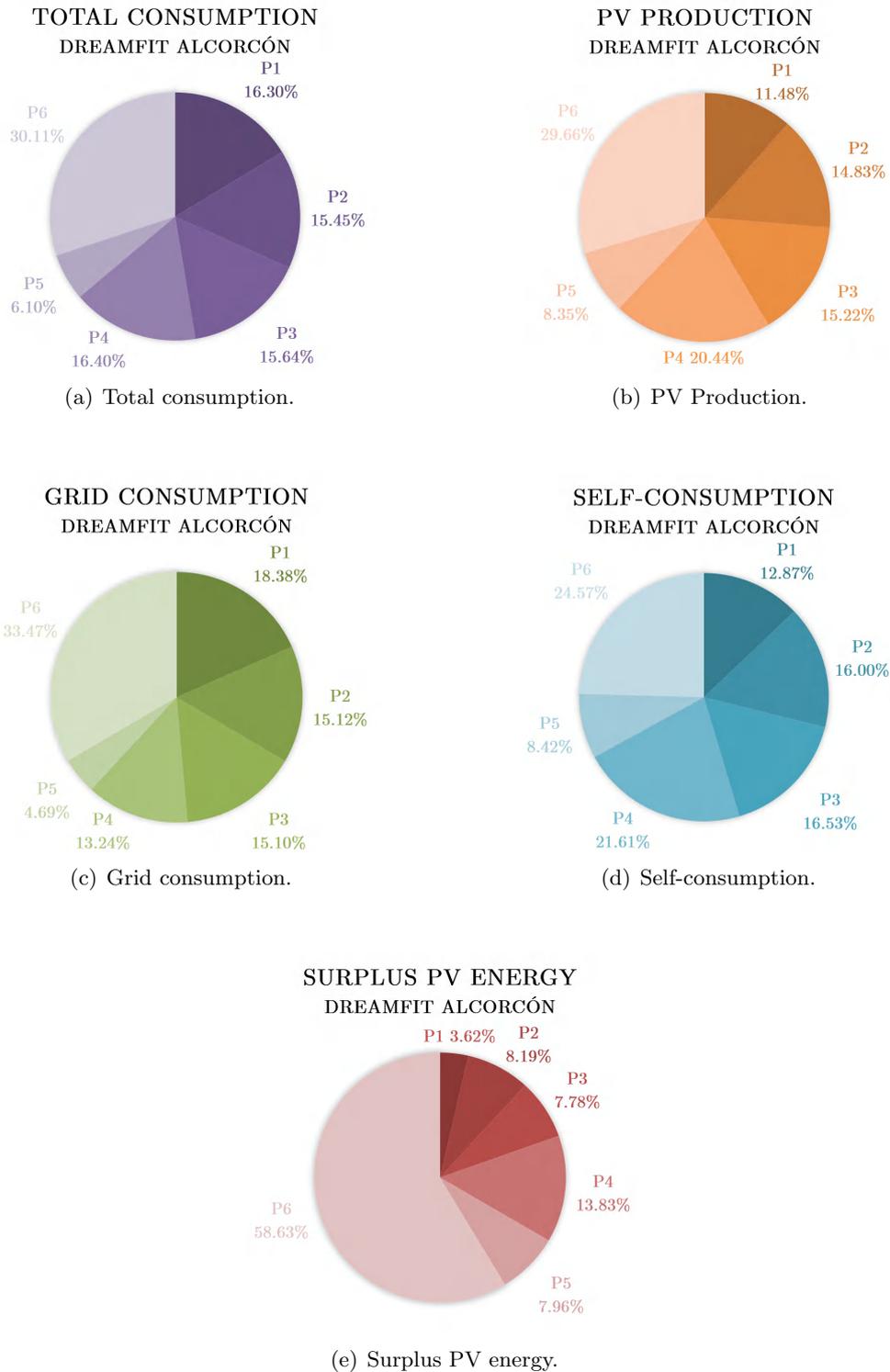


Figure 3.11. Tariff 3.0TD - Annual consumption allocation per period of Dreamfit Alcorcón.

<sup>3</sup>The purport of each element presented in figure 3.11 is explained in subsection 3.1.1.

The expected useful life of the project are 25 years, so next two pages include detailed tables 3.8 and 3.9 with all the incomes and expenses separated per pricing periods when appropriate. The economic analysis has been done comparing the current situation without PV plant versus the future status with the DER installed. The power and energy prices utilised are the aforementioned in subsections 3.2.1.2 and 3.2.1.4 respectively, whereas the rest of the utilised economic hypothetical data and rates are available in table 3.6.

The annual Operation and Maintenance Cost (O&M) of the PV plant has been consulted to the same engineering company as the rest of the project budget: Elecnor® [65], which is a multinational company specialised in renewable energy projects. It must be taken into account that there is no operation and maintenance cost considered for the first year of the project since it is included in the construction work contract.

Analysing tables 3.8 and 3.9 with year 1 and year 25 detailed economical data:

- Grid consumption increases year by year, while self-consumption and energy surpluses decreases over time. This fact is consistent with the power attenuation rate of the PV modules according to its data sheet.
- Energy and fixed power term total costs as well as O&M costs increase over time consistently with the CPI index.
- It has been supposed that the electricity tax will remain constant with a value of 5.11%.
- It has been considered that the pricing period coefficient for power penalty prices will remain constant over the following 25 years respecting equation 3.3.
- The actual charge considering the compensation mechanism increases year by year not only due to the hypothetical increase of energy prices and the modules' power attenuation rate, but also because it has been considered that the economic value of energy surplus will decrease with a 1.5% annual rate (according to table 3.6).

Finally, table 3.10 presents the economic balance and main results along the 25 years of the project useful life. Capital Expenditures (CAPEX) as well as Operational Expenditures (OPEX) have been considered, providing the year by year cash flows and the cumulative profit.

According to the utilised hypothesis regarding table 3.10, if energy prices rise according to Consumer Price Index (CPI), cash flows will increase slightly year by year regardless of modules' power attenuation. In fact, regarding the cumulative profit it can be confirmed that the project is expected to be profitable as of the fourth year, when the cumulative balance between expenses and incomes becomes positive.

Note that the Value Added Tax (VAT) has not been considered to perform the CAPEX & OPEX analysis of Dreamfit Alcorcón PV plant.

At this point, the profitability of the project is assessed through the Internal Rate of Return (IRR) and the PayBack Period. Hence, the IRR of the 25-year project is computed applying the following equation with the Cash Flows (CF) presented in table 3.10:

$$0 = \sum_{n=0}^{25} \frac{CF_n}{(1 + IRR)^n} \rightarrow \boxed{IRR = 25.96\%} \quad (3.7)$$

The PayBack Period (PB) is computed applying the following equation:

$$0 = \sum_{n=0}^{PB} CF_n \quad (3.8)$$

Then, taking into account that the summation of cash flows which represent the cumulative profit becomes positive between the third and the fourth year of the project lifetime:

$$PB = 3 \text{ years} + \frac{1}{CF_4} \cdot \sum_{n=0}^3 CF_n \text{ years} = 3.86 \text{ years} \rightarrow \boxed{PB \approx 4 \text{ years}} \quad (3.9)$$

Additionally, the payback period is evaluated graphically in figure 3.12. The figure assesses the summation of cash flows considering CPI index as well as any other economical rate mentioned in table 3.6, id est, the figure shows also the Net Present Value (NPV) of the project:

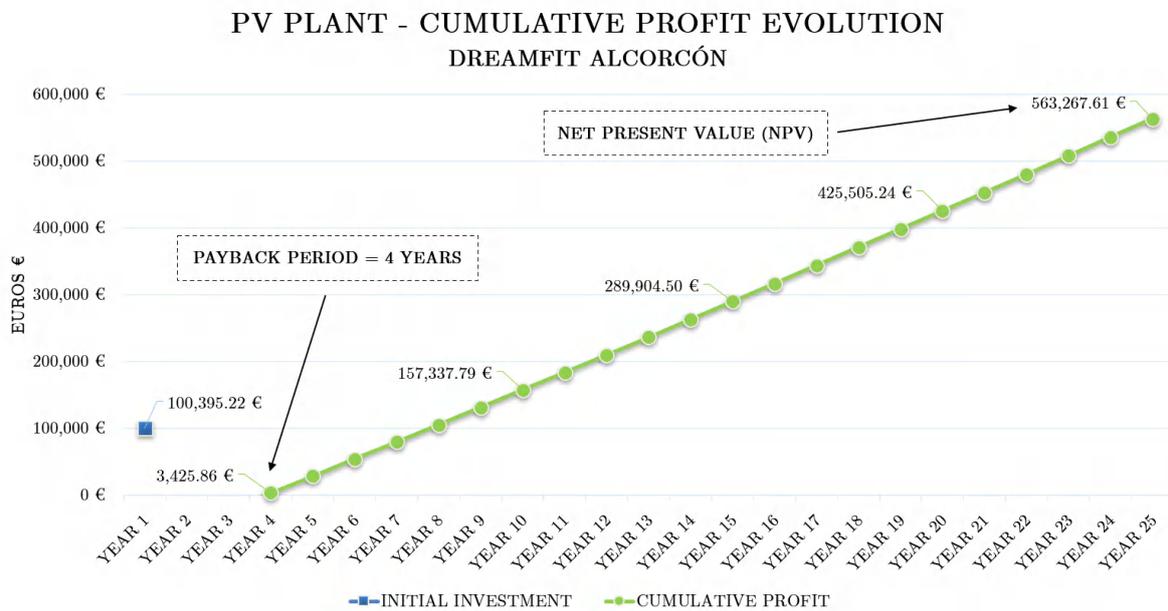


Figure 3.12. Cumulative profit evolution of Dreamfit Alcorcón PV plant.

Then, the profitability and the payback period of the PV plant project are:

$$\boxed{IRR = 25.96\%} \quad \boxed{Payback Period = 4 \text{ years}} \quad (3.10)$$

Furthermore, table 3.10 as well as figure 3.12 and equation 3.10 reveal that the PV project of Dreamfit Alcorcón will recover the initial investment in four years with an IRR greater than the 25% along the useful life of the Distributed Energy Resource.

In conclusion, the Dreamfit Alcorcón PV plant project is profitable.

All in all, comparing table 3.10 with the *Detailed economic results* table of the PVsyst Simulation Report as well as the payback period, the Net Present Value or any other economical parameter, it can be concluded that the analysis performed through MATLAB is valid. Therefore, the *economic.m* function can be extrapolated to future Dreamfit PV projects ✓.

Table 3.8. Economic study - Detailed results for the first useful year.

DREAMFIT ALCORCÓN PV PLANT - ECONOMIC ANALYSIS																																					
YEAR 1	JANUARY			FEBRUARY			MARCH			APRIL			MAY			JUNE			JULY			AUGUST			SEPTEMBER			OCTOBER			NOVEMBER			DECEMBER			TOTAL
	P1	P2	P6	P1	P2	P6	P2	P3	P6	P4	P5	P6	P4	P5	P6	P3	P4	P6	P1	P2	P6	P3	P4	P6	P3	P4	P6	P4	P5	P6	P2	P3	P6	P1	P2	P6	
TOTAL CONSUMPTION (MWh)	19.3	10.8	13.2	15.9	9.1	12.0	14.6	8.4	11.7	14.0	7.7	10.9	12.7	10.0	11.7	16.9	9.1	11.5	23.2	12.9	10.3	19.4	11.0	10.5	17.3	9.6	10.1	17.0	9.6	9.0	14.5	7.9	11.8	14.5	7.3	12.0	447.57
GRID CONSUMPTION (MWh)	15.1	7.9	11.5	11.6	5.8	9.2	8.7	3.8	7.8	7.9	2.9	7.3	6.6	5.7	7.5	10.1	3.3	6.2	14.1	4.7	6.3	12.0	4.0	6.2	10.7	3.5	5.8	11.5	4.4	6.8	10.5	5.5	9.2	10.4	4.5	9.4	278.40
SELF-CONSUMPTION (MWh)	4.3	2.9	1.8	4.3	3.3	2.8	5.9	4.6	3.9	6.2	4.8	3.6	6.1	4.3	4.3	6.8	5.8	5.3	9.1	8.1	4.0	7.4	7.0	4.3	6.7	6.1	4.2	5.4	5.2	2.2	4.1	2.5	2.6	4.1	2.8	2.6	169.16
SURPLUS PV ENERGY (MWh)	0.1	0.0	0.6	0.4	0.3	0.5	1.0	0.6	1.7	0.9	1.6	2.3	0.8	0.3	1.8	0.6	0.7	2.0	0.3	0.2	2.1	0.3	0.3	2.8	0.6	0.6	1.6	0.8	0.5	0.8	0.5	0.1	0.4	0.3	0.3	0.8	29.73
DREAMFIT ALCORCÓN - ANNUAL ELECTRICITY COST WITHOUT PV PLANT:																																					
ACTIVE ENERGY (THOUSAND €)	4.02	1.98	1.46	3.31	1.68	1.32	2.69	1.30	1.29	1.83	0.83	1.20	1.66	1.08	1.29	2.59	1.19	1.26	4.82	2.37	1.14	2.97	1.43	1.16	2.66	1.25	1.11	2.21	1.04	0.98	2.67	1.22	1.29	3.01	1.34	1.32	65.95
REACTIVE ENERGY (THOUSAND €)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FIXED POWER P1-P6 (THOUSAND €)	0.68			0.62			0.68			0.66			0.68			0.66			0.68			0.68			0.66			0.68			0.66			0.68			8.06
POWER PENALTY (THOUSAND €)	0.15	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.21	0.03	0.00	1.01	0.34	0.00	0.11	0.03	0.00	0.06	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	2.20
TAX 5.11269632% (THOUSAND €)	0.42			0.36			0.30			0.23			0.24			0.30			0.53			0.33			0.29			0.25			0.30			0.33			3.90
TOTAL (THOUSAND €)	8.72			7.40			6.26			4.76			4.97			6.25			10.89			6.71			6.05			5.18			6.15			6.78			80.11
DREAMFIT ALCORCÓN - ANNUAL ELECTRICITY COST WITH PV PLANT:																																					
ACTIVE ENERGY (THOUSAND €)	3.13	1.45	1.26	2.42	1.07	1.01	1.61	0.59	0.85	1.02	0.32	0.80	0.86	0.62	0.82	1.54	0.43	0.68	2.93	0.87	0.69	1.84	0.52	0.69	1.64	0.46	0.64	1.50	0.48	0.74	1.93	0.84	1.01	2.15	0.83	1.04	41.29
PV COMPENSATION (THOUSAND €)	0.00	0.00	0.03	0.02	0.01	0.02	0.05	0.03	0.08	0.04	0.08	0.11	0.04	0.02	0.09	0.03	0.03	0.10	0.01	0.01	0.11	0.02	0.02	0.14	0.03	0.03	0.08	0.04	0.02	0.04	0.03	0.01	0.02	0.02	0.02	0.04	1.49
ACTUAL CHARGE (THOUSAND €)	3.13	1.45	1.23	2.40	1.05	0.98	1.56	0.56	0.77	0.98	0.24	0.69	0.82	0.60	0.73	1.51	0.40	0.58	2.92	0.86	0.59	1.83	0.50	0.55	1.61	0.43	0.56	1.46	0.45	0.70	1.90	0.83	0.99	2.14	0.81	1.00	39.80
FIXED POWER P1-P6 (THOUSAND €)	0.62			0.56			0.62			0.60			0.62			0.60			0.62			0.62			0.60			0.62			0.60			0.62			7.28
POWER PENALTY (THOUSAND €)	0.12	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.17	0.00	0.55	0.00	0.00	0.11	0.00	0.00	0.08	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	1.17
TAX 5.11269632% (THOUSAND €)	0.33			0.26			0.18			0.13			0.14			0.17			0.28			0.18			0.17			0.17			0.22			0.23			2.47
MAINTENANCE (THOUSAND €)	0.00			0.00			0.00			0.00			0.00			0.00			0.00			0.00			0.00			0.00			0.00			0.00			0.00
TOTAL (THOUSAND €)	6.88			5.34			3.68			2.64			2.94			3.42			5.81			3.78			3.44			3.44			4.55			4.81			50.71

Table 3.9. Economic study - Detailed results for the last useful year.

DREAMFIT ALCORCÓN PV PLANT - ECONOMIC ANALYSIS																																								
YEAR 25	JANUARY			FEBRUARY			MARCH			APRIL			MAY			JUNE			JULY			AUGUST			SEPTEMBER			OCTOBER			NOVEMBER			DECEMBER			TOTAL			
	P1	P2	P6	P1	P2	P6	P2	P3	P6	P4	P5	P6	P4	P5	P6	P3	P4	P6	P1	P2	P6	P3	P4	P6	P3	P4	P6	P4	P5	P6	P2	P3	P6	P1	P2	P6				
TOTAL CONSUMPTION (MWh)	19.3	10.8	13.2	15.9	9.1	12.0	14.6	8.4	11.7	14.0	7.7	10.9	12.7	10.0	11.7	16.9	9.1	11.5	23.2	12.9	10.3	19.4	11.0	10.5	17.3	9.6	10.1	17.0	9.6	9.0	14.5	7.9	11.8	14.5	7.3	12.0	447.57			
GRID CONSUMPTION (MWh)	15.6	8.3	11.7	12.2	6.2	9.5	9.5	4.4	8.3	8.7	3.6	7.8	7.4	6.3	8.0	11.0	4.1	6.9	15.3	5.8	6.8	13.0	4.9	6.8	11.5	4.3	6.4	12.2	5.1	7.1	11.0	5.8	9.5	10.9	4.9	9.8	300.73			
SELF-CONSUMPTION (MWh)	3.7	2.5	1.5	3.7	2.9	2.4	5.1	4.0	3.4	5.4	4.1	3.1	5.3	3.7	3.7	5.9	5.0	4.6	7.9	7.1	3.5	6.4	6.1	3.7	5.8	5.3	3.7	4.7	4.5	1.9	3.5	2.1	2.2	3.6	2.4	2.2	146.83			
SURPLUS PV ENERGY (MWh)	0.1	0.0	0.5	0.3	0.2	0.4	0.9	0.5	1.5	0.7	1.4	2.0	0.7	0.3	1.5	0.5	0.6	1.8	0.3	0.2	1.9	0.3	0.3	2.4	0.5	0.6	1.4	0.7	0.4	0.7	0.5	0.1	0.4	0.3	0.3	0.7	25.81			
DREAMFIT ALCORCÓN - ANNUAL ELECTRICITY COST WITHOUT PV PLANT:																																								
ACTIVE ENERGY (THOUSAND €)	5.97	2.94	2.16	4.91	2.49	1.96	3.99	1.92	1.91	2.71	1.24	1.79	2.46	1.61	1.92	3.85	1.77	1.87	7.16	3.52	1.69	4.41	2.12	1.72	3.95	1.85	1.65	3.27	1.54	1.46	3.97	1.81	1.92	4.47	1.99	1.97	97.93			
REACTIVE ENERGY (THOUSAND €)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
FIXED POWER P1-P6 (THOUSAND €)	1.02			0.92			1.02			0.98			1.02			0.98			1.02			0.98			1.02			0.98			1.02			0.98			1.02			11.97
POWER PENALTY (THOUSAND €)	0.15	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.21	0.03	0.00	1.01	0.34	0.00	0.11	0.03	0.00	0.06	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	2.20
TAX 5.11269632% (THOUSAND €)	0.63			0.53			0.45			0.34			0.36			0.45			0.75			0.48			0.44			0.37			0.44			0.49			0.53			
TOTAL (THOUSAND €)	12.87			10.93			9.29			7.06			7.37			9.16			15.48			9.89			8.95			7.68			9.12			10.02			117.82			
DREAMFIT ALCORCÓN - ANNUAL ELECTRICITY COST WITH PV PLANT:																																								
ACTIVE ENERGY (THOUSAND €)	4.82	2.26	1.91	3.77	1.70	1.56	2.60	1.01	1.35	1.68	0.57	1.27	1.44	1.01	1.31	2.50	0.79	1.12	4.72	1.59	1.12	2.96	0.94	1.11	2.63	0.84	1.05	2.36	0.82	1.15	3.01	1.32	1.56	3.37	1.33	1.60	66.14			
PV COMPENSATION (THOUSAND €)	0.00	0.00	0.02	0.01	0.01	0.01	0.01	0.01	0.03	0.02	0.05	0.02	0.04	0.06	0.02	0.01	0.05	0.02	0.02	0.06	0.01	0.01	0.06	0.01	0.01	0.08	0.02	0.02	0.04	0.02	0.01	0.02	0.02	0.00	0.01	0.01	0.01	0.02	0.83	
ACTUAL CHARGE (THOUSAND €)	4.82	2.26	1.90	3.76	1.69	1.54	2.57	0.99	1.31	1.65	0.53	1.21	1.42	1.00	1.26	2.48	0.77	1.07	4.71	1.58	1.06	2.95	0.93	1.03	2.61	0.82	1.00	2.34	0.80	1.13	2.99	1.32	1.55	3.36	1.32	1.58	65.31			
FIXED POWER P1-P6 (THOUSAND €)	0.92			0.83			0.92			0.89			0.92			0.89			0.92			0.89			0.92			0.89			0.92			0.89			0.92			10.81
POWER PENALTY (THOUSAND €)	0.36	0.08	0.01	0.19	0.06	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.00	0.26	0.00	0.00	0.91	0.01	0.00	0.20	0.01	0.00	0.17	0.00	0.00	0.09	0.00	0.00	0.08	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	2.57
TAX 5.11269632% (THOUSAND €)	0.53			0.41			0.30			0.22			0.24			0.28			0.47			0.31			0.28			0.27			0.35			0.37			4.02			
MAINTENANCE (THOUSAND €)	0.62			0.62			0.62			0.62			0.62			0.62			0.62			0.62			0.62			0.62			0.62			0.62			7.42			
TOTAL (THOUSAND €)	11.48			9.11			6.71			5.12			5.51			6.37			10.28			6.97			6.39			6.18			7.79			8.24			90.14			

Table 3.10. Economic CAPEX & OPEX study - Balances and main results.

DREAMFIT ALCORCÓN - CAPEX & OPEX ANALYSIS																
INVESTMENT 100,395.22 €	WITHOUT PV PLANT					WITH PV PLANT									CASH FLOW	CUMULATIVE PROFIT
	ACTIVE ENERGY	FIXED POWER	POWER PENALTY	TAX 5.11%	TOTAL	ACTIVE ENERGY	SURPLUS ENERGY	ACTUAL CHARGE	FIXED POWER	POWER PENALTY	TAX 5.11%	O&M	TOTAL			
YEAR 1	65,951.89 €	8,061.50 €	2,196.14 €	3,896.36 €	<b>80,105.91 €</b>	41,288.46 €	1,486.66 €	39,801.80 €	7,278.87 €	1,167.14 €	2,466.76 €	0.00 €	50,714.57 €	29,391.34 €	-71,003.88 €	
YEAR 2	67,284.12 €	8,224.35 €	2,196.14 €	3,972.80 €	<b>81,677.41 €</b>	42,260.88 €	1,456.31 €	40,804.57 €	7,425.91 €	1,212.38 €	2,527.86 €	5,101.00 €	57,071.71 €	24,605.70 €	-46,398.18 €	
YEAR 3	68,616.35 €	8,387.19 €	2,196.14 €	4,049.24 €	<b>83,248.92 €</b>	43,238.77 €	1,426.20 €	41,812.57 €	7,572.94 €	1,259.96 €	2,589.35 €	5,202.00 €	58,436.82 €	24,812.11 €	-21,586.07 €	
YEAR 4	69,948.58 €	8,550.03 €	2,196.14 €	4,125.68 €	<b>84,820.43 €</b>	44,222.15 €	1,396.34 €	42,825.81 €	7,719.97 €	1,308.56 €	2,651.16 €	5,303.00 €	59,808.50 €	25,011.93 €	3,425.86 €	
YEAR 5	71,280.81 €	8,712.87 €	2,196.14 €	4,202.12 €	<b>86,391.94 €</b>	45,211.00 €	1,366.72 €	43,844.28 €	7,867.00 €	1,358.07 €	2,713.28 €	5,404.00 €	61,186.64 €	25,205.30 €	28,631.16 €	
YEAR 6	72,613.04 €	8,875.72 €	2,196.14 €	4,278.55 €	<b>87,963.45 €</b>	46,205.34 €	1,337.35 €	44,867.99 €	8,014.04 €	1,408.26 €	2,775.70 €	5,505.00 €	62,570.99 €	25,392.46 €	54,023.62 €	
YEAR 7	73,945.26 €	9,038.56 €	2,196.14 €	4,354.99 €	<b>89,534.96 €</b>	47,205.16 €	1,308.22 €	45,896.94 €	8,161.07 €	1,459.20 €	2,838.43 €	5,606.00 €	63,961.64 €	25,573.32 €	79,596.95 €	
YEAR 8	75,277.49 €	9,201.40 €	2,196.14 €	4,431.43 €	<b>91,106.47 €</b>	48,210.46 €	1,279.34 €	46,931.12 €	8,308.10 €	1,510.90 €	2,901.46 €	5,707.00 €	65,358.59 €	25,747.88 €	105,344.83 €	
YEAR 9	76,609.72 €	9,364.24 €	2,196.14 €	4,507.87 €	<b>92,677.98 €</b>	49,221.23 €	1,250.70 €	47,970.53 €	8,455.14 €	1,563.59 €	2,964.81 €	5,808.00 €	66,762.08 €	25,915.90 €	131,260.73 €	
YEAR 10	77,941.95 €	9,527.09 €	2,196.14 €	4,584.31 €	<b>94,249.49 €</b>	50,237.49 €	1,222.31 €	49,015.18 €	8,602.17 €	1,617.57 €	3,028.50 €	5,909.00 €	68,172.42 €	26,077.06 €	157,337.79 €	
YEAR 11	79,274.18 €	9,689.93 €	2,196.14 €	4,660.75 €	<b>95,821.00 €</b>	51,259.23 €	1,194.16 €	50,065.07 €	8,749.20 €	1,673.02 €	3,092.53 €	6,010.00 €	69,589.82 €	26,231.18 €	183,568.97 €	
YEAR 12	80,606.41 €	9,852.77 €	2,196.14 €	4,737.19 €	<b>97,392.51 €</b>	52,286.45 €	1,166.26 €	51,120.18 €	8,896.24 €	1,729.47 €	3,156.88 €	6,111.00 €	71,013.77 €	26,378.74 €	209,947.71 €	
YEAR 13	81,938.63 €	10,015.61 €	2,196.14 €	4,813.62 €	<b>98,964.01 €</b>	53,319.14 €	1,138.61 €	52,180.54 €	9,043.27 €	1,786.85 €	3,221.54 €	6,212.00 €	72,444.21 €	26,519.81 €	236,467.52 €	
YEAR 14	83,270.86 €	10,178.46 €	2,196.14 €	4,890.06 €	<b>100,535.52 €</b>	54,357.32 €	1,111.20 €	53,246.13 €	9,190.30 €	1,845.14 €	3,286.52 €	6,313.00 €	73,881.10 €	26,654.43 €	263,121.95 €	
YEAR 15	84,603.09 €	10,341.30 €	2,196.14 €	4,966.50 €	<b>102,107.03 €</b>	55,400.98 €	1,084.03 €	54,316.95 €	9,337.34 €	1,904.37 €	3,351.82 €	6,414.00 €	75,324.48 €	26,782.56 €	289,904.50 €	
YEAR 16	85,935.32 €	10,504.14 €	2,196.14 €	5,042.94 €	<b>103,678.54 €</b>	56,450.12 €	1,057.11 €	55,393.01 €	9,484.37 €	1,964.64 €	3,417.43 €	6,515.00 €	76,774.44 €	26,904.10 €	316,808.60 €	
YEAR 17	87,267.55 €	10,666.98 €	2,196.14 €	5,119.38 €	<b>105,250.05 €</b>	57,504.74 €	1,030.44 €	56,474.30 €	9,631.40 €	2,025.99 €	3,483.37 €	6,616.00 €	78,231.06 €	27,018.99 €	343,827.59 €	
YEAR 18	88,599.77 €	10,829.83 €	2,196.14 €	5,195.82 €	<b>106,821.56 €</b>	58,564.84 €	1,004.01 €	57,560.83 €	9,778.44 €	2,088.35 €	3,549.62 €	6,717.00 €	79,694.24 €	27,127.32 €	370,954.91 €	
YEAR 19	89,932.00 €	10,992.67 €	2,196.14 €	5,272.25 €	<b>108,393.07 €</b>	59,630.42 €	977.82 €	58,652.60 €	9,925.47 €	2,152.13 €	3,616.22 €	6,818.00 €	81,164.41 €	27,228.66 €	398,183.57 €	
YEAR 20	91,264.23 €	11,155.51 €	2,196.14 €	5,348.69 €	<b>109,964.58 €</b>	60,701.48 €	951.89 €	59,749.59 €	10,072.50 €	2,218.59 €	3,683.22 €	6,919.00 €	82,642.91 €	27,321.67 €	425,505.24 €	
YEAR 21	92,596.46 €	11,318.35 €	2,196.14 €	5,425.13 €	<b>111,536.09 €</b>	61,778.02 €	926.19 €	60,851.83 €	10,219.54 €	2,286.98 €	3,750.59 €	7,020.00 €	84,128.93 €	27,407.15 €	452,912.39 €	
YEAR 22	93,928.69 €	11,481.20 €	2,196.14 €	5,501.57 €	<b>113,107.60 €</b>	62,860.04 €	900.74 €	61,959.29 €	10,366.57 €	2,356.23 €	3,818.27 €	7,121.00 €	85,621.36 €	27,486.24 €	480,398.63 €	
YEAR 23	95,260.92 €	11,644.04 €	2,196.14 €	5,578.01 €	<b>114,679.11 €</b>	63,947.54 €	875.54 €	63,072.00 €	10,513.60 €	2,426.36 €	3,886.26 €	7,222.00 €	87,120.22 €	27,558.88 €	507,957.51 €	
YEAR 24	96,593.14 €	11,806.88 €	2,196.14 €	5,654.45 €	<b>116,250.61 €</b>	65,040.52 €	850.58 €	64,189.94 €	10,660.64 €	2,497.36 €	3,954.56 €	7,323.00 €	88,625.49 €	27,625.12 €	535,582.63 €	
YEAR 25	97,925.37 €	11,969.72 €	2,196.14 €	5,730.88 €	<b>117,822.12 €</b>	66,138.98 €	825.87 €	65,313.11 €	10,807.67 €	2,569.18 €	4,023.18 €	7,424.00 €	90,137.14 €	27,684.98 €	563,267.61 €	



## Section 4

# Environmental Impact

### Contents

---

4.1	Introduction . . . . .	129
4.2	Methodology . . . . .	129
4.3	Results of the Environmental Impact Study . . . . .	130

---

### 4.1 Introduction

The environmental impact analysis presented in this section is based on the so-called Life Cycle Emissions (LCE), which represent the equivalent emissions of  $CO_2$  associated to a specific energy amount or a given component. Life Cycle Emissions includes the production, operation, maintenance, disposal and waste management of components or energy amounts, id est, it covers the total life cycle of assets.

In the particular case of Dreamfit Alcorcón PV plant, the electricity generated by the PV installation will replace the same amount of electricity in the existing power network. Thus, renewable energies such us solar photovoltaic have an intrinsic positive environmental impact.

### 4.2 Methodology

If the carbon footprint of the power system electricity production per kWh is greater than the one for the PV installation, there will be a net saving of equivalent Carbon Dioxide emissions.

Hence, the total carbon balance for a photovoltaic facility regardless of being used for self-consumption or not is the difference between the produced and the saved amount of equivalent  $CO_2$  emissions. Then, the carbon balance of a PV installation depends on five key factors that have been considered to perform the environmental impact analysis [66]:

- **PV System Lifetime.** Expected useful life of the PV plant [*years*].
- **Annual Degradation** (*%/year*). PV Modules' power attenuation over time.
- **Power Network LCE.** The Life Cycle Emission of the power network [ $g_{eq} CO_2/kWh$ ].
- **PV System LCE.** The Life Cycle Emissions of the PV plant [ $g_{eq} CO_2/kWh$ ].
- **PV Production.** Energy generated by the Distributed Energy Resource [*kWh*].

### 4.3 Results of the Environmental Impact Study

The aforementioned five key factors required to assess the carbon balance of Dreamfit Alcorcón PV plant are presented below:

1. **PV System Lifetime.** 25 years guaranteed by the PV modules' manufacturer.
2. **Annual Degradation.** 0.55%/year according to PV modules data sheet.
3. **Power Network LCE.** 287  $g_{eq} CO_2/kWh$  according to International Energy Agency [67].
4. **PV System LCE.** 167.80  $t_{eq} CO_2$  according to International Energy Agency and assuming an average load per PV module of approximately 15  $kg/m^2$  following equation 2.70 [67]:

Table 4.1. PV system Life Cycle Emissions.

PV SYSTEM LIFE CYCLE EMISSIONS			
ITEM	LCE	QUANTITY	SUBTOTAL
PV Modules	1,424 $kg_{eq} CO_2/kW_p$	111 $kW_p$	158,064 $kg_{eq} CO_2$
PV Support Structure	1.91 $kg_{eq} CO_2/kg$	5,000 kg	9,550 $kg_{eq} CO_2$
Solar Inverter	190 $kg_{eq} CO_2/units$	1 unit	190 $kg_{eq} CO_2$
<b>TOTAL</b>	N/A	N/A	<b>167,804 <math>kg_{eq} CO_2</math></b>

5. **PV Production.** 198,897.59  $kWh$  in the year 1 with the production study 3.1.4.

Then, considering the PV system lifetime, the annual degradation and the Life Cycle Emissions, the saved emissions of equivalent  $CO_2$  along the useful life of the PV plant are displayed in the next figure:

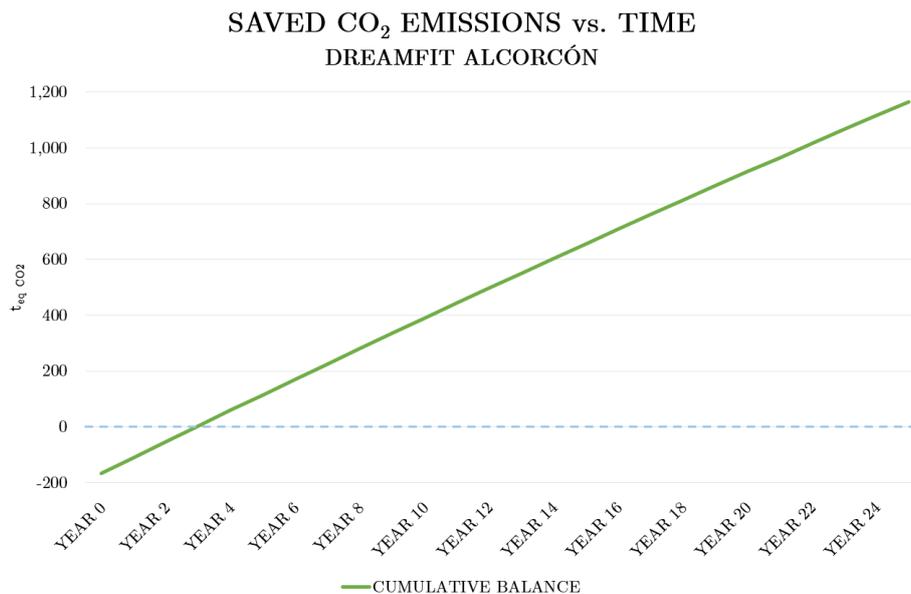


Figure 4.1. Saved  $CO_2$  emissions along the useful life of the PV plant.

Finally, next table shows the expected year by year saved emissions as well as the cumulative balance of equivalent Carbon Dioxide emissions:

Table 4.2. Environmental impact - Balances and main results.

YEAR	PV PRODUCTION (MWh)	SAVED EMISSIONS ( $t_{eq} CO_2$ )	CUMULATIVE BALANCE ( $t_{eq} CO_2$ )
YEAR 0	0.00	-167.80	-167.80
YEAR 1	198.90	57.08	-110.72
YEAR 2	197.80	56.77	-53.95
YEAR 3	196.71	56.46	2.50
YEAR 4	195.62	56.14	58.65
YEAR 5	194.52	55.83	114.47
YEAR 6	193.43	55.51	169.99
YEAR 7	192.33	55.20	225.19
YEAR 8	191.24	54.89	280.07
YEAR 9	190.15	54.57	334.65
YEAR 10	189.05	54.26	388.90
YEAR 11	187.96	53.94	442.85
YEAR 12	186.86	53.63	496.48
YEAR 13	185.77	53.32	549.79
YEAR 14	184.68	53.00	602.80
YEAR 15	183.58	52.69	655.48
YEAR 16	182.49	52.37	707.86
YEAR 17	181.39	52.06	759.92
YEAR 18	180.30	51.75	811.67
YEAR 19	179.21	51.43	863.10
YEAR 20	178.11	51.12	914.22
YEAR 21	177.02	50.80	965.02
YEAR 22	175.92	50.49	1,015.51
YEAR 23	174.83	50.18	1,065.69
YEAR 24	173.74	49.86	1,115.55
YEAR 25	172.64	49.55	<b>1,165.10</b>

All in all, figure 4.1 and table 4.2 reveal that this project is also interesting from an environmental point of view, since tons of polluting emissions would be replaced yearly.

In conclusion, this 25-year project will save the emission of 1,165.10  $t_{eq} CO_2$  ✓.



## Section 5

# Conclusions

The conclusions of the Master Thesis have been related to the attainment of the main target of the project as well as of the four sub-goals presented in subsection 1.4. Therefore:

- The **main target** of the project consisted of developing a **model** to include a photovoltaic generation plant for self-consumption at any Dreamfit gym in the medium term. The model has been developed based on two MATLAB® programming functions:
  - **Function *tfm.m***. By means of the hour by hour consumption of the facility for a whole year and the solar irradiation of a Typical Meteorological Year (TMY), the algorithm returns the **optimal PV peak power** to install in order to maximise the self-consumed energy while minimising the surplus energy following the RD 244/2019.

Additionally, the function *tfm.m* performs a **production study** whose accuracy has been contrasted with a simulation developed with the professional software PVsyst® under the same hypothetical constraints, parameters and assumptions:

Table 5.1. Production study assessment.

ANNUAL RESULTS	PVsyst (kWh/year)	MATLAB (kWh/year)	DEVIATION
TOTAL CONSUMPTION	447,567.75	447,567.75	N/A
PV PRODUCTION	205,570.00	198,897.59	-3.25%
SURPLUS PV ENERGY	30,310.00	29,733.28	-1.90%
GRID CONSUMPTION	277,100.00	278,403.45	0.47%
SELF-CONSUMPTION	170,470.00	169,164.30	-0.77%

<b>OPTIMAL PEAK POWER</b>	<b>111 kW</b>
---------------------------	---------------

Differences among results obtained by MATLAB and PVsyst are due to simplifications in terms of power losses and technical specifications of the electrical devices.

- **Function *economic.m***. Through the output data obtained from the *tfm.m* function, the initial investment cost of the project and other economical assumptions such as the power and energy prices per period, the maintenance cost or the Consumer Price Index (CPI), the algorithm returns the **six optimal powers** that should be **contracted per period** for a 3.0TD electricity tariff if the PV plant is included. In addition, the program also returns the **payback period** of the project.

Additionally, the function *economic.m* performs an **economic study** whose accuracy has been contrasted with a simulation developed with the professional software PVsyst® under the same hypothetical constraints, parameters and assumptions:

Table 5.2. Economic study assessment.

ANNUAL RESULTS	PVsyst	MATLAB	DEVIATION
INITIAL INVESTMENT (€)	100,395.22	100,395.22	N/A
NET PRESENT VALUE YEAR 25 (€)	552,451.00	563,267.61	1.96%
PAYBACK PERIOD (years)	4.50	3.86	-14.22%
LEVELISED COST OF ENERGY (€/kWh)	0.071	0.070	-1.41%

Differences among results obtained by MATLAB and PVsyst are due to PVsyst does not compute the economical performance under the particular specifications of the Spanish 3.0TD electricity tariff, but with a single-period tariff that has been adjusted as much as possible as explained at the second annex.

Thus, the required **scalable model** for the design of Distributed Generation Resources has been obtained, and could be replicated at any Dreamfit gym in order to incorporate a self-consumption PV plant in the medium term ✓.

- The four **sub-goals** of the project have also been attained:
  - **Self-Consumption.** Almost 170 *MWh* per year will be self-consumed by Dreamfit Alcorcón due to the deployment of the PV plant, self-consuming more than 85% of the annual energy generated by the Distributed Energy Resource ✓.
  - **Emissions.** The emission of more than 50 *t<sub>eq</sub> CO<sub>2</sub>* per year will be avoided due to this renewable energy project, reducing climate change and fostering the compliance with the Sustainable Development Goals ✓.
  - **Energy Efficiency and Profitability.** Dreamfit Alcorcón will reduce its grid consumption almost a 40% per year due to the PV modules ✓.
  - **Health.** The gym will not only self-consume PV energy, but also will inject almost 30 *MWh* per year of green energy to the grid, supporting its motto *we are health* ✓.
- The **model has been applied** to Dreamfit Alcorcón, developing a **pilot project** of 100 *kW<sub>n</sub>* through this Master Thesis that includes all the requirements according to the current regulation [68]: project memory, technical specifications, health and safety study, project budget developed with Presto® and plans developed with Autocad®. Thus, the project can actually be executed in practice and will be executed in 2022 ✓.

## Section 6

# Annexes

1. Alignment with the Sustainable Development Goals.
2. Levelised Cost of Energy - PVsyst Check.
3. Maintenance Plan.
4. Gantt Chart.
5. Optimal PV Peak Power & Production Study Algorithm: *tfm.m* MATLAB function.
6. Economic CAPEX & OPEX Study Algorithm: *economic.m* MATLAB function.
7. PVsyst Simulation Report.
8. PV Modules Data Sheet.
9. Inverter Data Sheet.

**NOTE.** The included versions of both MATLAB® functions are summarised adaptations with its most important attributes. Otherwise more than 1,410 lines of code would occupy 30 pages.



ecological transition. Therefore, Dreamfit will request the partial financing of the project with these recovery funds.

- **Sustainable cities and communities** (SDG 11). The commitment of Dreamfit regarding sustainability started more than three years ago, when the steering committee decided to create the position of *Energy Management and Efficiency Technician*. Dreamfit intends to be self-sufficient in the long term, and therefore the first step in that path stands for self-consuming more than 35% of the energy consumed annually by Dreamfit Alcorcón in the short term, what will be achieved through this project.
- **Responsible consumption and production** (SDG 12). The PV plant located at the roof of Dreamfit Alcorcón is conceived by the organisation as the next improvement in the field of energy management and efficiency. Since the year 2018 Dreamfit has reduced the yearly consumption of the whole company more than a 25%. In accordance with its strategy of responsible consumption, the PV plant will reduce the annual grid energy consumed by Dreamfit Alcorcón in more than 150 *MWh/year*.
- **Climate action** (SDG 13). Only with this PV plant and assuming a lifetime of 25 years, more than 1,000  $t_{eq} CO_2$  of polluting emissions will be avoided. Nonetheless, this project is understood by Dreamfit as a scalable solution that pretends to be executed in the rest of the gyms within the company in the medium term, contributing against climate change.

## Annex 2. Levelised Cost of Energy - PVsyst Check

The purpose of this annex consists of computing the Levelised Cost Of Energy (LCOE) of the Dreamfit Alcorcón PV plant and comparing it with the result obtained by means of PVsyst. The LCOE viability analysis is a Master Thesis requirement of the Comillas Pontifical University®.

According to the PVsyst Simulation Report, the LCOE of the project is 0.071 €/kWh. This result has been obtained supposing a **single-period energy price** that has been established considering the gym consumption distribution per period as well as the energy price per period utilised for the economic study. Then, following the consumption distribution per period provided at figure 3.11(a) and the energy prices presented at subsection 3.2.1.4:

Table 6.1. Consumption tariff for PVsyst economic study.

PERIOD	P1	P2	P3	P4	P5	P6	TOTAL
CONSUMPTION	16.30%	15.45%	15.64%	16.40%	6.10%	30.11%	100%
ENERGY PRICE (€/kWh)	0.207797	0.184083	0.153379	0.130097	0.108142	0.11001	N/A
WEIGHT (€)	0.033871	0.028441	0.023988	0.021336	0.006597	0.033124	<b>0.147357</b>

The result obtained at table 6.1 justifies why the consumption tariff price utilised for the PVsyst simulation has been 0.15 €/kWh ✓.

The Levelised Cost Of Energy (LCOE) can be computed according to equation 6.1:

$$LCOE = INV \cdot f_a + F \cdot f_{\Sigma}^F \cdot f_a + OM \cdot f_{\Sigma}^{OM} \cdot f_a \quad (6.1)$$

Where:

- $INV$  → Initial Investment [€/kWh].
- $F$  → Fuel Cost [€/kWh].
- $OM$  → Operation and Maintenance Cost [€/kWh].

Additionally:

- $f_a$  → Amortisation Factor [-]:

$$f_a = i \cdot \frac{(1+i)^N}{(1+i)^N - 1} \quad (6.2)$$

- $f_{\Sigma}$  → Accumulation Factor [-]:

$$f_{\Sigma} = k \cdot \frac{(1-k^N)}{1-k} \rightarrow k = \frac{1+r}{1+i} \quad (6.3)$$

Where:

- $i$  → Weighted Average Cost of Capital (WACC) or Discount Rate [%].
- $N$  → Useful Life of the Project [years].
- $r$  → Nominal Rate [%].

According to the assumptions presented in table 3.6 considered for the economic assessment of the project as well as respecting the data utilised for the PVsyst Simulation:

- Weighted Average Cost of Capital:  $i = 6\%$ .
- Useful Life of the Project:  $N = 25 \text{ years}$ .
- Consumer Price Index (CPI) Overrun:  $r = 2.02\%$ .

The amortisation factor can be computed applying equation 6.2:

$$f_a = 0.06 \cdot \frac{(1 + 0.06)^{25}}{(1 + 0.06)^{25} - 1} \longrightarrow \boxed{f_a = 0.07823} \quad (6.4)$$

The O&M accumulation factor can be computed applying equation 6.3:

$$k = \frac{1 + 0.0202}{1 + 0.06} = 0.962 \rightarrow f_{\Sigma}^{OM} = 0.962 \cdot \frac{1 - 0.962^{25}}{1 - 0.962} \longrightarrow \boxed{f_{\Sigma}^{OM} = 15.70} \quad (6.5)$$

The Fuel accumulation factor is not computed since the generation plant designed is based of PV technology, which requires no fuel at all but a renewable source of energy which is the sun. Therefore, the term  $F \cdot f_{\Sigma}^F \cdot f_a$  in the equation 6.1 can be ignored.

Finally, applying equation 6.1:

$$LCOE = \underbrace{\frac{100,395.22 \text{ €}}{198,897.59 \text{ kWh}}}_{\text{Table 3.6}} \cdot 0.07823 + \cancel{F \cdot f_{\Sigma}^F \cdot f_a} + \underbrace{\frac{5,000 \text{ €}}{198,897.59 \text{ kWh}}}_{\text{Table 3.6}} \cdot 15.70 \cdot 0.07823 \quad (6.6)$$

Then:  $\boxed{LCOE = 0.070 \text{ €/kWh}}$

Comparing the LCOE obtained with the one provided by PVsyst, the accuracy of the model developed by means of the algorithms *tfm.m* and *economic.m* can be once again verified ✓.

Assuming that the nominal rate of the disposal of energy is equal to the nominal rate of the O&M, which has been considered to take the value of the Consumer Price Index (CPI), both rates would be:  $f_{\Sigma}^{OM} = f_{\Sigma}^{DE} = 15.70$ .

Thus, the Levelised Revenue Of Electricity (LROE) can be computed as follows:

$$LROE = DE \cdot f_{\Sigma}^{DE} \cdot f_a \quad (6.7)$$

Where:

- $DE \rightarrow$  Disposal of Energy [ $\text{€/kWh}$ ].

Imposing the value for the Disposal of Energy utilised for the PVsyst simulation in accordance with table 6.1 ( $DE = 0.15 \text{ €/kWh}$ ), the LROE can be computed applying equation 6.7:

$$LROE = 0.15 \text{ €/kWh} \cdot 14.70 \cdot 0.07823 \longrightarrow \boxed{LROE = 0.172 \text{ €/kWh}} \quad (6.8)$$

The profitability of the project was demonstrated by means of the Internal Rate of Return and the Payback Period criteria in subsection 3.2.4 . In this case, since  $LROE \geq LCOE$ , the profitability of the project has been demonstrated through the Levelised Cost of Energy ✓.

### Annex 3. Maintenance Plan

The maintenance plan of Dreamfit Alcorcón PV plant has been consulted to Elecnor® [65].

The scope of the maintenance offer can be summarised in four points:

- Preventive and Technical-Legal Maintenance.
- Monitoring of the facility.
- Corrective Maintenance (24h).
- Document Management and Intervention Register.

Preventive maintenance will involve, at least, an annual review. The maintenance contract will include the maintenance tasks of all the components recommended by the manufacturers. The combination between preventive and corrective maintenance of the facility ensures its proper operation, increases production and extends the useful life of the Distributed Energy Resource.

The **corrective maintenance** plan includes all the replacement operations necessary to ensure the proper operation of the facility during its useful life.

Specifically, the corrective maintenance of the PV plant will include:

- Visit to the facility after an incident within the following five working days.
- Fault resolution within the following ten working days.
- Analysis and budgeting of the works and replacements necessary for the correct operation.
- The economic costs of corrective maintenance, within the agreed scope among parts, are included at the annual fee of the maintenance contract. Neither labour nor equipment replacements required beyond the warranty period are included.

The **preventive maintenance** plan encompasses visual inspection, performance verification and other operations which should allow maintaining the operating conditions, performance, protection and durability of the facility within acceptable limits.

Specifically, the preventive maintenance of the PV plant will include:

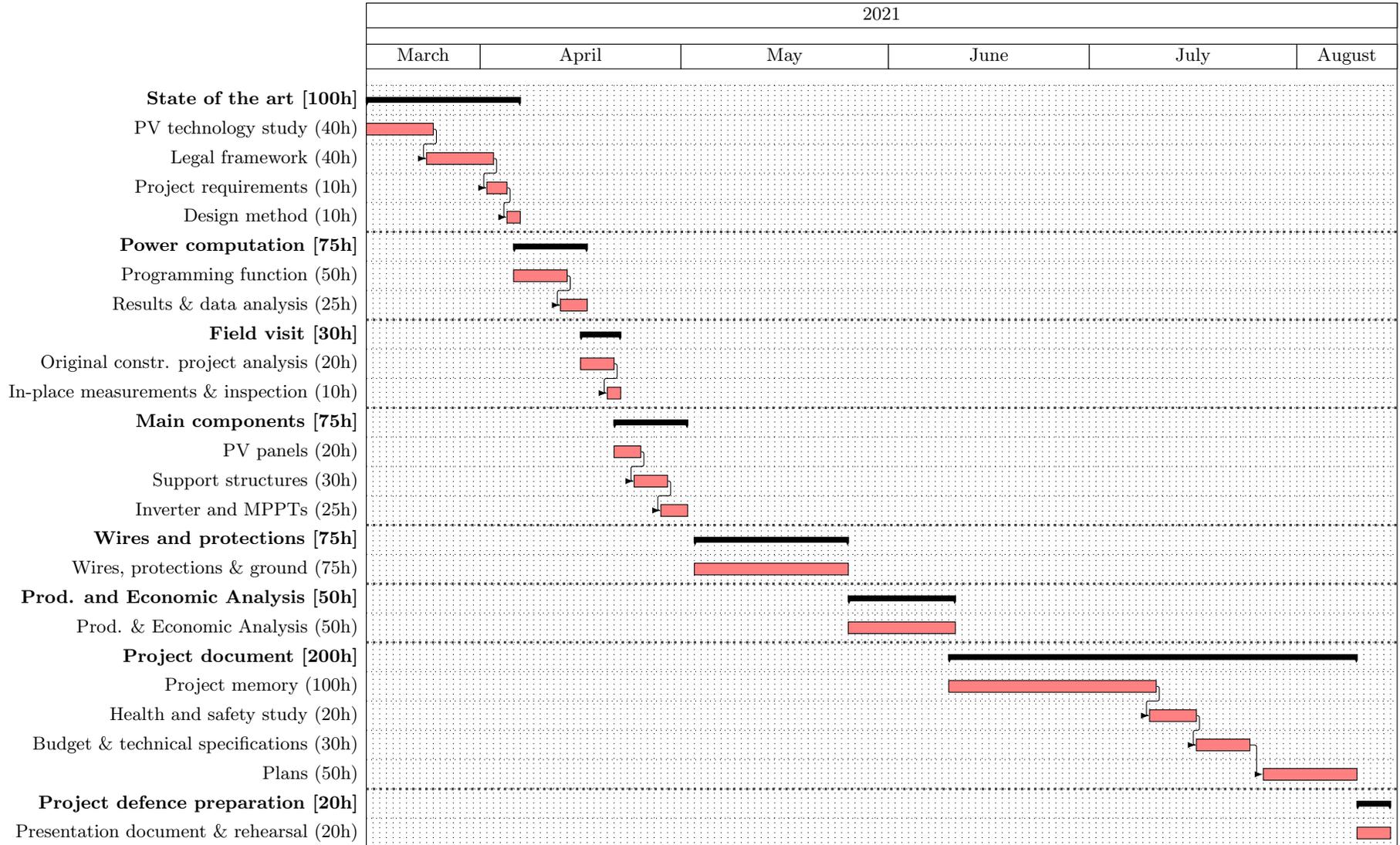
- Review of the monitoring system every six months, checking the calibration and cleanliness of the power meters, the operation and calibration of the data acquisition system and the data storage.
- Visit to the facility every six months, reviewing every component of the facility at least once a year in accordance with the manufacturer recommendation.
- The visit will include checking the electrical protections, the status of PV modules, connections, system orientation, inverter, mechanical state of cables and terminals, etc.
- Preparation of a technical report for each of the visits that reflects the state of the facilities and the detected incidents.

Maintenance will be carried out by qualified technical personnel under the responsibility of the maintenance company. In both cases, the maintenance operations carried out will be recorded in a maintenance book, which will contain the identification of the maintenance personnel (name, qualification and authorisation of the company).

Delving into the preventive maintenance, next page includes the detailed list of tasks covered by the contract, specifying periodicity and description.

- **PV Modules:**
  - Review probable unforeseen shading due to possible objects every six months.
  - Inspection and cleaning of dirt from the modules (due to dust, bird droppings, etc.) every six months.
  - Review of the general status of PV modules every six months.
  - Checking the wiring and connectors every six months.
  - Check the tightness of cable tubes and canalisation every twelve months.
- **Mounting Structure:**
  - Review of the signs indicating the nomenclature of the structure every twelve months.
  - General review of the mounting structure every twelve months.
  - Status review of elements within the canalisation cable tubes every twelve months.
  - Inspection of the structure connection to grounding system every twelve months.
- **DC Side of the Facility:**
  - Insulation inspection every six months.
  - Measurement and collection of voltage and current data per string every six months.
  - Checking the status of the protection elements every twelve months.
  - Re-tightening of terminals and connections every twelve months.
  - Cleaning of the direct current side of the facility every twelve months.
  - Thermographic inspection and thermographic report every twelve months.
- **DC/AC Inverter:**
  - Check and document direct current and alternating current voltages with a power meter every six months.
  - Inspection inverter status: terminals, protections and connections every six months.
  - Inspection of the outer cabinet status every twelve months.
  - Inspection and cleaning of informational stickers every twelve months.
  - Cleaning of filters and air inlets for inverter ventilation every twelve months.
  - Re-tighten terminals and inverter connections every twelve months.
  - Check electronic communication buses every twelve months.
  - Cleaning the interior of the inverter every twelve months.
  - Thermographic inspection of the inverter every twelve months.
  - Inverter report including one week power curves obtained through a network analyser every twelve months.
- **AC Side of the Facility:**
  - Inspection of terminals and connections every six months.
  - Inspection of protection elements status and operation: automatic or residual current switches every six months.
  - External inspection of the AC boxes every twelve months.
  - Status inspection of the fixing system every twelve months.
  - Review of the electrical panel signalling systems every twelve months.
  - Inspection of the interior insulation of electrical panels every twelve months.
  - Multimeter measurements on each power line every twelve months.
  - Re-tighten terminals and connections every twelve months.
  - Cleaning of the alternating current side of the facility including the interior of AC boxes every twelve months.
  - Thermographic inspection and report of the AC boxes every twelve months.
  - Revision of the electronic components every twelve months.

## Annex 4. Gantt Chart



```

function [pp_opt] = tfm()
    %SUMMARISED VERSION - ADRIÁN CECILIO - MASTER THESIS - DREAMFIT ALCORCÓN

    %INPUT DATA MATRIX (ROWS x COLUMNS = 8760 x 7) - DATA PER HOUR:
    data = xlsread('TMY.xlsx');

    pr = 0.887; %PR = PERFORMANCE RATIO (PVSYST)
    energy_pv = zeros(8760,1); %PV ENERGY AVAILABLE
    consumption = zeros(8760,1); %FACILITY TOTAL ENERGY CONSUMED
    excess = zeros(8760,1); %EXCESSIVE PV PRODUCTION
    grid = zeros(8760, 1); %GRID ENERGY CONSUMED
    self_consumed = zeros(8760, 1); %PV ENERGY SELF-CONSUMED

    %TARGET --> MIN COMPENSATED ENERGY & MAX SELF CONSUMED ENERGY:
    energy_pv_opt = zeros(8760,1); %OPTIMAL PV ENERGY AVAILABLE
    excess_opt = zeros(8760,1); %OPTIMAL EXCESSIVE PV PRODUCTION
    grid_opt = zeros(8760, 1); %OPTIMAL GRID ENERGY CONSUMED
    self_consumed_opt = zeros(8760, 1); %OPTIMAL PV ENERGY SELF-CONSUMED
    pp_opt = 0; %OPTIMAL PV PEAK POWER TO INSTALL

    %OPTIMAL PEAK POWER COMPUTATION BETWEEN 50 kW AND 125 kW:
    for pp=50:125
        pow = 0; %CONTROL VARIABLE
        for i = 1:8760
            energy_pv(i) = data(i,6)*pp*pr;
            if energy_pv(i) <= 110 %INVERTER LIMIT 110 kW
                consumption(i) = data(i,7);
                excess(i) = energy_pv(i) - consumption(i);
                grid(i) = consumption(i) - energy_pv(i);
                if excess(i) <= 0
                    excess(i) = 0;
                    self_consumed(i) = energy_pv(i);
                elseif excess(i) > 0
                    self_consumed(i) = consumption(i);
                end
                if grid(i) < 0
                    grid(i) = 0;
                end
            else
                pow = 1;
            end
        end
        if ((sum(self_consumed) - sum(excess)) > (sum(self_consumed_opt)-sum
(excess_opt)) && pow == 0)
            energy_pv_opt = energy_pv;
            excess_opt = excess;
            grid_opt = grid;
            self_consumed_opt = self_consumed;
            pp_opt = pp;
        end
    end
end
end

```

```
function [power_opt, payback_period] = economic()
    %SUMMARISED VERSION - ADRIÁN CECILIO - MASTER THESIS - DREAMFIT ALCORCÓN

    %INPUT DATA MATRIX (ROWS x COLUMNS = 8760 x 7) - DATA PER HOUR:
    data = xlsread('TMY.xlsx');

    pr = 0.887; %PR = PERFORMANCE RATIO (PVSYST)
    investment = 100395.22; %INITIAL PV PLANT INVESTMENT INVESTMENT
    %HYPOTHETICAL ENERGY&POWER PRICES PER PERIOD AND PRICING PERIOD COEFF.:
    energy_cost = [0.207797 0.184083 0.153379 0.130097 0.108142 0.110010];
    power_cost = [0.053690 0.037759 0.019193 0.016729 0.012053 0.007225];
    k = [1 0.873773 0.35234 0.267883 0.107572 0.107572];
    excess_cost = 0.05; %HYPOTHETICAL ENERGY COMPENSATION PRICE
    ipc_overrun = 0.0202; %ANNUAL COST INCREASE RATE
    excess_depreciation = 0.015; %ANNUAL COMPENSATION COST DECREASE RATE
    pv_attenuation = 0.0055; %ANNUAL PV MODULES POWER ATTENUATION
    maintenance = 5000; %ANNUAL PV PLANT MAINTENANCE COST
    period_hour = zeros(8760,1); %PERIOD 1-6 HOURS 1-8760 TARIFF 3.0TD

    %PEAK POWER INSTALLED:
    fprintf('Enter the PV peak power installed')
    pp_peak = 0;
    while (pp_peak <= 0 || pp_peak >= 150)
        pp_peak = input(' at the photovoltaic field: ');
    end

    %1. WEEKDAY COMPUTATION:
    fprintf('Enter the week day of the 1st of January of the analysed year')
    first_day = 0;
    while (first_day <= 0 || first_day >= 8)
        first_day = input('\nif MONDAY = 1 and SUNDAY = 7: ');
    end
    h = 0; week_day = zeros(8760, 1); %DAY OF THE WEEK M-T-W-T-F-S-S
    for i = 1:8760
        week_day(i) = first_day; h = h + 1;
        if h == 24
            first_day = first_day + 1; h = 0;
            if first_day == 8
                first_day = 1;
            end
        end
    end

    %2. CONSUMPTION DISTRIBUTION:
    for i = 1:8760
        energy_pv(i) = data(i,6)*pp_peak*pr;
        consumption(i) = data(i,7); grid(i) = consumption(i) - energy_pv(i);
        excess(i) = energy_pv(i) - consumption(i);
        if excess(i) <= 0
            excess(i) = 0;
            self_consumed(i) = energy_pv(i);
        elseif excess(i) > 0
            self_consumed(i) = consumption(i);
        end
    end
end
```

```

end
if grid(i) < 0
    grid(i) = 0;
end
end
%JANUARY:
month_day = 1; h = 1; grid_01 = zeros(6, 1);
energy_pv_01 = zeros(6,1); consumption_01 = zeros(6,1);
excess_01 = zeros(6,1); self_consumed_01 = zeros(6, 1);
for i=1:744
    %WORKING DAYS YEAR 2019:
    if (week_day(i) >= 1 && week_day(i) <= 5 && month_day ~= 1)
        if (h >= 1 && h <= 8) %P6:
            consumption_01(6) = consumption_01(6) + consumption(i);
            energy_pv_01(6) = energy_pv_01(6) + energy_pv(i);
            excess_01(6) = excess_01(6) + excess(i);
            grid_01(6) = grid_01(6) + grid(i); period_hour(i) = 6;
            self_consumed_01(6) = self_consumed_01(6) + self_consumed(i);
        elseif (h == 9 || (h >= 15 && h <= 18) || (h >= 23 && h <= 24)) %P2:
            consumption_01(2) = consumption_01(2) + consumption(i);
            energy_pv_01(2) = energy_pv_01(2) + energy_pv(i);
            excess_01(2) = excess_01(2) + excess(i);
            grid_01(2) = grid_01(2) + grid(i); period_hour(i) = 2;
            self_consumed_01(2) = self_consumed_01(2) + self_consumed(i);
        elseif ((h >= 10 && h <= 14) || (h >= 19 && h <= 22)) %P1:
            consumption_01(1) = consumption_01(1) + consumption(i);
            energy_pv_01(1) = energy_pv_01(1) + energy_pv(i);
            excess_01(1) = excess_01(1) + excess(i);
            grid_01(1) = grid_01(1) + grid(i); period_hour(i) = 1;
            self_consumed_01(1) = self_consumed_01(1) + self_consumed(i);
        end
    end
    %WEEKENDS AND NATIONAL BANK HOLIDAYS YEAR 2019:
    elseif ((week_day(i) >= 6 && week_day(i) <= 7) || month_day == 1)
        consumption_01(6) = consumption_01(6) + consumption(i);
        energy_pv_01(6) = energy_pv_01(6) + energy_pv(i);
        excess_01(6) = excess_01(6) + excess(i);
        grid_01(6) = grid_01(6) + grid(i); period_hour(i) = 6;
        self_consumed_01(6) = self_consumed_01(6) + self_consumed(i);
    end
    h = h + 1;
    if h == 25
        h = 1; month_day = month_day + 1;
    end
end
end

%3. OPTIMAL POWER PER PERIOD:
h = period_hour; power_opt = zeros(6, 1);
power_excess_it = zeros(6, 1); %ITERATIVE ANNUAL EXCESS POWER COST
power_cost_opt = inf; %OPTIMAL ANNUAL FIXED POWER COST
power_excess_opt = inf; %OPTIMAL ANNUAL EXCESS POWER COST
for p1 = 95:150
    for p5 = p1:175
        power = [p1 p5 p5 p5 p5 155];
    end
end

```

```

        power_cost_it = (p1*power_cost(1)+p5*power_cost(2)+p5*power_cost(3)
+ p5*power_cost(4)+p5*power_cost(5)+155*power_cost(6))*365;
        %JANUARY
        power_excess_it_01 = zeros(6, 1);
        for i = 1:744
            if (grid(i)*1.2) > power(h(i))
                power_excess_it_01(h(i)) = power_excess_it_01(h(i)) + 4*(grid
(i)*1.2-power(h(i)))^2;
            end
        end
        for i=1:6
            power_excess_it(i) = power_excess_it(i) + k(i)*1.406368*sqrt
(power_excess_it_01(i));
        end
        power_excess_total = sum(power_excess_it);
        if (power_cost_it + power_excess_total) <= (power_cost_opt +
power_excess_opt)
            power_cost_opt = power_cost_it;
            power_excess_opt = power_excess_total;
            power_opt = [p1 p5 p5 p5 p5 155];
        end
        power_excess_it = zeros(6, 1);
    end
end

%4. POWER PENALTY COST:
power = [143 155 155 155 155 155]; %CURRENT DF ALC CONTR POWERS (kW)
power_excess_current_01 = zeros(6, 25); power_opt_01 = zeros(6, 25);
power_excess_opt_01 = zeros(6, 25); power_current_01 = zeros(6, 25);
for yr = 1:25
    %JANUARY:
    for i = 1:744
        if (1.2*consumption(i)) > power(h(i))
            power_excess_current_01(h(i), yr) = power_excess_current_01(h(i),
yr) + 4*(consumption(i)*1.2-power(h(i)))^2;
        end
        if (grid(i)*1.2*(1+pv_attenuation*(yr-1)) > power_opt(h(i)))
            power_excess_opt_01(h(i), yr) = power_excess_opt_01(h(i), yr) + 4*
(grid(i)*1.2*(1+pv_attenuation*(yr-1))-power_opt(h(i)))^2;
        end
    end
    for i=1:6
        power_current_01(i, yr) = power_current_01(i, yr) + k(i)*1.406368*sqrt
(power_excess_current_01(i, yr));
        power_opt_01(i, yr) = power_opt_01(i, yr) + k(i)*1.406368*sqrt
(power_excess_opt_01(i, yr));
    end
end

%5. ENERGY TERM TOTAL COST:
total_consumption_cost = zeros(25,1);
total_grid_cost = zeros(25, 1); total_maintenance_cost = zeros(25,1);
total_excess_cost = zeros(25,1); total_actual_charge = zeros(25,1);

```

```

consumption_ec = sum(consumption_ec);
self_consumed_ec = sum(self_consumed_ec); excess_ec = sum(excess_ec);
for yr=1:25
    for i=1:6
        total_consumption_cost(yr) = total_consumption_cost(yr) + consumption_ec(i) *
*energy_cost(i)*(1+ipc_overrun*(yr-1));
        total_grid_cost(yr) = total_grid_cost(yr) + (consumption_ec(i) -
(self_consumed_ec(i)*(1-pv_attenuation*(yr-1))))*energy_cost(i)*(1+ipc_overrun*(yr-
1));
        total_excess_cost(yr) = total_excess_cost(yr) + excess_ec(i)*excess_cost*
(1-excess_depreciation*(yr-1))*(1-pv_attenuation*(yr-1));
    end
    total_maintenance_cost(yr) = maintenance*(1+ipc_overrun*(yr-1));
    total_actual_charge(yr) = total_grid_cost(yr) - total_excess_cost(yr);
end
total_maintenance_cost(1) = 0; %FIRST YEAR OF MAINTENANCE INCLUDED

%6. POWER TERM TOTAL COST:
power_current_cost = zeros(25, 1); power_opt_cost = zeros(25, 1);
fixed_current_cost = zeros(25, 1); fixed_opt_cost = zeros(25, 1);
power_current_01 = sum(power_current_01);
power_opt_01 = sum(power_opt_01);
for i=1:25
    power_current_cost(i) = power_current_01(i)+power_current_02(i) *
+power_current_03(i)+power_current_04(i)+power_current_05(i)+power_current_06(i) *
+power_current_07(i)+power_current_08(i)+power_current_09(i)+power_current_10(i) *
+power_current_11(i)+power_current_12(i);
    power_opt_cost(i) = power_opt_01(i)+power_opt_02(i)+power_opt_03(i) *
+power_opt_04(i)+power_opt_05(i)+power_opt_06(i)+power_opt_07(i)+power_opt_08(i) *
+power_opt_09(i)+power_opt_10(i)+power_opt_11(i)+power_opt_12(i);
    fixed_current_cost(i) = fixed_current_cost(i) + (power(1)*power_cost(1) *
+power(2)*power_cost(2)+power(3)*power_cost(3)+power(4)*power_cost(4)+power(5) *
*power_cost(5)+power(6)*power_cost(6))*(1+ipc_overrun*(i-1))*365;
    fixed_opt_cost(i) = fixed_opt_cost(i) + (power_opt(1)*power_cost(1) *
+power_opt(2)*power_cost(2)+power_opt(3)*power_cost(3)+power_opt(4)*power_cost(4) *
+power_opt(5)*power_cost(5)+power_opt(6)*power_cost(6))*(1+ipc_overrun*(i-1))*365;
end

%7. PAYBACK PERIOD COMPUTATION:
no_pv_cost = 0; yes_pv_cost = 0; pow = 0; payback_period = inf;
for yr=1:25
    %NO PV PLANT:
    no_pv_cost = no_pv_cost + (total_consumption_cost(yr) + fixed_current_cost *
(yr) + power_current_cost(yr))*1.0511269632;
    %YES PV PLANT:
    yes_pv_cost = yes_pv_cost + total_maintenance_cost(yr) + *
(total_actual_charge(yr) + fixed_opt_cost(yr) + power_opt_cost(yr))*1.0511269632;
    if ((no_pv_cost - yes_pv_cost) > investment) && pow == 0
        payback_period = yr; pow = 1;
    end
end
end
end

```

# PVsyst - Simulation report

## Grid-Connected System

Project: Dreamfit Alcorcón

Variant: 1.0

No 3D scene defined, no shadings

System power: 111 kWp

C/Los Robles S/N (Alcorcón) - Spain



### Client

Dreamfit Alcorcón  
C/ Los Robles S/N, 12B  
CP 28922, Alcorcón, Spain  
B40257990

**dreamfit.**

### Author

Adrián Cecilio Benito  
Comillas Pontifical University  
Official Master's Degree in Industrial Engineering



**COMILLAS**  
UNIVERSIDAD PONTIFICIA  
ICA I



**PVsyst V7.2.2**

VC0, Simulation date:  
25/07/21 18:31  
with v7.2.2

Adrián Cecilio Benito

**Project summary**

**Geographical Site**  
C/Los Robles S/N (Alcorcón)  
Spain

**Situation**  
Latitude 40.33 °N  
Longitude -3.84 °W  
Altitude 680 m  
Time zone UTC+1

**Project settings**  
Albedo 0.20

**Meteo data**  
C/Los Robles S/N (Alcorcón)  
PVGIS api TMY

**System summary**

**Grid-Connected System**

No 3D scene defined, no shadings

**PV Field Orientation**

Fixed plane  
Tilt/Azimuth 34 / 0 °

**Near Shadings**

No Shadings

**User's needs**

Ext. defined as file  
Hourly\_Parameter\_2019.csv

**System information**

**PV Array**

Nb. of modules 220 units  
Pnom total 111 kWp

**Inverters**

Nb. of units 1 Unit  
Pnom total 100 kWac  
Pnom ratio 1.111

**Results summary**

Produced Energy 200.8 MWh/year    Specific production 1807 kWh/kWp/year    Perf. Ratio PR 88.66 %  
Solar Fraction SF 38.09 %

**Table of contents**

Project and results summary	2
General parameters, PV Array Characteristics, System losses	3
Main results	4
Loss diagram	5
Special graphs	6
Predef. graphs	7
Cost of the system	8
Financial analysis	9

**PVsyst V7.2.2**

VC0, Simulation date:  
25/07/21 18:31  
with v7.2.2

Adrián Cecilio Benito

**General parameters****Grid-Connected System**

No 3D scene defined, no shadings

**PV Field Orientation****Orientation**

Fixed plane  
Tilt/Azimuth 34 / 0 °

**Sheds configuration**

No 3D scene defined

**Models used**

Transposition Perez  
Diffuse Imported  
Circumsolar separate

**Horizon**

Free Horizon

**Near Shadings**

No Shadings

**User's needs**

Ext. defined as file  
Hourly\_Parameter\_2019.csv

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year	
43353	37013	34738	32662	34511	37510	46399	40839	37019	35486	34217	33822	447568	kWh

**PV Array Characteristics****PV module**

Manufacturer Trina Solar  
Model TSM-DE18M-(II)-505  
(Original PVsyst database)

Unit Nom. Power 505 Wp  
Number of PV modules 220 units  
Nominal (STC) 111 kWp  
Modules 20 Strings x 11 In series

**At operating cond. (50°C)**

Pmpp 101 kWp  
U mpp 430 V  
I mpp 235 A

**Total PV power**

Nominal (STC) 111 kWp  
Total 220 modules  
Module area 526 m<sup>2</sup>

**Inverter**

Manufacturer Huawei Technologies  
Model SUN2000-100KTL-M1-400Vac  
(Original PVsyst database)

Unit Nom. Power 100 kWac  
Number of inverters 10 \* MPPT 10% 1 units  
Total power 100 kWac  
Operating voltage 200-1000 V  
Max. power (=>30°C) 110 kWac  
Pnom ratio (DC:AC) 1.11

**Total inverter power**

Total power 100 kWac  
Nb. of inverters 1 Unit  
Pnom ratio 1.11

**Array losses****Thermal Loss factor**

Module temperature according to irradiance  
Uc (const) 29.0 W/m<sup>2</sup>K  
Uv (wind) 0.0 W/m<sup>2</sup>K/m/s

**Module mismatch losses**

Loss Fraction 2.0 % at MPP

**IAM loss factor**

Incidence effect (IAM): Fresnel AR coating, n(glass)=1.526, n(AR)=1.290

**DC wiring losses**

Global array res. 30 mΩ  
Loss Fraction 1.5 % at STC

**Strings Mismatch loss**

Loss Fraction 0.1 %

**Module Quality Loss**

Loss Fraction -0.8 %

0°	30°	50°	60°	70°	75°	80°	85°	90°
1.000	0.999	0.987	0.962	0.892	0.816	0.681	0.440	0.000



**PVsyst V7.2.2**

VC0, Simulation date:  
25/07/21 18:31  
with v7.2.2

Adrián Cecilio Benito

**Main results**

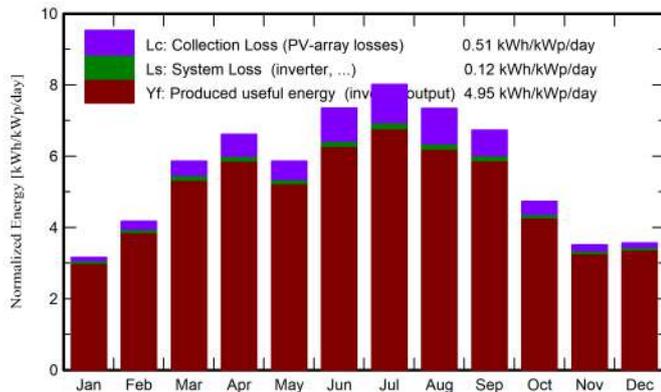
**System Production**

Produced Energy	200.8 MWh/year	Specific production	1807 kWh/kWp/year
		Performance Ratio PR	88.66 %
		Solar Fraction SF	38.09 %

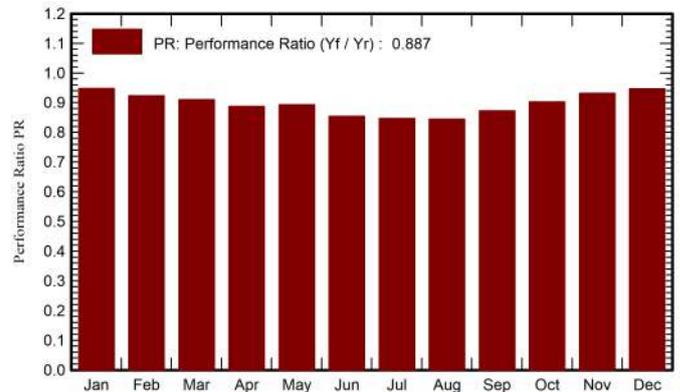
**Economic evaluation**

<b>Investment</b>		<b>Yearly cost</b>		<b>LCOE</b>	
Global	100'395.22 EUR	Annuities	0.00 EUR/yr	Energy cost	0.07 EUR/kWh
Specific	0.90 EUR/Wp	Running Costs	6'422.45 EUR/yr		
		Payback period	4.5 years		

**Normalized productions (per installed kWp)**



**Performance Ratio PR**



**Balances and main results**

	GlobHor	DiffHor	T_Amb	GlobInc	GlobEff	EArray	E_User	E_Solar	E_Grid	EFrGrid
	kWh/m <sup>2</sup>	kWh/m <sup>2</sup>	°C	kWh/m <sup>2</sup>	kWh/m <sup>2</sup>	MWh	MWh	MWh	MWh	MWh
<b>January</b>	61.2	30.65	4.29	98.1	96.4	10.57	43.35	9.48	0.856	33.87
<b>February</b>	79.9	33.78	7.66	117.0	115.1	12.29	37.01	10.76	1.244	26.25
<b>March</b>	141.3	52.93	9.03	181.7	178.3	18.82	34.74	14.72	3.665	20.02
<b>April</b>	180.3	64.56	14.49	198.4	194.2	20.03	32.66	14.73	4.823	17.93
<b>May</b>	186.8	81.48	14.00	181.7	177.1	18.44	34.51	14.56	3.454	19.95
<b>June</b>	235.7	67.28	23.06	220.7	215.3	21.44	37.51	17.86	3.069	19.65
<b>July</b>	259.4	53.56	24.48	248.4	242.7	23.92	46.40	20.98	2.374	25.42
<b>August</b>	215.0	53.47	25.68	227.8	223.1	21.89	40.84	18.27	3.100	22.56
<b>September</b>	165.0	47.74	19.14	202.1	198.6	20.06	37.02	16.98	2.615	20.04
<b>October</b>	106.2	45.41	14.42	146.7	144.2	15.06	35.49	12.50	2.216	22.98
<b>November</b>	66.7	31.98	9.21	105.4	103.6	11.15	34.22	9.71	1.195	24.51
<b>December</b>	60.4	25.12	5.09	110.4	108.6	11.89	33.82	9.93	1.699	23.90
<b>Year</b>	1758.0	587.95	14.24	2038.3	1997.3	205.57	447.57	170.47	30.310	277.10

**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

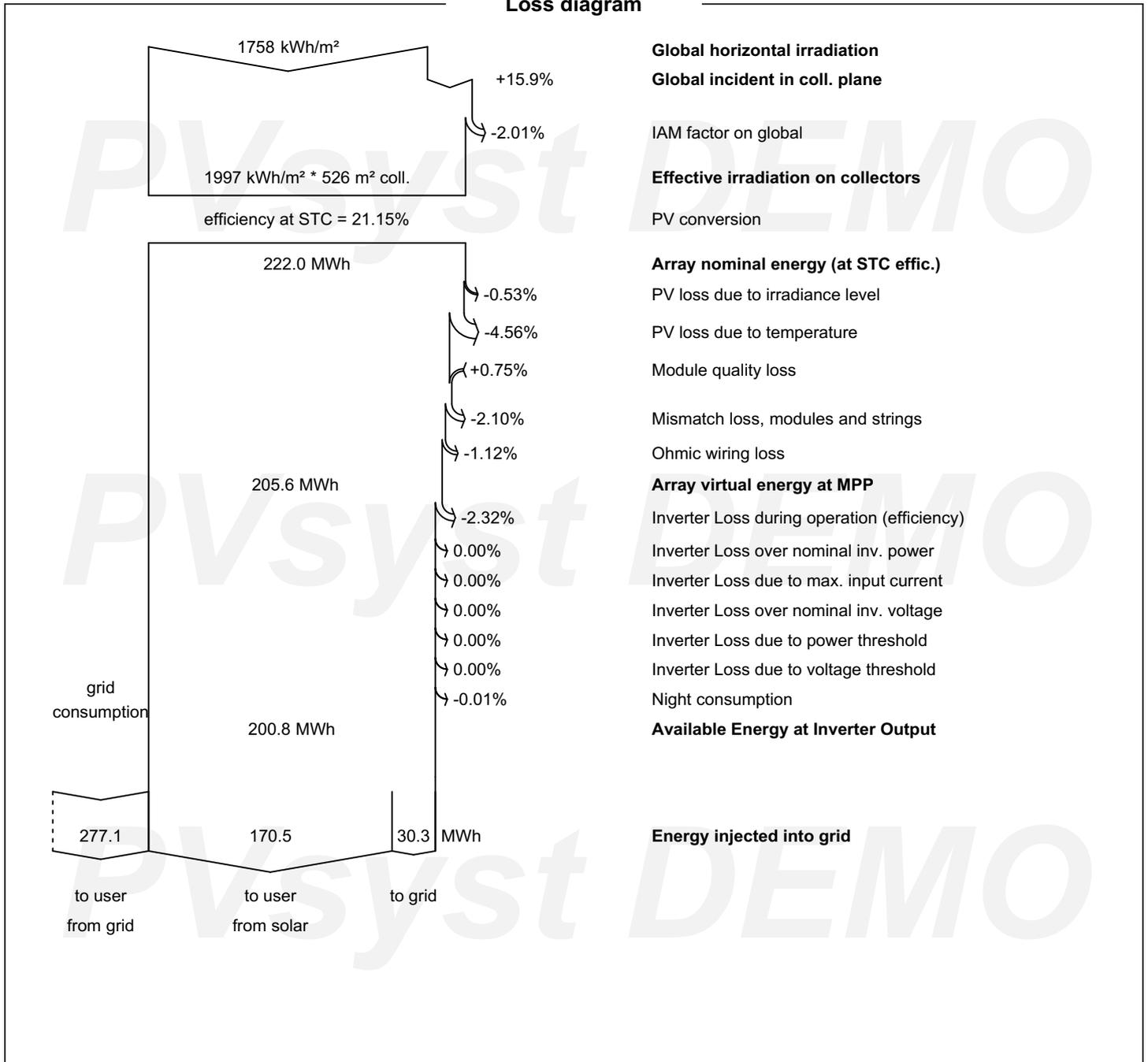


PVsyst V7.2.2

VC0, Simulation date:  
25/07/21 18:31  
with v7.2.2

Adrián Cecilio Benito

Loss diagram





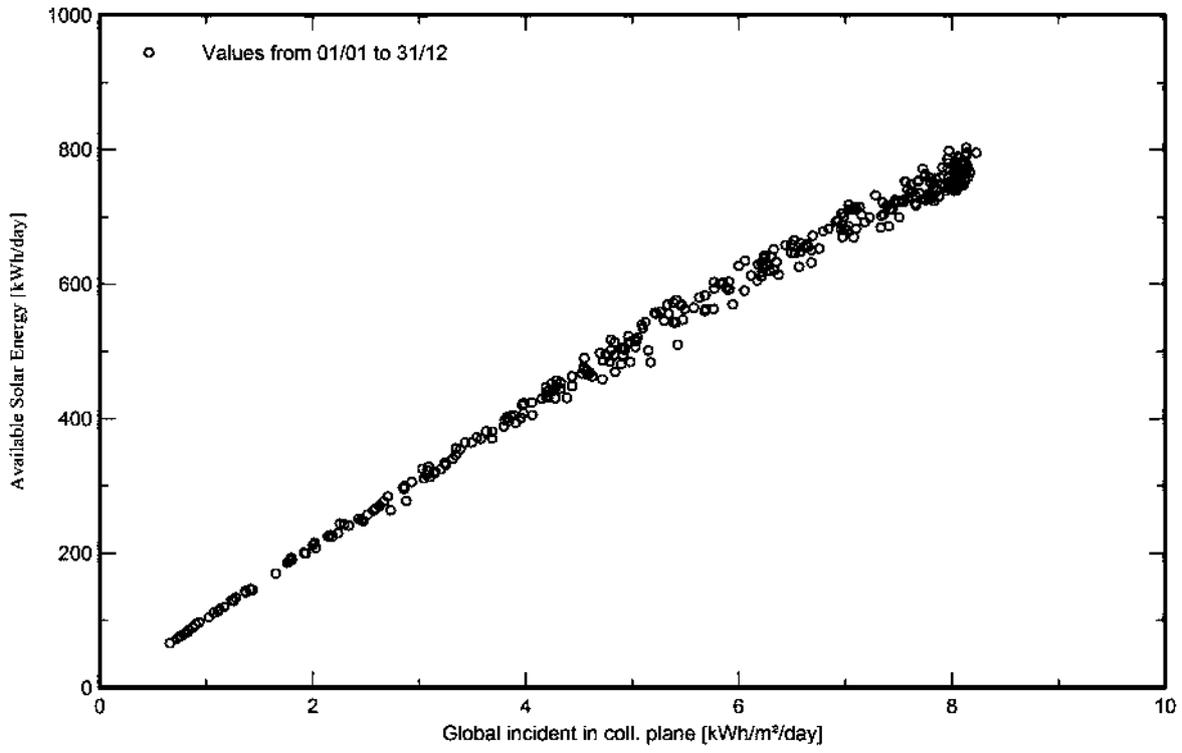
PVsyst V7.2.2

VC0, Simulation date:  
25/07/21 18:31  
with v7.2.2

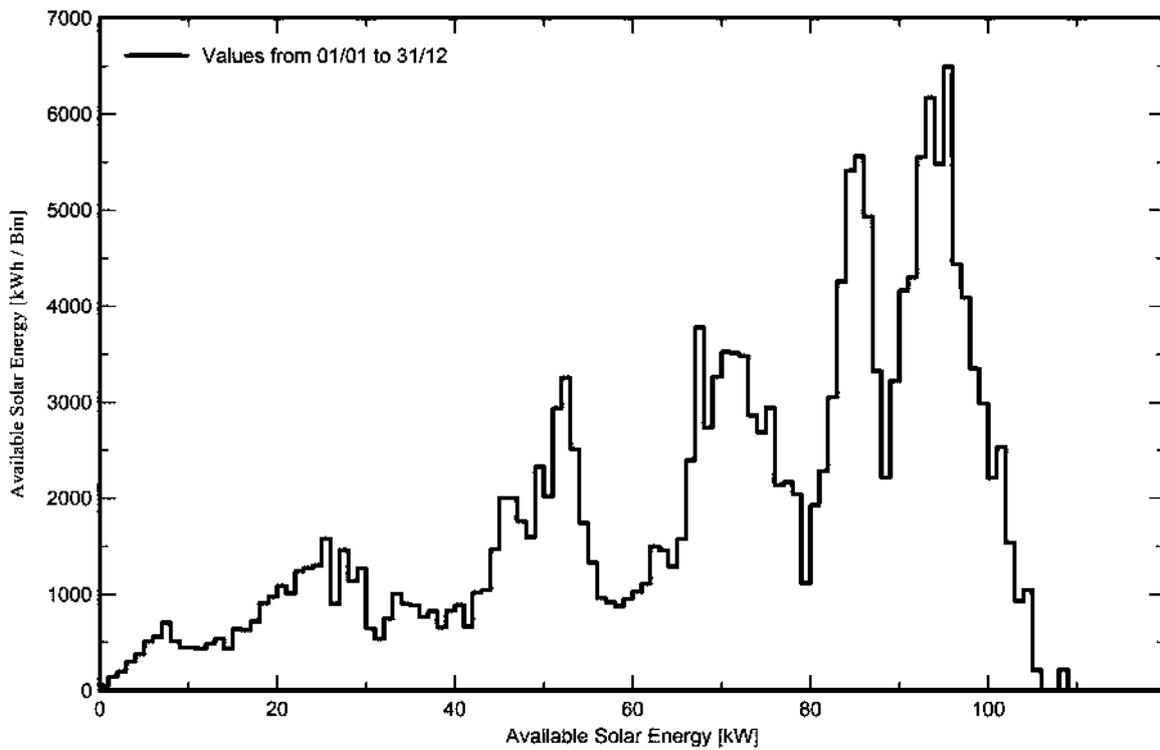
Adrián Cecilio Benito

Special graphs

Daily Input/Output diagram



System Output Power Distribution





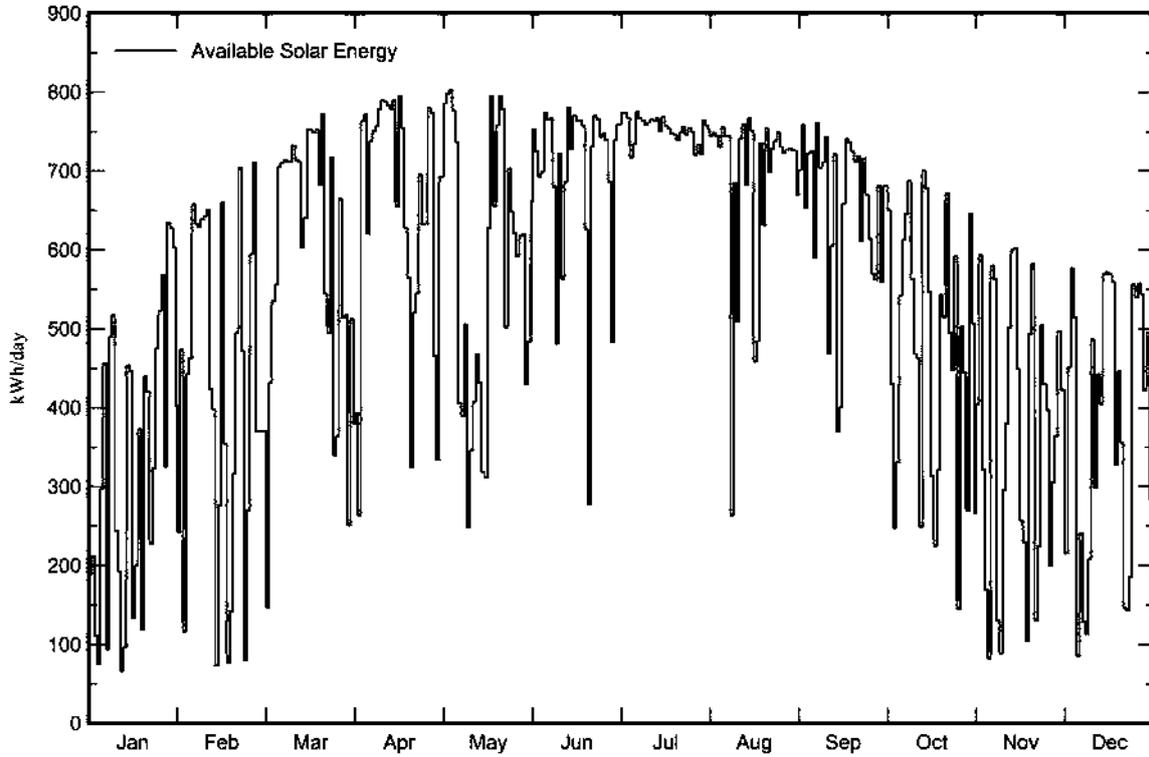
PVsyst V7.2.2

VC0, Simulation date:  
25/07/21 18:31  
with v7.2.2

Adrián Cecilio Benito

Predef. graphs

Daily System Output Energy



*PVsyst DEMO*

*PVsyst DEMO*



**PVsyst V7.2.2**

VC0, Simulation date:  
25/07/21 18:31  
with v7.2.2

Adrián Cecilio Benito

**Cost of the system**

**Installation costs**

Item	Quantity units	Cost EUR	Total EUR
DF ALCORCÓN PV PLANT			100'395.22
Total			100'395.22
Depreciable asset			0.00

**Operating costs**

Item	Total EUR/year
Maintenance	5'000.00
Total (OPEX)	5'000.00
Including inflation (2.02%)	6'422.45

**System summary**

Total installation cost	100'395.22 EUR
Operating costs (incl. inflation 2.02%/year)	6'422.45 EUR/year
Unused energy	170 MWh/year
Energy sold to the grid	30.3 MWh/year
Cost of produced energy (LCOE)	0.071 EUR/kWh





## PVsyst V7.2.2

VC0, Simulation date:  
25/07/21 18:31  
with v7.2.2

Adrián Cecilio Benito

## Financial analysis

## Detailed economic results (EUR)

	Electricity sale	Run. costs	Deprec. allow.	Taxable income	Taxes	After-tax profit	Self-cons. saving	Cumul. profit	% amorti.
2022	1'516	5'000	0	0	0	-3'484	25'059	-78'819	21.5%
2023	1'493	5'101	0	0	0	-3'608	25'566	-56'862	43.4%
2024	1'484	5'204	0	0	0	-3'720	26'072	-34'510	65.6%
2025	1'476	5'309	0	0	0	-3'833	26'578	-11'765	88.3%
2026	1'468	5'416	0	0	0	-3'949	27'084	11'371	111.3%
2027	1'460	5'526	0	0	0	-4'066	27'590	34'895	134.8%
2028	1'451	5'637	0	0	0	-4'186	28'097	58'805	158.6%
2029	1'443	5'751	0	0	0	-4'308	28'603	83'100	182.8%
2030	1'435	5'867	0	0	0	-4'433	29'109	107'777	207.4%
2031	1'427	5'986	0	0	0	-4'559	29'615	132'832	232.3%
2032	1'418	6'107	0	0	0	-4'689	30'121	158'265	257.6%
2033	1'410	6'230	0	0	0	-4'820	30'628	184'073	283.3%
2034	1'402	6'356	0	0	0	-4'954	31'134	210'252	309.4%
2035	1'394	6'485	0	0	0	-5'091	31'640	236'801	335.9%
2036	1'385	6'616	0	0	0	-5'230	32'146	263'717	362.7%
2037	1'377	6'749	0	0	0	-5'372	32'652	290'998	389.9%
2038	1'369	6'885	0	0	0	-5'517	33'159	318'639	417.4%
2039	1'361	7'025	0	0	0	-5'664	33'665	346'640	445.3%
2040	1'352	7'166	0	0	0	-5'814	34'171	374'997	473.5%
2041	1'344	7'311	0	0	0	-5'967	34'677	403'707	502.1%
2042	1'336	7'459	0	0	0	-6'123	35'183	432'767	531.1%
2043	1'328	7'610	0	0	0	-6'282	35'690	462'175	560.4%
2044	1'319	7'763	0	0	0	-6'444	36'196	491'927	590.0%
2045	1'311	7'920	0	0	0	-6'609	36'702	522'020	620.0%
2046	1'303	8'080	0	0	0	-6'777	37'208	552'451	650.3%
<b>Total</b>	<b>35'062</b>	<b>160'561</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>-125'499</b>	<b>778'345</b>	<b>552'451</b>	<b>650.3%</b>

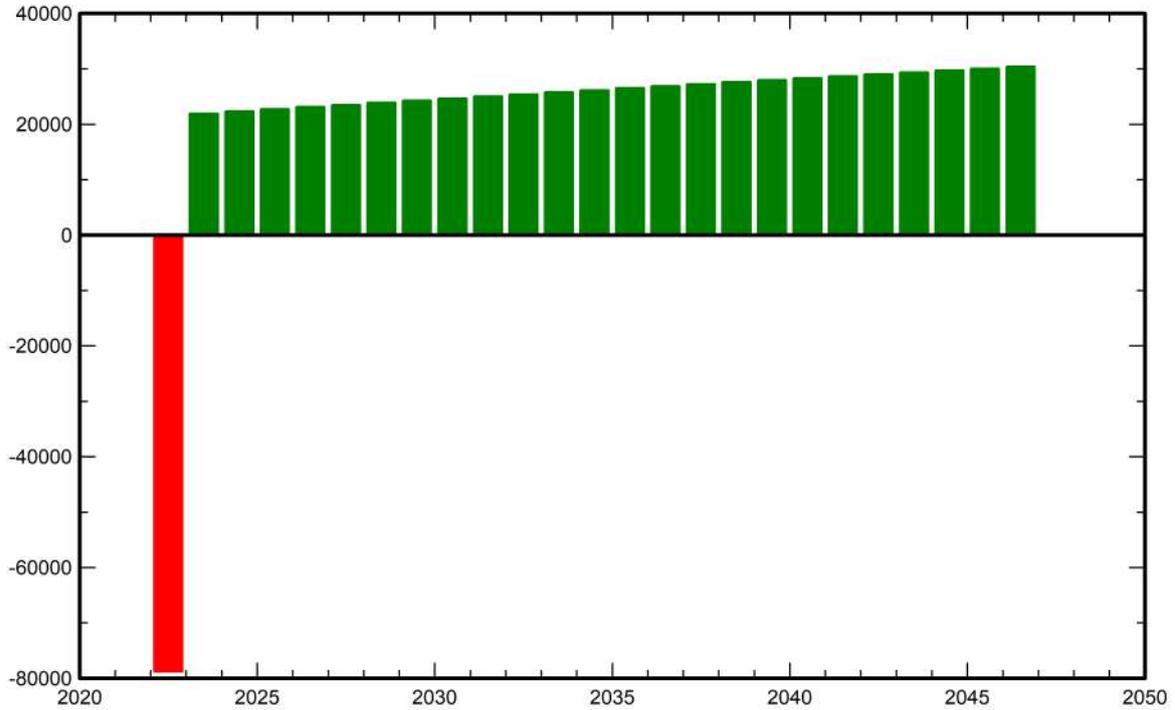


PVsyst V7.2.2

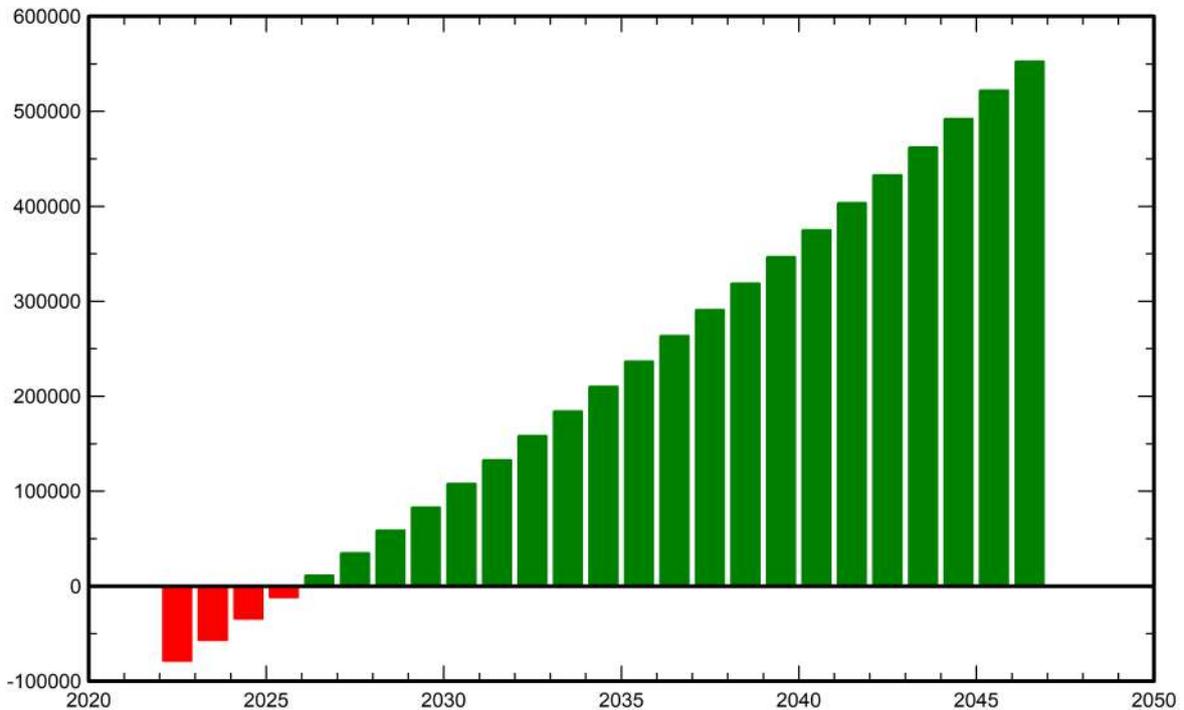
VC0, Simulation date:  
25/07/21 18:31  
with v7.2.2

Adrián Cecilio Benito

**Financial analysis**  
**Yearly net profit (EUR)**

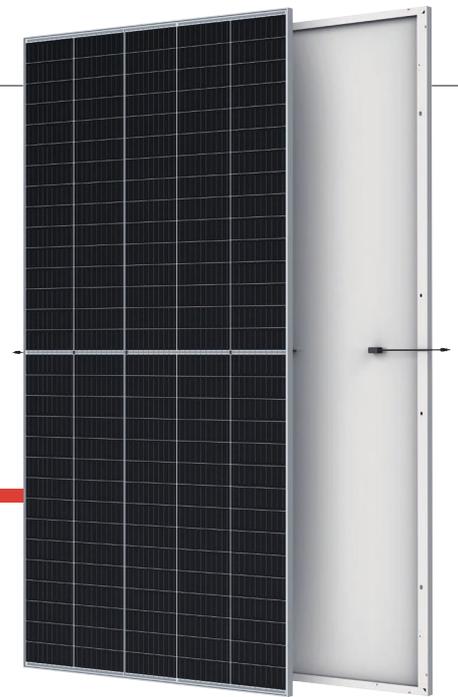


**Cumulative cashflow (EUR)**



# THE Vertex

## BACKSHEET MONOCRYSTALLINE MODULE



# 510W

MAXIMUM POWER OUTPUT

# 21.2%

MAXIMUM EFFICIENCY

# 0~+5W

POSITIVE POWER TOLERANCE

PRODUCTS  
TSM-DE18M(II)

POWER RANGE  
485-510W



### High customer value

- Lower LCOE (Levelized Cost Of Energy), reduced BOS (Balance Of System) cost, shorter payback time
- Lower guaranteed first year and annual degradation
- Designed for compatibility with existing mainstream system components
- Higher return on Investment



### High power up to 510W

- Large area cells based on 210mm silicon wafers and 1/3-cut cell technology
- Up to 21.2% module efficiency with high density interconnect technology
- Multi-busbar technology for better light trapping effect, lower series resistance and improved current collection



### High reliability

- Minimized micro-cracks with innovative non-destructive cutting technology
- Ensured PID resistance through cell process and module material control
- Resistant to harsh environments such as salt, ammonia, sand, high temperature and high humidity areas
- Mechanical performance up to 5400 Pa positive load and 2400 Pa negative load



### High energy yield

- Excellent IAM (Incident Angle Modifier) and low irradiation performance, validated by 3rd party certifications
- The unique design provides optimized energy production under inter-row shading conditions

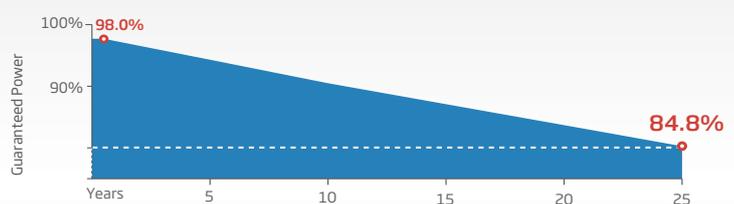
Founded in 1997, Trina Solar is the world's leading total solution provider for solar energy. With local presence around the globe, Trina Solar is able to provide exceptional service to each customer in each market and deliver our innovative, reliable products with the backing of Trina as a strong, bankable brand. Trina Solar now distributes its PV products to over 100 countries all over the world. We are committed to building strategic, mutually beneficial collaborations with installers, developers, distributors and other partners in driving smart energy together.

### Comprehensive Products and System Certificates

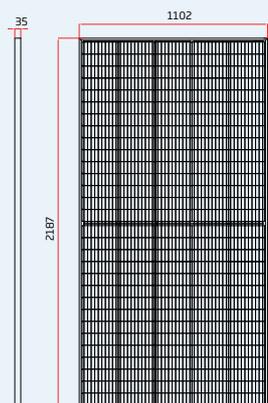
IEC61215/IEC61730/IEC61701/IEC62716  
 ISO 9001: Quality Management System  
 ISO 14001: Environmental Management System  
 ISO14064: Greenhouse Gases Emissions Verification  
 ISO45001: Occupational Health and Safety Management System



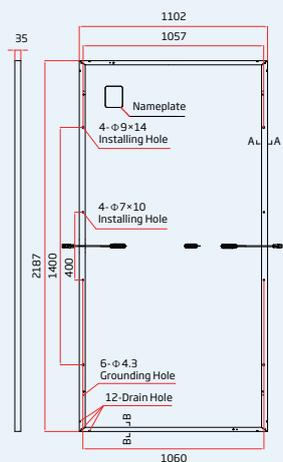
### Trina Solar's Vertex Backsheet Performance Warranty



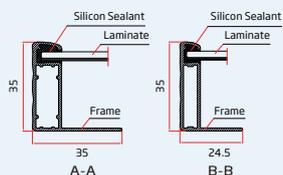
## DIMENSIONS OF PV MODULE(mm)



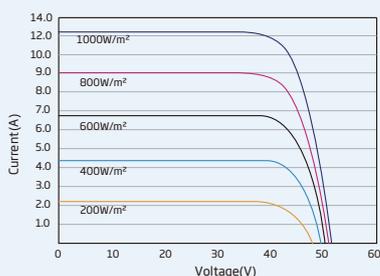
Front View



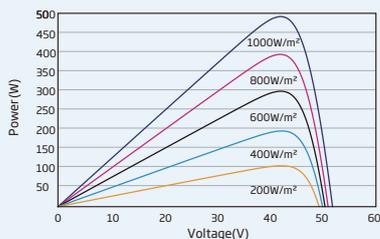
Back View



## I-V CURVES OF PV MODULE(495 W)



## P-V CURVES OF PV MODULE(495W)



## ELECTRICAL DATA (STC)

Peak Power Watts- $P_{MAX}$ (Wp)*	485	490	495	500	505	510
Power Tolerance- $P_{MAX}$ (W)	0 ~ +5					
Maximum Power Voltage- $V_{MPP}$ (V)	42.2	42.4	42.6	42.8	43.0	43.2
Maximum Power Current- $I_{MPP}$ (A)	11.49	11.56	11.63	11.69	11.75	11.81
Open Circuit Voltage- $V_{OC}$ (V)	51.1	51.3	51.5	51.7	51.9	52.1
Short Circuit Current- $I_{SC}$ (A)	12.07	12.14	12.21	12.28	12.35	12.42
Module Efficiency $\eta_m$ (%)	20.1	20.3	20.5	20.7	21.0	21.2

STC: Irradiance 1000W/m<sup>2</sup>, Cell Temperature 25°C, Air Mass AM1.5.

\*Measuring tolerance:  $\pm 3\%$ .

## ELECTRICAL DATA (NOCT)

Maximum Power- $P_{MAX}$ (Wp)	365	369	373	377	381	385
Maximum Power Voltage- $V_{MPP}$ (V)	39.9	40.0	40.2	40.4	40.6	40.5
Maximum Power Current- $I_{MPP}$ (A)	9.17	9.22	9.28	9.33	9.38	9.50
Open Circuit Voltage- $V_{OC}$ (V)	48.1	48.2	48.4	48.6	48.8	49.0
Short Circuit Current- $I_{SC}$ (A)	9.73	9.78	9.84	9.90	9.95	10.01

NOCT: Irradiance at 800W/m<sup>2</sup>, Ambient Temperature 20°C, Wind Speed 1m/s.

## MECHANICAL DATA

Solar Cells	Monocrystalline
Cell Orientation	150 cells
Module Dimensions	2187×1102×35 mm (86.10×43.39×1.38 inches)
Weight	26.5 kg (58.4 lb)
Glass	3.2 mm (0.13 inches), High Transmission, AR Coated Heat Strengthened Glass
Encapsulant Material	EVA
Backsheet	White
Frame	35 mm (1.38 inches) Anodized Aluminium Alloy
J-Box	IP 68 rated
Cables	Photovoltaic Technology Cable 4.0mm <sup>2</sup> (0.006 inches <sup>2</sup> ), Portrait: N 280mm/P 280mm(11.02/11.02inches) Landscape: N 1400 mm /P 1400 mm (55.12/55.12 inches)
Connector	MC4 EVO2 / TS4*

\*Please refer to regional datasheet for specified connector.

## TEMPERATURE RATINGS

NOCT(Nominal Operating Cell Temperature)	43°C ( $\pm 2^\circ\text{C}$ )
Temperature Coefficient of $P_{MAX}$	- 0.34%/ °C
Temperature Coefficient of $V_{OC}$	- 0.25%/ °C
Temperature Coefficient of $I_{SC}$	0.04%/ °C

(Do not connect Fuse in Combiner Box with two or more strings in parallel connection)

## WARRANTY

12 year Product Workmanship Warranty
25 year Power Warranty
2% first year degradation
0.55% Annual Power Attenuation

(Please refer to product warranty for details)

## MAXIMUM RATINGS

Operational Temperature	-40 ~ +85 °C
Maximum System Voltage	1500V DC (IEC)
Max Series Fuse Rating	20A

## PACKAGING CONFIGURATION

Modules per box: 31 pieces
Modules per 40' container: 620 pieces

# SUN2000-100KTL-M1 Smart PV Controller



10  
MPP Trackers



98.8% (@480V)  
Max. Efficiency



String-level  
Management



Smart I-V Curve Diagnosis  
Supported



MBUS  
Supported



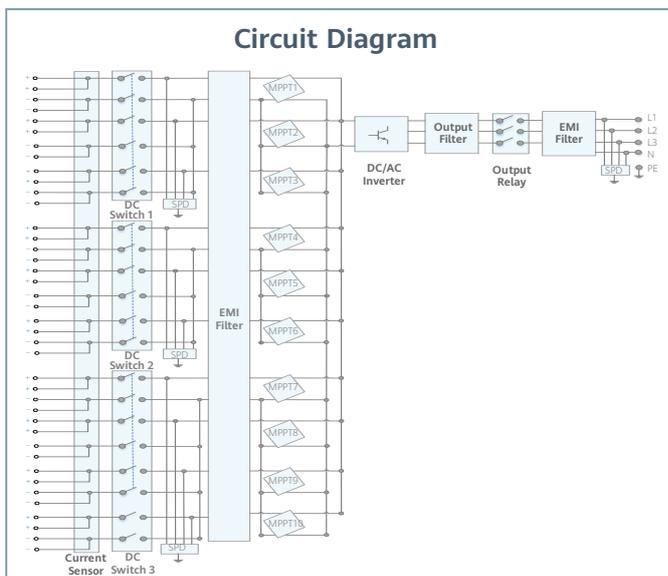
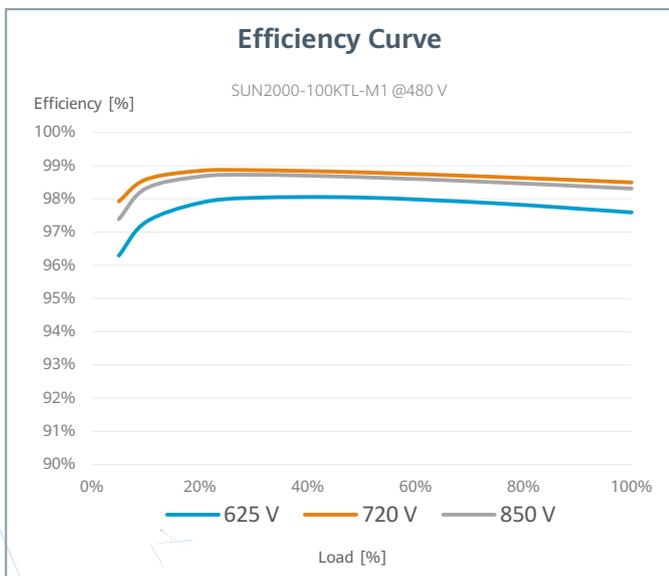
Fuse Free  
Design



Surge Arresters for  
DC & AC



IP66  
Protection



Technical Specification	SUN2000-100KTL-M1
-------------------------	-------------------

Efficiency	
Max. efficiency	98.8% @480 V, 98.6% @380 V / 400 V
European efficiency	98.6% @480 V, 98.4% @380 V / 400 V

Input	
Max. Input Voltage <sup>1</sup>	1,100 V
Max. Current per MPPT	26 A
Max. Short Circuit Current per MPPT	40 A
Start Voltage	200 V
MPPT Operating Voltage Range <sup>2</sup>	200 V ~ 1,000 V
Nominal Input Voltage	720 V @480 Vac, 600 V @400 Vac, 570 V @380 Vac
Number of MPP trackers	10
Max. input number per MPP tracker	2

Output	
Nominal AC Active Power	100,000 W
Max. AC Apparent Power	110,000 VA
Max. AC Active Power (cosφ=1)	110,000 W
Nominal Output Voltage	480 V/ 400 V/ 380 V, 3W+(N)+PE
Rated AC Grid Frequency	50 Hz / 60 Hz
Nominal Output Current	120.3 A @480 V, 144.4 A @400 V, 152.0 A @380 V
Max. Output Current	133.7 A @480 V, 160.4 A @400 V, 168.8 A @380 V
Adjustable Power Factor Range	0.8 leading... 0.8 lagging
Max. Total Harmonic Distortion	< 3%

Protection	
Input-side Disconnection Device	Yes
Anti-islanding Protection	Yes
AC Overcurrent Protection	Yes
DC Reverse-polarity Protection	Yes
PV-array String Fault Monitoring	Yes
DC Surge Arrester	Type II
AC Surge Arrester	Type II
DC Insulation Resistance Detection	Yes
Residual Current Monitoring Unit	Yes
Arc Fault Protection	Optional

Communication	
Display	LED indicators; WLAN adaptor + FusionSolar APP
RS485	Yes
USB	Yes
Smart Dongle-4G	4G / 3G / 2G via Smart Dongle – 4G (Optional)
Monitoring BUS (MBUS)	Yes (isolation transformer required)

General Data	
Dimensions (W x H x D)	1,035 x 700 x 365 mm
Weight (with mounting plate)	90 kg
Operating Temperature Range	-25°C ~ 60°C
Cooling Method	Smart Air Cooling
Max. Operating Altitude	4,000 m (13,123 ft.)
Relative Humidity	0 ~ 100%
DC Connector	Staubli MC4
AC Connector	Waterproof Connector + OT/DT Terminal
Protection Degree	IP66
Topology	Transformerless
Nighttime Power Consumption	< 3.5 W

Standard Compliance (more available upon request)	
Certificate	EN 62109-1/-2, IEC 62109-1/-2, EN 50530, IEC 62116, IEC 61727, IEC 60068, IEC 61683
Grid Connection Standards	VDE-AR-N4105, EN 50549-1, EN 50549-2, RD 661, RD 1699, C10/11

<sup>1</sup> The maximum input voltage is the upper limit of the DC voltage. Any higher input DC voltage would probably damage inverter.  
<sup>2</sup> Any DC input voltage beyond the operating voltage range may result in inverter improper operating.

## Document II

# TECHNICAL SPECIFICATIONS



# Document II. Technical Specifications

## Table of Contents

<b>1</b>	<b>Reference Framework</b>	<b>167</b>
1.1	Purpose of the Document . . . . .	167
1.2	Applicable Regulation . . . . .	167
1.3	General Provisions . . . . .	168
1.4	Project Framework . . . . .	168
1.5	Economic Valuation . . . . .	169
1.6	Tools and Instrumentation . . . . .	169
1.7	Control of Materials and Equipment . . . . .	170
<b>2</b>	<b>Electrical Works</b>	<b>171</b>
2.1	Generalities . . . . .	171
2.2	Electrical Canalisation . . . . .	171
2.3	Electrical Connections . . . . .	172
2.4	Insulated Wire Colours . . . . .	173
2.5	Ground System . . . . .	173
<b>3</b>	<b>Components and Materials</b>	<b>175</b>
3.1	Generalities . . . . .	175
3.2	Photovoltaic Modules . . . . .	176
3.3	Inverter . . . . .	176
3.4	Electrical Wires . . . . .	177
3.5	Grid Connection . . . . .	178
3.6	Measurement Devices . . . . .	178
3.7	Electrical Protections . . . . .	178
3.8	Ground System of the PV Facility . . . . .	179
3.9	Support Structure . . . . .	179
3.10	Harmonics and Electromagnetic Compatibility . . . . .	179
<b>4</b>	<b>Responsibilities, Reception and Tests</b>	<b>181</b>
4.1	Contractor . . . . .	181
4.2	Construction Project Manager . . . . .	182
4.3	Reception of the Construction Work . . . . .	182



# Section 1

## Reference Framework

### Contents

---

1.1	Purpose of the Document . . . . .	167
1.2	Applicable Regulation . . . . .	167
1.3	General Provisions . . . . .	168
1.4	Project Framework . . . . .	168
1.5	Economic Valuation . . . . .	169
1.6	Tools and Instrumentation . . . . .	169
1.7	Control of Materials and Equipment . . . . .	170

---

### 1.1 Purpose of the Document

The target of the Technical Specifications document consists of establishing the minimum technical requirements that the grid-connected PV plant must meet. The specifications developed are intended as a guide both for project installers and manufacturers. The document defines the minimum specifications that the PV facility must comply with to ensure its quality for the sake of the client while fostering the development of the technology and the project itself.

Therefore, the ultimate quality of the project will be assessed in terms of its performance and production. The scope of this Technical Specifications Document extends to the mechanical, the electrical and the electronic systems that constitute the facility.

Other than the alternatives outlined through this formal document, different solutions may be adopted exceptionally due to the own nature of the project or the development of the technology. Nevertheless, any needed variation must be properly and sufficiently justified, and will never imply a mitigation of the quality requirements presented herein. Besides, any alteration has to be previously authorised by the construction project manager.

### 1.2 Applicable Regulation

This Technical Specifications Document is entirely related to photovoltaic solar facilities intended for the generation of electricity at distribution level. Consequently, all the regulation related to solar power plants must be considered.

Specifically, the Royal Decrees that have been considered for this document are listed below:

- Royal Decree 842/2002, of second of August, which approves the Electrotechnical Regulation for Low Voltage.
- Royal Decree 1454/2005, of second of December, which modifies certain provisions related to the electric power sector.
- Royal Decree 314/2006, of seventeenth of March, which approves the Spanish Technical Building Code.
- Royal Decree 661/2007, of twenty fifth of May, which regulates the production of electrical energy under special regime.
- Royal Decree 1110/2007, of twenty fourth of August, which approves the unified regulation on points of measurement in the electrical power system.
- Royal Decree 1699/2011, of eighteenth of November, which regulates the connection to the national grid of low power electric generation facilities.
- Law 24/2013, of twenty sixth of December, related to the electric power sector.
- Royal Decree 413/2014, of sixth of June, which regulates the electricity generation by means of renewable, cogeneration and waste facilities.
- Royal Decree 900/2015, of ninth of October, which regulates the administrative conditions, technical and economic modalities of electricity supply with self-consumption as well as the self-consumption production.
- Royal Decree-Law 15/2018, of fifth of October, which establishes urgent measures for energy transition and consumer protection.
- Royal Decree 244/2019, of fifth of April, which regulates the administrative, technical and economic conditions for self-consumption in Spain.

### 1.3 General Provisions

The different documents that make up this engineering project complement each other. Thus, if a specific construction work is indicated in some plans but it does not appear in other plans, it must be executed by the CONTRACTOR anyhow without any compensation. Nonetheless, the information will be consulted and contrasted with the CONSTRUCTION PROJECT MANAGER before executing any work that may give rise to different interpretations

The same criteria are applied to both the supplementary materials and works not mentioned in the project, or in case of any erroneous work description that omits indispensable technical details which are generally admitted as necessary for the normal execution of construction works.

The OWNER reserves the right to make changes in the facility plans after the award, providing always the necessary sketches. These modifications do not imply budget variations unless leading to a change unforeseeable during the tender phase.

### 1.4 Project Framework

The readiness for the construction works execution is implicitly assumed by the mere fact of participating in the tender. Additionally, the CONTRACTOR acknowledges having visited the site, ascertained the accessibility as well as the execution conditions, etc. Consequently, it is assumed that the required execution works have been properly assessed.

Therefore, no claims will be accepted on the part of the CONTRACTOR related to omissions, errors within the plans or any other misunderstood technical or non-technical fact. In this sense, any figure or number provided in the project has only information purposes.

The CONTRACTOR must always have on site an appropriate headcount for the execution of the assembly program according to the task being carried out. Moreover, the staff will be specific for each duty and will have the required preparation for the achievement of every work. Besides, all the construction guilds will work in a coordinated harmony in order to ensure the success of the project.

In the execution of the works that have been agreed between both parties, the CONTRACTOR will be the sole responsible, not having the right to any compensation for the higher costs incurred, nor for the wrong manoeuvres committed during the execution and neither for technical inspections due to negligences during the execution. Similarly, it will also be liable before the courts for accidents occurred during the execution both due to inexperience or due to safety issues not properly faced.

In case the CONSTRUCTION PROJECT MANAGER declares any part of the work as poorly executed, the CONTRACTOR shall have the obligation to demolish the affected zone and re-execute it as many times as necessary, not having the right to any kind of compensation.

The CONTRACTOR may not do any work that implies a supplement of expenses without written authorisation from the CONSTRUCTION PROJECT MANAGER. Additionally, in case of using materials with higher qualities and prices than those initially stipulated, the expenses will be assumed by the CONTRACTOR.

All taxes on the goods and assets to be supplied as well as the levies on labour and accessories will be faced by the CONTRACTOR .

## 1.5 Economic Valuation

The economic valuation of the units actually required during the construction work will be deducted by multiplying the number of units by the unit price stipulated. In this sense, the total sum will not exceed the total budget approved among both parties under no circumstances. Consequently, the number of units contemplated in the project measurements will not be considered for the final economic valuation.

The construction works not completed will be paid according to the unit prices stated in the budget. Therefore, other economic valuation criteria will not be accepted.

Auxiliary construction works will be credited according to the project measurements, the conditions and the unit prices established by the outsourced construction company.

## 1.6 Tools and Instrumentation

The CONTRACTOR will bring all the required tools and instrumentation as well as the equipment needed for the correct development of each construction task.

Hence, there must be on the construction site any tool or instrumentation necessary for both the correct execution and the commissioning of the facility, id est: insulation meters, underground cable fault detectors, multimeters, equipment for earth measuring and for relay taring, etc.

The CONSTRUCTION PROJECT MANAGER reserves the right to refuse at any time all those tools or instrumentation considered inadequate.

## 1.7 Control of Materials and Equipment

The supply of all the materials and equipment required during the construction will be managed by the CONTRACTOR.

The CONTRACTOR shall be responsible for the management of all the materials and equipment, including the workforce as well as the means needed for goods reception both in the factory and on the construction site. The storage, preservation, handling, transport and maintenance even after assembling the equipment will also be managed by the CONTRACTOR, at least until the final delivery of the construction to the CONSTRUCTION PROJECT MANAGER.

The CONTRACTOR shall satisfactorily repair or replace all materials and equipment that could result damaged or unusable due to the improper or incomplete development of its chores.

The CONSTRUCTION PROJECT MANAGER will have access and may supervise all the activities related to the manufacture, storage, handling and maintenance of both equipment and materials. The CONTRACTOR will establish the corresponding general procedure for storage, handling and maintenance in the Quality Plan of the Construction Work. Within this plan, both the technical and operational aspects of the storage of all the equipment and materials must be considered, including a specific definition of the required processes, the technical conditions as well as the responsibilities for each activity.

The filler materials must be stored in a conditioned area, free of humidity and with a suitable ambient temperature.

## Section 2

# Electrical Works

### Contents

2.1	Generalities . . . . .	171
2.2	Electrical Canalisation . . . . .	171
2.3	Electrical Connections . . . . .	172
2.4	Insulated Wire Colours . . . . .	173
2.5	Ground System . . . . .	173

---

### 2.1 Generalities

This second section of the document is mainly based on the Spanish Electrotechnical Regulation for Low Voltage [19]. Hence, the section covers the assembly specifications of the electrical canalisation. Nonetheless, it includes not only the canalisation *per se*, but also the fastening system, the covers and the protection shields considered in the design, deployment or connection of wires, as well as the ground system and the light system.

The general instructions and requirements that must be respected for the suitable preparation, execution and documentation of the assembly works are presented in this section.

### 2.2 Electrical Canalisation

Prior to the construction works, the CONTRACTOR will carry out a detailed stakeout according to the specific location of the equipment, the general geometry and the layout of the structure.

Additionally, the next two points should be taken into account in terms of the electrical canalisation:

- The routing of the canalisation will be done by means of parallel lines that will follow the vertical and horizontal lines of the structures and walls that withstand or delimit the canalisation itself.
- The detailed stakeout developed by the CONTRACTOR on the construction site will be presented to the CONSTRUCTION PROJECT MANAGER and will require its approval before kicking off each piece of work.

The canalisation may be of any of the following materials:

- Concrete.
- Cement.
- Fibre cement.
- Plastic or synthetic.
- Metal.

## 2.3 Electrical Connections

Before the final connection of the equipment through the sized cables, the CONTRACTOR shall carry out the following operational checks:

- The wire strands will be stripped by means of the appropriate tools in order not to damage the wire nor the cable insulation.
- It will be carried out a full test of the cables continuity before the execution of any connection. The verification must be done in open-circuit conditions with a DC battery acting as the power supply. The usage of a acoustic-luminous device during the test will be mandatory.
- It will also be carried out a thorough and complete insulation test between conductors and between every conductor and ground.
- The insulation resistance value will be computed multiplying by 100 the maximum service voltage, obtaining a result measured in ohms. Thus, the maximum leakage current is set to 10 *mA* performing the analysis according to the applicable regulation [72, 73]. Then, the resistance obtained will be considered acceptable if and only if it is equal or exceeds a value of 0.25 *MΩ*. In practice, the measurement of the insulation resistance will be done throughout a Megger® [74] which must be able to provide:
  - **Low Voltage Circuits.** A no-load DC voltage between 500 *V* and 1000 *V*.
  - **High Voltage Circuits.** A no-load DC voltage between 2500 *V* and 5000 *V*.

In order to ensure that all the required tests that have been mentioned above are correctly developed, the CONTRACTOR will prepare a formal Procedure for the Electrical Continuity and Wire Insulation Test that will be handed to the CONSTRUCTION PROJECT MANAGER.

The specified document must capture the following information in a detailed manner:

- Devices within the facility and its schemes to verify the electrical continuity of the cables.
- Required measures of the insulation resistance.
- Devices and its schemes needed to measure the insulation resistance.
- Table with the admissible insulation resistance depending on the service voltage applied.
- Mandatory precautionary measures required during the analysis and test processes.

The connection of the different strands will be done by means of a crimping tool that shall ensure a control over the pressure applied over the terminals. The terminal used in both electrical cabinets and panels will be peak or eyelet type and generally pre-insulated, depending on the point where it will be connected.

The cable and the required strands must be labelled in parallel to the execution of the electrical connections.

## 2.4 Insulated Wire Colours

The colour of the insulated wires will respect the applicable legislation according to the Spanish Electrotechnical Regulation for Low Voltage.

Therefore, the identifying colour of each wire will be [75]:

- Neutral: pale blue.
- Protection: green-yellow.
- Phase: black.
- Phase: brown.
- Phase: grey.

The layout of the cables will also follow the applicable technical instruction of the Electrotechnical Regulation for Low Voltage [76]. Then, each cable end must be supplied with an authorised identification.

## 2.5 Ground System

The join between cables or between cables and bared copper strips will be done according to the instructions provided in the Project Memory (document I), applying one of the techniques mentioned below:

- Aluminium-thermal welding.
- Bolted joints.
- Terminals.

In the particular case of welded joints, the CONTRACTOR will execute a formal document called Procedure for the Completion of a Aluminium-Thermal Welding, which must be approved by the CONSTRUCTION PROJECT MANAGER. The procedure must include a description of the variables of the process as well as the ways and means required for the compliance of the conditions presented below:

- **Preparation of Joins:**

- The conductive materials will be cleaned before the join until having the characteristic metal shine. Both a sandpaper or steel brush can be used for this operation.
- Wet or damp conductors must be perfectly dry before the join, since welding in such circumstances would cause the appearance of porosity, constituting a rejected union.
- The conductors that have been treated with oils or grease will be previously degreased by means of a suitable product.
- The moulds used to carry out the welding will be those recommend by the approved manufacturer depending on the materials to be joined.
- Adding supplements to the moulds will not be allowed. Therefore, there will be a specific and unique mould design for each type of welded joint.

- 
- The moulds will be properly cleaned and dried before welding works.
  - **Execution of the Welding:**
    - The instructions of the manufacturer must be taken into account and reflected on the welding procedure.
    - The heat produced during the joining process will not cause the fusion of any of the elements to be joined.
    - The welding procedure must present the criteria used to approve or reject a welding. Additionally, it must be detailed that any welding containing cracks, pores or spills will be totally rejected.
    - The maximum number of times that the same mould can be used will be established according to the manufacturer recommendation. Nonetheless, the maximum number of usages will not exceed 50 welds under no circumstances. Moreover, a random 5% of the joins made with the same mould will be tested as an additional security measure.
  - **Special Bolted Joints:** The bolted joints between platens or those that include special staples or terminals will be performed considering some key warnings:
    - Previously, the contact surfaces will be carefully cleaned in order to accomplish a join with the minimum electrical resistance.
    - The cleaning process explained in the previous bullet point will be carried out without eliminating the galvanised of the platens. This approach will be applied to any other galvanised structure.
    - The CONTRACTOR will apply the required tightening torque to bolts and screws in order to ensure the continuity of the join.

## Section 3

# Components and Materials

### Contents

---

3.1	Generalities . . . . .	175
3.2	Photovoltaic Modules . . . . .	176
3.3	Inverter . . . . .	176
3.4	Electrical Wires . . . . .	177
3.5	Grid Connection . . . . .	178
3.6	Measurement Devices . . . . .	178
3.7	Electrical Protections . . . . .	178
3.8	Ground System of the PV Facility . . . . .	179
3.9	Support Structure . . . . .	179
3.10	Harmonics and Electromagnetic Compatibility . . . . .	179

---

### 3.1 Generalities

This third section of the document is mainly based on the regulated Technical Specifications of Grid-Connected Facilities [77].

As a general principle, at least a class II electrical insulation level must be ensured regarding both equipment and materials, including the photovoltaic modules, the inverter, the wires as well as the electrical boxes and cabinets [78].

The facility will include all the required elements and features to ensure the power supply quality at any moment. The operation of the PV plant should not cause breakdowns within the power system, nor a decrease in the safety conditions of the grid nor any other alteration not permitted by the regulation.

Likewise, the operation of the PV plant shall not result in dangerous work conditions for the maintenance and exploit staff of the national distribution grid.

The materials located in outdoor environments will be thoroughly protected against weather conditions, specially against the long term effect of the solar radiation and the humidity.

All the safety elements and the protection required to ensure the security of both the individuals and the facility itself will be included. In this respect, the protection against direct and indirect contact, short-circuits and against electrical overloads must be guaranteed. Additionally, any protective element needed in accordance with the current legislation will have to be incorporated.

In terms of safety and operation of the facility equipment, every label or indicator will be written in any of the Spain official languages according to the facility location. Besides, this information must be placed in an accessible area to ease its consultation and verification.

### 3.2 Photovoltaic Modules

Every PV module will have to comply with the regulated specifications [79], as well as being qualified by a recognised laboratory such as TÜV SÜD® [80]. This information will be accredited by the corresponding official certificate.

The PV modules will contain in a indelible and visible manner the model and the manufacturer name or logo. Besides, every module shall have an individual identification number or a series number related to its manufacture date.

The modules will have to fit with the technical features described in the whole engineering project, including the technical specifications exposed in this document. In case of variations with respect to these features, the hypothetical approval would be provided by the CONSTRUCTION PROJECT MANAGER, who would have to make a decision regarding two documents that must be presented by the CONTRACTOR: the certification of the modules and the justification of the change.

A PV module will be considered acceptable only if the actual maximum power and the short-circuit current referred to the Standard Testing Conditions (STC) are comprehended within a  $\pm 10\%$  margin of the rated values specified in the data sheet.

The PV modules will be rejected in case manufacturing defects such as stains or breaks are present at any element, or if there is a lack of alignment between cells or even between bubbles in the encapsulant. High efficiency of the cells will be positively valued.

In order to ease the maintenance and the repair of the PV modules as well as due to safety reasons, the required protective elements including fuses and circuit breakers will be installed. Thus, the protective system has to enable the independent disconnection of the DC and the AC side, as well as the different strings of the photovoltaic field.

### 3.3 Inverter

The inverter has to be suitable for its connection to the national power grid, as well as tolerant to variable input power to provide the maximum power available in the photovoltaic field at any moment.

The basic features required for the inverter are summarised below:

- Operating principle as a current source.
- Automatically commuted.
- Automatic tracking of the maximum power point within the photovoltaic field.
- It will not work in islanding mode under no circumstances.

The inverter must comply with the Electromagnetic Compatibility and the Electrical Security Directives developed by the European Union Commission [81, 82]. Both community directives must be certified by the manufacturer through the incorporation of protective measures.

These protective measures must act as a barrier against various phenomena:

- Short-circuits in the alternating current side.
- Grid voltage out of range.
- Grid frequency out of range.
- Overvoltages, avoided through varistors or a similar device.
- Disturbances present in the grid such as short voltage interruptions, pulses, cycle defects, absence and return of the grid, etc.

The inverter will count with the signalling needed to ensure its correct operation and will incorporate the essential automatic controls to enable its supervision and handling.

Moreover, the inverter will include at least the following manual controls:

- General switching on/off of the inverter.
- Connection and disconnection of the inverter to the AC interface.

The electrical features required for the inverter are explained below:

- The inverter will deliver power in a continuous way even when the solar irradiance is a 10% greater than the STC conditions. Besides, the inverter must withstand peaks with a magnitude 30% greater than the STC conditions during periods up to ten seconds.
- The efficiency values at the 25% and at the 100% of the rated output power will have to be higher than 85% and 88% respectively for inverters with a rated power lower than 5 kW; and higher than 90% and 92% for inverters with a rated power greater than 5kW [83].
- The self-consumption required by the inverter in night mode, id est, in no-production mode, has to be lower than the 5% of its rated power.
- The power factor of the generated power shall be greater than 0.95 as long as the inverter works between 25% and 100% of its rated power.

The inverter will have a minimum protection degree according to the current legislation [84]:

- Inverter at an inaccessible location within a building: minimum IP 20.
- Inverter at an accessible location within a building: minimum IP 30.
- Inverter located at an outdoor environment: minimum IP 65.

The inverter must be able to operate properly between 0°C and 40°C and between 0% and 85% of relative humidity.

### 3.4 Electrical Wires

The positive and negative of each group of modules will be disposed separately and protected in accordance with the applicable regulation.

The electrical conductors will be copper wires with the proper section in order to avoid an excessive voltage drop and possible overheating issues. Specifically, regardless of the working conditions, both the DC side and the AC side conductors will have enough section to ensure a

voltage drop lower than 1.5%. The reference voltage must be measured at the connection boxes, considering the whole length of the wires.

The length of the cables must be enough to avoid the generation of stress forces at any element of the facility nor the possible stumble due to the normal transit of people.

The direct current cables will have double insulation and will be suitable for outdoor environments, either its installation uncovered or underground [85].

### 3.5 Grid Connection

The grid connection of the PV facility must comply with the Royal Decree 1699/2011, which regulates the connection to the national grid of low power electric generation facilities.

Specifically, article 13 must be carefully respected. In this sense, the connection of the PV plant will be done at the closest point to the general protection box within the consumer grid, in order to protect simultaneously the generation plant and the consumer loads.

In case of having a connection point to the national distribution grid in high voltage, since there must be a power transformer owned by the consumer, the PV facility will be connected to the electrical panel located at the low voltage output of the transformer.

The OWNER of the internal grid, id est, the consumer, must be the same owner of every single load or generation facility connected to its power grid.

The generation plants connected to an internal grid will never have a rated power greater than 100 *kW*. In any case, the facility may not exceed the available capacity at connection point to the distribution network or the power assigned to the consumer [86].

### 3.6 Measurement Devices

The measurement devices of the PV facility must comply with the Royal Decree 1110/2007, which approves the unified regulation on points of measurement in the electrical power system.

Specifically, articles 8 and 9 within the Royal Decree shall be carefully respected. In this sense, the PV facility and the measurement equipment must supply the data required for the correct invoicing of each consumer depending on the access tariff and the balance between the energy consumed from the grid and injected to the grid. Of course, both the reactive power and the active power demanded by the consumer will have to be controlled [87].

### 3.7 Electrical Protections

The electrical protections of the PV facility must comply with the Royal Decree 1699/2011, which regulates the connection to the national grid of low power electric generation facilities.

Specifically, article 14 must be carefully respected. In this sense, for three-phase connections every phase must be protected to be able to withstand [21]:

- The minimum and the maximum connection frequency: 48 *Hz* and 50.5 *Hz* respectively.
- The minimum and maximum phase voltage:  $0,85 \cdot V_{rated}$  and  $1.15 \cdot V_{rated}$  respectively.

Regardless of the voltage at which a PV plant is connected to the network, it will be equipped with a protection system that guarantees the disconnection in case of a network failure or an internal failure. Then, the PV plant cannot disturb the proper operation of the distribution networks even during an incident.

### 3.8 Ground System of the PV Facility

The ground system of the PV facility must comply with the Royal Decree 1699/2011, which regulates the connection to the national grid of low power electric generation facilities.

Specifically, article 15 must be carefully respected. In this sense, the ground system of the interconnected facilities will be done without disturbing the ground system conditions of the distribution grid, ensuring that no defects are transmitted to the distribution network. Additionally, the electrical ground of the generation PV plant will be connected to a ground system independent of the distribution company neutral wire [88].

### 3.9 Support Structure

The support structure must be able to withstand, taking into account the weight of the PV panels, both the wind load and the snow load. Additionally, the design and construction of the structure will enable the thermal expansion processes related to changes of temperature.

The design of the PV support structure will be done considering the optimal tilt and azimuth angles specified in the Project Memory (document I). The screws will be made of stainless steel. In the event of a galvanised PV support structure, galvanised screws will be accepted too, except for fastening the modules to the structure, which will be screws of stainless steel.

Depending on the profiles material, different specifications must be followed:

- Rolled steel cold formed: UNE-EN 10219-1 and UNE-EN 10219-2.
- Hot galvanised steel: UNE-EN ISO 14713, UNE-EN ISO 10684 and UNE-EN ISO 1461.

The structure itself will not cast any shadow to the modules. In case of installing the structure on the roof of a building, the sealing of the building roof must be guaranteed.

### 3.10 Harmonics and Electromagnetic Compatibility

The harmonics and electromagnetic compatibility of the PV facility must comply with the Royal Decree 1699/2011, which regulates the connection to the national grid of low power electric generation facilities.

Specifically, article 16 must be carefully respected. In this sense, the distribution company can analyse the wave quality in the connection point prior to commissioning the facility. In fact, the distribution company can install with this purpose a network analyser in the connection point once notified to the consumer. The aim of the quality of service audit stands for reviewing that the PV plant does not affect to other consumers nor to the distribution grid beyond the established limits [89].



## Section 4

# Responsibilities, Reception and Tests

### Contents

---

4.1 Contractor . . . . .	<b>181</b>
4.2 Construction Project Manager . . . . .	<b>182</b>
4.3 Reception of the Construction Work . . . . .	<b>182</b>

---

### 4.1 Contractor

The CONTRACTOR will present to the OWNER of the facility a delivery note in document format containing the supplied components, materials, data sheets, as well as the maintenance and operation requirements according to each manufacturer.

This formal document will be signed by both parties involved and each of them will keep an original copy. The data sheets must be written in Spanish in order to ease its interpretation by the maintenance team.

Before commissioning the PV modules, the inverter or any signal meter, these main components must have overcome a factory test run. Therefore, any of these components will require a quality certified without which will not be accepted.

Regardless of the aforementioned requirements within this document, the CONTRACTOR will have to complete at least the following tests and tasks [90]:

- Operation and commissioning of all systems.
- Develop start and stop tests under different operating statuses.
- Testing all the elements and measures related to protection, security and alarm.
- Once the test and commissioning of the facility is completed, the provisional reception of the construction work can take place. Nonetheless, the record will not be signed until every component within the PV plant have worked properly for 240 consecutive hours, without any kind of interruption nor stop due to failures or system errors. Besides, the record will not be signed if either of the following requirements are not met:
  - Submission of all the documentation within these technical specifications.
  - Removal of all the excess material from the construction site.
  - Cleaning of all occupied areas and transporting all the waste to dump.

- The CONTRACTOR will be the sole responsible of the system operation while the provisional reception record is not signed. Thus, it is assumed that the CONTRACTOR workers have the required training.
- The CONTRACTOR will have to repair the faults that may occur if its origin is related to hidden defects in the design or materials, or if related to the construction or assembly phase. Then, the CONTRACTOR commits to solve these issues without charge.
- In any case, the CONTRACTOR must abide by the provisions of current legislation regarding hidden defects [91].

## 4.2 Construction Project Manager

Before signing the final certificate of the construction work, the main responsibilities of the CONSTRUCTION PROJECT MANAGER can be summarised as follows:

- Prepare as many complementary documents and rectifications as required.
- Attend the construction works as many times as required to solve the contingencies that may occur, as well as to establish the precise sequence to get the correct solution.
- Approve both the partial certifications of the construction work and the final settlement, and advise the OWNER on the act of reception.
- Plan the quality and economic control of the construction work taking into account the project itself, the contract and the technical regulation.
- Approve the Health and Safety Study for its application in the construction site.
- Carry out the stakeout of the construction work and prepare the corresponding records with the CONTRACTOR acceptance.
- Check the temporary facilities, auxiliary means and the Labour Risk Prevention systems, controlling the correct execution.
- Manage the material execution in accordance with the project itself, the technical standards and the applicable regulation.
- Carry out the required revisions to ensure the constructive quality in accordance with the project specifications and the applicable technical regulation.
- Complete the measurements of performed work and give conformity (if applicable) according to the relationships established, the certifications and the settlement of the work.

## 4.3 Reception of the Construction Work

Prior to the reception of the construction work, the CONTRACTOR will provide the final documentation of the project. This document must highlight the ultimate status of the facility, including the as-built plans, the actual measurements, the routes, etc.

The public officer designated by the Public Administration, the CONSTRUCTION PROJECT MANAGER and the CONTRACTOR must be present during the provisional reception of the construction work. Necessarily, there will be a record to formalise the meeting.

The CONTRACTOR will have to submit the relevant authorisations for the commissioning and usage of the facility when required. Every authorisation must be provided by official organisms, so, if this requirement is not met, the reception of the work will not take place. Once the provisional reception of the work has been completed, the CONTRACTOR will guarantee all the construction works as well as the materials utilised at least for a whole year. During this period every single deviation observed in the facility will be corrected and any failure or breakdown will be repaired with no charges if related to the execution of the project.



**Document III**

**HEALTH AND SAFETY STUDY**



# DOCUMENT III. Health and Safety Study

## Table of Contents

<b>1</b>	<b>Reference Framework</b>	<b>189</b>
1.1	Aim of the Health and Safety Study . . . . .	189
1.2	Applicable Regulation . . . . .	189
<b>2</b>	<b>Provisional Facilities</b>	<b>191</b>
2.1	Provisional Facilities for the Labour Force . . . . .	191
2.1.1	Generalities . . . . .	191
2.1.2	First Aid and Healthcare . . . . .	192
2.1.2.1	First Aid Kit . . . . .	192
2.1.2.2	Preventive Medicine . . . . .	193
2.1.2.3	Emergencies . . . . .	193
2.1.3	Construction Machinery . . . . .	193
2.2	Provisional Electrical Installation . . . . .	193
<b>3</b>	<b>Risks and Preventive Measures</b>	<b>195</b>
3.1	Introduction . . . . .	195
3.2	Affected Services and Third Party Risks . . . . .	196
3.3	Risks and Preventive Measures in Construction Activities . . . . .	196
3.3.1	Clearance and Grubbing . . . . .	196
3.3.2	Excavations . . . . .	197
3.3.3	Formwork . . . . .	197
3.3.4	Steel Positioning . . . . .	198
3.3.5	Assembly of Photovoltaic Modules . . . . .	199
3.3.6	Electrical Installation . . . . .	200
3.3.7	Electrical Grid Connection . . . . .	202
3.3.8	Work at Height . . . . .	203
3.4	Risks and Preventive Measures in Construction Machinery . . . . .	204
3.4.1	Earth-Moving Machinery . . . . .	204
3.4.2	Transportation trucks . . . . .	204
3.4.3	Concrete Mixers . . . . .	205
3.4.4	Cranes . . . . .	205
3.4.5	Circular Table Saws . . . . .	207

DOCUMENT III. TABLE OF CONTENTS

---

- 3.4.6 Hand Tools . . . . . 207
- 3.4.7 General Manipulation of Tools and Machines . . . . . 208
- 3.4.8 Electrical Welding . . . . . 209
- 3.5 Risks and Prevention Measures: Auxiliary Resources . . . . . 210
  - 3.5.1 Hand Ladder . . . . . 210
  - 3.5.2 Accessories: Stirrups, Cables, Chains and Hooks . . . . . 210

# Section 1

## Reference Framework

### Contents

---

1.1	Aim of the Health and Safety Study . . . . .	189
1.2	Applicable Regulation . . . . .	189

---

### 1.1 Aim of the Health and Safety Study

The health and safety study has the purpose of analysing, studying, developing and complementing the provisions regarding risk prevention of occupational accidents as well as occupational diseases, the mandatory hygiene and well-being facilities and any other regulatory requirement.

### 1.2 Applicable Regulation

Specifically, the Royal Decrees that have been considered for this document are listed below:

- Law 31/1995, of eighth of November, related to occupational risk prevention.
- Royal Decree 485/1997, of fourteenth of April, on the minimum provisions of both safety and health signs at work.
- Royal Decree 773/1997, of thirtieth of May, on minimum provisions of safety and health related to the use of personal protective equipment by the workers.
- Royal Decree 1215/1997, of eighteenth of July, which establishes the minimum health and safety requirements for the use of work equipment by the workers.
- Royal Decree 216/1999, of fifth of February, which establishes the minimum health and safety requirements for temporary agencies.
- Royal Decree 374/2001, of eighth of November, related to health and safety protection of workers against chemical agents at work.
- Royal Decree 614/2001, of eighth of June, on minimum provisions for protection of the health and safety of workers against electrical risks.
- Royal Decree 171/2004, of thirtieth of January, which develops the article 24 within the Law 31/1995 related to labour risk prevention in order to coordinate business activities.
- Royal Decree 1311/2005, of fourth of November, on health and safety protection of workers exposed to risks that are derived or may be derived from mechanical vibrations.
- Royal Decree 286/2006, of tenth of March, on health and safety protection of workers against risks that are related to noise exposure.
- Royal Decree 842/2002, of second of August, which approves the Electrotechnical Regulation for Low Voltage.



## Section 2

# Provisional Facilities

### Contents

---

2.1	Provisional Facilities for the Labour Force . . . . .	<b>191</b>
2.1.1	Generalities . . . . .	191
2.1.2	First Aid and Healthcare . . . . .	192
2.1.2.1	First Aid Kit . . . . .	192
2.1.2.2	Preventive Medicine . . . . .	193
2.1.2.3	Emergencies . . . . .	193
2.1.3	Construction Machinery . . . . .	193
2.2	Provisional Electrical Installation . . . . .	<b>193</b>

---

## 2.1 Provisional Facilities for the Labour Force

### 2.1.1 Generalities

The entrepreneur has the responsibility of ensuring the security, the safety and the health of every worker in accordance with the fourteenth article of the Law 31/1995, which is related to occupational risk prevention.

The planning of the risk prevention measures is contemplated and established as one of the main tenets of preventive activities in the fifteenth article of the Law 31/1995. The preventive measures must integrate the technique, the work organisation, the conditions, the social relationships and the influence of environmental factors at work. In fact, the mentioned law enumerates the general characteristics required for establishments, installations, equipment, products and any other existing item in the workplace.

The minimal requirements in terms of sanitary and common services at construction sites depending on the number of workers is stated on the fifth article of the Royal Decree 1627/1997. Considering the expected volume of workers, applying a global vision to analyse the issues related to continuous and simultaneous movement of people within the construction site is needed when designing the provisional facilities.

The design of the provisional facilities tries to simplify sorting labours, to ease housekeeping tasks and to ensure the hygiene of all the workers.

Then, the design principles of the provisional facilities are presented below:

- Apply the principles that regulate these facilities according to current legislation.

- Give all workers equal treatment in terms of quality and comfort, regardless of race and customs or whether they are subcontracted, self-employed or any other employee relation.
- Solve in an ordered and efficient way the possible mobility inside the temporary installations, without serious interference between users.
- Enable the temporary facilities to hold meetings in a dignified way with the union or for training purposes just by removing the furniture or reorganising it.
- Organise a safe entrance, stay and departure of workers and any kind of resource from the construction site.

The temporary facilities for workers will be located inside prefabricated metal modules with thermal and acoustic insulation based on a sandwich panel. These temporary facilities will be mounted on a lightweight concrete foundation. They will look simple, but worthy, and must be removed at the end of the construction work.

Each of the clothing rooms has enough capacity for 10 workers. Then, adapting the number of clothing rooms depending on its necessity, it is possible to provide clothing service to all the workers assigned to the construction work in accordance with the hiring curve. The clothing room will have individual cabinets or lockers to store clothes and personal possessions. Those cabinets or lockers will be protected with a key.

The clothing rooms will be easily accessible, will have enough dimensions and will count with enough seats and space to enable each worker to dry its working clothes when necessary. Depending on the specific circumstances of the construction site (for instance in case of manipulating hazardous substances, moisture, dirt, etc.), the possibility to store both working clothes and streetwear clothes as well as personal possession in separate lockers must be ensured. Separate toilets for men and women will be arranged in the vicinity of the construction site, or at least they will be used separately.

The canteen is unnecessary because Dreamfit Alcorcón is located within the urban area of the city. Additionally, the workers have a break-time long enough to have lunch in any close establishment. Workers will have access to drinking water in sufficient quantity, which will be supplied periodically.

## 2.1.2 First Aid and Healthcare

### 2.1.2.1 First Aid Kit

As defined in Royal Decree 1627/1997 as well as in Royal Decree 486/1997 in terms of minimum provisions for the protection of the health and safety of workers, the construction site will count with first aid materials. Additionally, there are some requirements related to time of arrival in case of work accident that must be respected. Summarising:

- **First aid.** There will be a portable first aid kit in the construction site ✓.
- **Minor accident.** There is a health centre 5 minutes away from Dreamfit Alcorcón ✓.

The first aid kit will be located at the clothing room. Each first aid kit will contain: hydrogen peroxide, 96° alcohol, an antiseptic, ammonia, cotton wool, sterile gauze, bandages, tape, antispasmodics, plastic bags for ice and water, sterile gloves and sterile eye drops.

In the first aid kit there will be a clearly visible sign indicating all the telephones of the nearest hospital centres: doctors, ambulances, fire brigade, police, etc.

### 2.1.2.2 Preventive Medicine

In order to avoid occupational diseases as much as possible in this construction work, as well as accidents derived from physical, psychological, alcoholism and any other dangerous drug addictions, the contractor and the subcontractors, in compliance with current labour legislation, will carry out the medical examinations prior to hiring workers in this construction work.

Moreover, the contractor will demand all the possible subcontractors the compliance with this mandatory safety requirement.

### 2.1.2.3 Emergencies

There must be a clearly visible sign indicating the assistance centres closest to the construction work in the event of an accident:

- Emergencies: 112.
- Toxicological information: 91 562 04 20.
- Municipal police (Alcorcón): 91 112 70 92.
- National police: 091.
- Spanish military police: 062.
  
- Health centre: 91 643 06 36 / 91 643 06 06.
- Hospital: 91 621 94 00.

### 2.1.3 Construction Machinery

Fixed construction machinery is generally assumed to be owned by the contractor. The machinery that is expected to be used in the execution of the project is indicated below:

- Machines:
  - Transportation truck.
  - Forklift.
- Support facilities:
  - Tubular scaffolds.
  - Pallet truck.

## 2.2 Provisional Electrical Installation

The existing electric distribution panels in Dreamfit Alcorcón will be used to supply the required power in order to fulfil the construction works.

The temporary electric distribution panels used will be identified with an indelible inscription including the name of the owner company and the series number, as well as the dates of its official technical reviews. The periodicity of these technical reviews is set in 6 months.

All the electric distribution panels will have a key lock to ensure that they can only be handled by authorised personnel. Both the current input and output to the distribution panels must have regulatory stuffing boxes.

The bases and jacks will be standardised and approved for the voltages, currents and the specific zone of use. Connections via clamps must be limited to major powers. The connection bars and clamps will be protected against direct contacts.

These electric distribution panels shall meet the conditions required for mobile outdoor installations and will be strategically located to reduce as much as possible the number of lines and their length. Specifically, the panels will comply with the following three conditions:

- The degree of tightness against water, dust and mechanical resistance against impacts will be ensured by means of a protection rate of at least I.P. 5-4-3 [92].
- Its metal casing will be connected to ground.
- All the electric distribution panels will be locked under the responsibility of the manager or the designated specialist, keeping the panel doors always closed.

In this sense, all the conductors will be insulated for a voltage of 1,000V. The wires will be overhead cables, and the electrical hose connections will be made with watertight bases and jacks. Portable power tools such as drills, ceramic cutters, etc., do not have to carry grounding rods since all them will have to carry double isolation.

A general check of the temporary electrical installation will be done daily. Nevertheless, a careful revision will take place every fifteen days, or whenever there is a modification that would require it. Special attention will be paid to the operation of the differential switches. Any element in poor conditions or that shows inadequacies for its usage will be replaced immediately.

The use of non calibrated rudimentary fuses is strictly prohibited.

## Section 3

# Risks and Preventive Measures

### Contents

---

3.1	Introduction . . . . .	<b>195</b>
3.2	Affected Services and Third Party Risks . . . . .	<b>196</b>
3.3	Risks and Preventive Measures in Construction Activities . . . . .	<b>196</b>
3.3.1	Clearance and Grubbing . . . . .	196
3.3.2	Excavations . . . . .	197
3.3.3	Formwork . . . . .	197
3.3.4	Steel Positioning . . . . .	198
3.3.5	Assembly of Photovoltaic Modules . . . . .	199
3.3.6	Electrical Installation . . . . .	200
3.3.7	Electrical Grid Connection . . . . .	202
3.3.8	Work at Height . . . . .	203
3.4	Risks and Preventive Measures in Construction Machinery . . . . .	<b>204</b>
3.4.1	Earth-Moving Machinery . . . . .	204
3.4.2	Transportation trucks . . . . .	204
3.4.3	Concrete Mixers . . . . .	205
3.4.4	Cranes . . . . .	205
3.4.5	Circular Table Saws . . . . .	207
3.4.6	Hand Tools . . . . .	207
3.4.7	General Manipulation of Tools and Machines . . . . .	208
3.4.8	Electrical Welding . . . . .	209
3.5	Risks and Prevention Measures: Auxiliary Resources . . . . .	<b>210</b>
3.5.1	Hand Ladder . . . . .	210
3.5.2	Accessories: Stirrups, Cables, Chains and Hooks . . . . .	210

---

### 3.1 Introduction

This section is focused on the main risks that will be faced at the construction work. Hence, the following subsections include the risk analysis of every work structured in the same four areas for every specific hazard:

- Most frequent risks related with the specific task analysed.
- Preventive measures to reduce the occurrence of the risk.
- Collective protective measures only when the workers as a whole have been analysed.
- Personal protective equipment to protect every worker individually.

## 3.2 Affected Services and Third Party Risks

In order to minimise the risk to third parties, special attention will be paid to the incorporation of trucks onto public roads, as well as to the access of trucks to the construction site.

## 3.3 Risks and Preventive Measures in Construction Activities

### 3.3.1 Clearance and Grubbing

#### Most frequent risks:

- Accidents and collisions caused by machinery.
- Rollover and slippage of machines.
- Fall of people from height.
- Fall of people from the same height level.
- Dust generation.
- Landslides.

#### Preventive measures:

- Signalling of the work zone.
- The machinery manoeuvres will be directed by people other than the driver.
- Whenever a machine is working it will have the anchor footing resting on the ground.
- Thorough control of excavation walls or interruption of the work during more than 24 hours after rainy days.
- Staff cannot stay in the vicinity of the machines during its manipulation ( $\geq 5 m$ ).
- Notice of trucks entering the public highway by an operator other than the driver.
- Correct arrangement of the land when loading trucks.
- The machines will not be used in any case as personnel transport.
- Do not collect materials on the edges of excavations.
- Do not collect materials in the transit areas.
- Traffic signalling in an ordered and simple way.

#### Collective protections:

- Signalling and lighting.
- Beacons tape to delimit the work area.
- Optical-acoustic signals for construction vehicles.
- Protection of workers at electrical installations.
- Fire prevention.

#### Personal protective equipment:

- Workwear.
- Certified helmet.
- Wetsuits when necessary.
- Leather gloves.
- Anti-vibration belt.
- Safety footwear.

### 3.3.2 Excavations

**Most frequent risks:**

- Accidents and collisions caused by machinery.
- Rollover and slippage of machines.
- Fall of people from height.
- Fall of people from the same height level.
- Dust generation.
- Landslides.

**Preventive measures:**

- Signalling of the work zone.
- The machinery manoeuvres will be directed by people other than the driver.
- Whenever a machine is working it will have the anchor footing resting on the ground.
- Thorough control of excavation walls or interruption of the work during more than 24 hours after rainy days.
- Staff cannot stay in the vicinity of the machines during its manipulation ( $\geq 5 m$ ).
- Notice of trucks entering the public highway by an operator other than the driver.
- Correct arrangement of the land when loading trucks.
- The machines will not be used in any case as personnel transport.
- Do not collect materials on the edges of excavations.
- Do not collect materials in the transit areas.
- Traffic signalling in an ordered and simple way.

**Collective protections:**

- Signalling.
- Beaconing tape to delimit the work area.
- Optical-acoustic signals for construction vehicles.
- Lighting.
- Protection of workers at electrical installations.
- Fire prevention.

**Personal protective equipment:**

- Workwear.
- Certified helmet.
- Wetsuits when necessary.
- Leather gloves.
- Anti-vibration belt.
- Safety footwear.

### 3.3.3 Formwork

**Most frequent risks:**

- Fall of people and/or objects from height.
- Fall of people from the same height level.

- Stepping on sharp objects.
- Entrapment.
- Electrical contact.
- Detachment due to improper stacking of the formwork timber.
- Hands and body blows during the nailing.
- Cut due to the usage of hand saws.
- Overexertion.
- Shock due to an uncontrolled falling or due to the turn of the suspended load.
- Inhalation of dust.
- Any risk related to the handling of machines and vehicles.

**Preventive measures:**

- The presence of workers at the mixing areas is forbidden.
- Order and cleanliness during the execution of the works.
- No person shall remain within the range of action of the machines.
- Materials will be stacked outside the transit area and will not cause any overload at the edges of the excavations.
- Do not transport loads above workers.
- No worker will remain at the vertical of the lifted loads.

**Personal protective equipment:**

- Leather gloves.
- Safety footwear.
- Tool belt.
- Certified polyethylene helmet.
- Anti-glare safety glasses.
- Workwear for rainy weather.

### 3.3.4 Steel Positioning

**Most frequent risks:**

- Fall of people and/or objects from height.
- Fall of people from the same height level.
- Stepping on sharp objects.
- Entrapment.
- Electrical contact.
- Overexertion.
- Any risk related to the handling of machines and vehicles.
- Shock due to an uncontrolled falling or due to the turn of the suspended load.
- Bumps and cuts due to tools.
- Cuts and wounds in hands and feet due to the handling of steel round cylinders.
- Trips and sprains when walking on the steel frames.

**Preventive measures:**

- The presence of workers at the mixing areas is forbidden.
- Order and cleanliness during the execution of the works.

- No person shall remain within the range of action of the machines.
- Materials will be stacked outside the transit area and will not cause any overload at the edges of the excavations.
- Do not transport loads above workers.
- No worker will remain at the vertical of the lifted loads.
- There will be a buffer dedicated to the classified collection of steel round cylinders as close as possible to the steel frame assembly.
- Scraps will be collected and stored in a specific space for its subsequent loading and transport to the dump.

**Personal protective equipment:**

- Leather gloves.
- Safety footwear.
- Tool belt.
- Certified polyethylene helmet.
- Anti-glare safety glasses.
- Workwear for rainy weather.

### 3.3.5 Assembly of Photovoltaic Modules

**Most frequent risks:**

- Falls of the personnel involved in the work due to an incorrect usage of the support facilities.
- Uncontrolled falling or turn of suspended loads.
- Falls of materials and/or tools used in the construction works.
- Risks derived from both the uploading and the reception of materials.
- Particle projection during work.
- Entrapment due to heavy objects.
- Fall of people and/or objects from height.
- Fall of people from the same height level.
- Head and limb blows.
- Cuts and wounds in hands and feet due to the handling of hand tools.
- Stepping on sharp objects.
- Electrical contact.
- Overexertion.

**Preventive measures:**

- No worker will remain at the vertical of the lifted loads.
- Do not transport loads above workers.
- The transportation by crane or truck-crane of the construction materials will be done through its suspension in two different points in order to avoid any sliding issue.
- Structure works will not be carried out when there is ice, snow, rain, winds exceeding  $50\text{km}/\text{hour}$  nor storm threat.
- Before using any machine or tool, it will be checked that it is in optimal conditions in terms of mechanisms and safety guards.
- The manoeuvres needed to place the structure will be governed by the required number of operators to ensure safety. The materials will be hoisted in the precise cut state according to the size required for the assembly.

- The layout of electrical hoses or cables will be done, when possible, in an orderly manner.
- Climbing directly over the structure is prohibited.
- Travelling along the structure without tying the seat belt is forbidden.
- Order and cleanliness during the execution of the works.
- In works at a height over 2m of height, the use of a safety harness will be mandatory.
- There will be a buffer dedicated to the classified collection of materials as close as possible to the assembly locations.
- The construction site will be kept free of both broken fragments and PV modules to avoid the risk of cuts.
- During the storage, transportation and placement of PV modules, they will have to remain always in an upright position.
- It is prohibited to stay or work in the vertical of the installation point of the PV panels.

**Collective protections:**

- Connection of all the electrical equipment to ground.
- Double insulated or reinforced portable tools.
- Differential protection of the electrical distribution panels.

**Personal protective equipment:**

- Leather gloves.
- Safety footwear.
- Tool belt.
- Certified polyethylene helmet.
- Anti-glare safety glasses.
- Mandatory seat belt required in all work carried out at height lacking the adequate collective protection.
- Workwear for rainy weather.

### 3.3.6 Electrical Installation

**Most frequent risks:**

- Blows against objects.
- Blows or cuts due to hand tools.
- Electrocutions due to:
  - Inattention.
  - Non-insulated tools or bypassed protections.
  - Direct connection without male-female jacks.
- Fall of people and/or objects from height.
- Fall of people from the same height level.
- Direct and indirect electrical contacts.
- Risks derived from voltage drops in the installation caused by overloads.
- Incorrect performance of the ground system:
  - Installation issues.
  - Ground spikes that cancel the electrical distribution panel protection.
- Skin burns and overexertion.
- Step over sharp objects or materials.

**General preventive measures:**

- Order and cleanliness.
- Undertake the connections without voltage.
- Develop voltage tests only when the installation is completed.
- The illumination of the construction site will not be lower than 100 *lux* measured at 2 *m* from the ground.
- Use tool belts whenever working at height.
- The electrical assembly will be carried out exclusively by authorised, qualified and specialised personnel.
- The operational tests of the photovoltaic plant will be announced in advance to all the construction workers to avoid possible accidents.
- Live parts will be covered with insulating material.
- Interposition of barriers or envelopes to reduce incidents.
- Residual differential current devices set to 100 *mA* must be used to ensure its operation in the event of protection failure or due to negligences.
- Exposed conductive parts shall be connected to ground respecting the specific conditions required depending on the connection type.
- The protection system shall prevent defects or failures from creating dangerous hazards.
- Periodic review of tools and machines, replacing those with a deteriorated insulation.
- Correct isolation of portable machines.
- Work areas will always be perfectly lit.
- Placing posters with the message “DO NOT CONNECT: PERSONNEL WORKING” during the commissioning of the facility.
- Stairs and platforms under optimal conditions.
- Stairs will be equipped with a non-slip floor.
- All the electrical auxiliary machinery will be maintained under optimal conditions.

**Preventive measures related to the electrical conductors:**

- The section of the wiring will always be adequate for the expected power load based on the calculation design.
- The wires will have a protective insulation without appreciable defects.
- The temporary electrical connection between hoses will be made by means of standardised watertight moisture connectors.

**Preventive measures related to the electrical distribution panels:**

- The metallic electrical distribution panels will have the casing connected to ground.
- The electrical distribution panels will have standardised outdoor sockets.
- Every socket will supply electrical power to a single appliance, machine or tool.
- Outdoor electrical distribution panels will be adequate and will be protected from rainwater by additional effective visors.

**Preventive measures related to the ground connection:**

- The metallic parts of all electrical equipment will be grounded.
- The grounding wire will have a standardised insulation yellow-green.
- The earth connection cannot be sectioned at any part of its route.
- The grounding of the machines or tools not equipped with double insulation will be done through the neutral wire combined with the corresponding electrical distribution panel.

**Collective protections:**

- Signalling of the work zone.
- Beaconing tape delimiting the work area.
- Protection of people in the electrical installation.
- Fire prevention.
- Insulating tools.

**Personal protective equipment:**

- Workwear.
- Insulating protective gloves.
- Certified protective helmet.
- Electricity insulating boots.
- Voltage testers available for the workforce.

### 3.3.7 Electrical Grid Connection

**Most frequent risks:**

- Direct and indirect electrical contacts.
- Step over sharp objects or materials.
- Fall of objects or detachments.
- Skin burns.
- Blows or cuts due to hand tools.

**Preventive measures:**

- The illumination of the construction site will not be lower than 100 *lux* measured at 2 *m* from the ground.
- Electric machines and tools will be connected by jacks to the electrical distribution panels.
- All the electrical auxiliary machinery will be maintained under optimal conditions.
- Order and cleanliness, revision of ladders, electrical connections and earthing of all the machinery.
- Undertake the connections without voltage.
- Periodic review of tools and machines, replacing those with a deteriorated insulation.
- Correct isolation of portable machines.
- The electrical assembly will be carried out exclusively by authorised, qualified and specialised personnel.
- Portable lighting will be done using watertight lamp holders with insulated handle and bulb protection grid, powered by 24 *V*.
- The operational tests of the photovoltaic plant will be announced in advance to all the construction workers to avoid possible accidents.
- Live parts will be covered with insulating material.
- Interposition of barriers, obstacles or envelopes to reduce incidents.
- Residual differential current devices set to 100 *mA* must be used to ensure its operation in the event of protection failure or due to negligences.
- Exposed conductive parts shall be connected to ground respecting the specific conditions required depending on the connection type.
- The protection system shall prevent defects or failures from creating dangerous hazards.

**Personal protective equipment:**

- Workwear.
- Seat belt for working at height.
- Insulating protective gloves.
- Certified protective helmet.
- Safety footwear.

**3.3.8 Work at Height****Most frequent risks:**

- Fall of people and/or objects from height.
- Fall of people from the same height level.

**Preventive measures:**

- Obligation to check the state of the slings before its usage.
- The personnel exposed to height risk will have both the required training and experience as well as the security elements needed to carry out these tasks complying with the current legislation.
- The wear of the equipment must be avoided reducing the rubbing with sharp edges, with rough surfaces, with corrosive surfaces, etc.
- Do not expose the ropes, straps or harnesses to the harmful effects of soldering, of the sun, of dust, or of any other aggressive agent needlessly.
- Indicate any abnormality perceived in the equipment, not using again any equipment that has suffered a fall.
- After every usage, dry the equipment if necessary and store it away from humidity, light and any other aggressive agent.
- Before starting a work task that involves special danger, the construction project manager must ensure that the form, the human resources and the safety protocol are properly established and followed.
- It is forbidden to stand under suspended loads while the hoisting process.
- The zones located below the construction areas will remain delimited to avoid blows or injuries due to the falling of materials or objects to lower areas.
- A sign will be placed indicating the presence of the construction works.
- The obligation to wear a certified helmet as well as the restricted access to any person not related to the construction.
- In those areas close to the existing yards, these yards will be protected by means of standardised horizontal hole nets to avoid the falling of people or materials into the void.

**Personal protective equipment:**

- Workwear.
- Seat belt for working at height.
- Insulating protective gloves.
- Certified protective helmet.
- Safety footwear.

## 3.4 Risks and Preventive Measures in Construction Machinery

### 3.4.1 Earth-Moving Machinery

#### Most frequent risks:

- Rollover and entrapment.
- Collisions between machines.
- Run over people.
- Noise, vibrations and environmental dust.
- Fall of people while getting on and off the machines.

#### Preventive measures:

- Machines must include roll-over cabin or security gantry.
- Drivers are cannot leave the machine without turning off the engine.
- During earth transports, the bucket will remain as low as possible to move in order to provide maximum stability.
- Transport or lift people inside the bucket is not allowed.
- The machines to be used in this work will be equipped with lights and a recoil horn.
- The engine must be turned on only once it has been verified that there is no one in the shovel operating area.

#### Personal protective equipment:

- Workwear.
- Anti-vibration belt.
- Insulating protective gloves.
- Certified protective helmet.
- Safety footwear.
- Leather gloves.
- Hearing protectors.
- Safety goggles.

### 3.4.2 Transportation trucks

#### Most frequent risks:

- Rollover and entrapment.
- Collisions between machines.
- Run over people.
- Noise, vibrations and environmental dust.
- Fall of people while getting on and off the machines.

#### Preventive measures:

- Transportation trucks must be in both perfect maintenance and conservation conditions.
- The truck barge will be lowered immediately after unloading as well as before its departure.
- The construction site entrances and exits done by the trucks will be carried out with caution and aided by the signs of workers.

- In case of vehicles having to stop at ramps, they will be braked with buffers.
- Loading trucks above the maximum load established by the manufacturer is expressly prohibited to prevent overload risks.
- The driver will remain out of the cab during the loading.

**Personal protective equipment:**

- Workwear.
- Anti-vibration belt.
- Insulating protective gloves.
- Certified protective helmet.
- Safety footwear.
- Leather gloves.
- Hearing protectors.
- Safety goggles.

### 3.4.3 Concrete Mixers

**Most frequent risks:**

- Rollover and entrapment.
- Electrical contacts.
- Overexertion.
- Blows due to moving parts.
- Dust and environmental noise.

**Preventive measures:**

- In order to avoid entrapment hazards, the concrete mixers will be protected by means of a metal casing to preserve the transmission mechanisms (belts, gears, etc.).
- The casing and any other metallic part of the machine will be connected to ground.
- The control panel of the concrete mixers will be watertight to prevent any electrical risk.
- Cleaning operations will be carried out after the electrical disconnection of the concrete mixers to avoid both the electrical risk and the entrapment risk.
- The power cable will be three-wire (1,000 V).

**Personal protective equipment:**

- Waterproof workwear.
- Anti-dust safety goggles.
- Leather gloves.
- Safety footwear.
- Certified protective helmet.

### 3.4.4 Cranes

**Most frequent risks:**

- Fall of people from height.
- Fall of people and objects from the same height level due to crane collapse.

- Cuts, bumps and entrapment produced by handling tools and heavy objects.
- Electrical contacts.
- Overexertion.
- Spillage or collapse of loads during its transport.
- Blows of the load to people or objects during the air transport.

**Preventive measures:**

- The cranes will be located in the places agreed with between the contractor and the construction project manager.
- The crane will be equipped with a sign in a visible place in which the maximum permissible peak load must be clearly stated.
- The crane fastening cables used to hold loads with a 10% of broken wires will be replaced immediately and will be reported to the construction project manager.
- The cranes or truck-cranes to be used in this construction work will be equipped with standardised steel hooks with safety latches.
- The transportation of people through the air using the crane hook is forbidden.
- In case of storm, the crane will be left out of service to avoid the electrical risk.
- At the end of work days, four crane manoeuvres are required to ensure safety:
  1. Lift the hook with no loads next to the crane mast.
  2. Leave the boom in the weather vane position.
  3. Set the controls to zero.
  4. Open the breakers of the crane after the disconnection of the electrical supply of the machine in the main electrical distribution panel.
- The crane operation will be paralysed under a regime of wind equal or over  $70 \text{ km/h}$  due to safety reasons.
- The cranes will be equipped with load limiting mechanisms (for the hook) and load displacement mechanisms (for the boom), to prevent the risk of tipping.
- The crane installer will provide a commissioning certificate in order to guarantee its correct assembly and operation.
- The cranes used in the construction work will comply with the Technical Instruction related to the Regulation of Lifting Devices.
- Loads that are hoisted to the ground will not be lifted by the crane to prevent the machine from tipping.
- Loads cannot be dragged through tension forces created by inclined cables to minimise the crane fall risk.
- Objects and materials cannot stay at the crane hook during night or weekends to prevent accidents and thefts.
- Not properly strapped loads can cause injury to any worker, so the strapping process must always be reviewed.
- Hanging loads with defective slings is forbidden to prevent the occurrence of accidents.
- Lifting loads whose weight is equal to or greater than the limit established by the crane manufacturer are prohibited.

**Personal protective equipment:**

- Workwear.
- Safety footwear.
- Certified protective helmet.

### 3.4.5 Circular Table Saws

**Most frequent risks:**

- Cuts, bumps and entrapment produced due to heavy objects.
- Electrical contacts.
- Particle and dust emission.

**Preventive measures:**

- The circular table saw will be disabled during periods of inactivity.
- The power supply of the disc saws to be used in this construction work will be carried out by means of anti-humidity hoses equipped with watertight jacks through the electrical distribution panel, to avoid electrical risks.
- The excess material and waste derived from the saw usage will be collected and piled up.

**Personal protective equipment:**

- Workwear and leather gloves.
- Anti-dust face mask.
- Safety footwear.
- Certified protective helmet.
- Anti-glare safety glasses.

### 3.4.6 Hand Tools

**Most frequent risks:**

- Blows and cuts due to the projection of fragments.
- Skin burns.
- Fall of objects.
- Electrical contacts.
- Vibrations and environmental noise.

**Preventive measures:**

- Hand tools will be used in those tasks for which they have been conceived.
- Hand tools will be checked before every usage and those under bad conservation conditions will be discarded.
- Tools will be kept clean of industrial oils, greases and any other slippery substances.
- Workers will receive specific instructions on the proper use of every required tool.

**Personal protective equipment:**

- Workwear and leather gloves.
- Anti-dust face mask with replaceable filter.
- Safety footwear.
- Certified protective helmet.
- Hearing protectors.
- Anti-glare safety glasses.

### 3.4.7 General Manipulation of Tools and Machines

**Most frequent risks:**

- Overturms produced by the machines.
- Subsidence, cuts and collisions.
- Formation of aggressive or annoying atmospheres.
- Environmental noise.
- Explosion and fires.
- Blows and projection of materials.
- Electrical contacts.
- Those risks inherent to the location and the work itself.

**Preventive measures:**

- Motors with transmission elements such as shafts and pulleys will be equipped with anti-entrapment protective housings.
- Electric motors will be covered with protective housings to avoid electrical direct contacts. The operation without casing is forbidden.
- Gears of any type, mechanically, electrically or manually driven will also include anti-entrapment protections.
- Damaged machines that cannot be removed from the site will be marked with the following warning legend: “MACHINE FAILED, DO NOT CONNECT”.
- Only authorised personnel will be able to use specific machines or tools.
- Machines that are not manually held will always rest on level and firm elements.
- Both the electrical machines and tools to be used in this construction work will be electrically protected by means of double insulation.
- The transmissions driven by belts will always be protected by means of a frame that supports a metal mesh. These transmissions must be arranged properly to allow the observation of the mechanism and to reduce the entrapment risk of operators or objects.
- Machines and tools with cutting capacity will have the disc protected by means of an anti-projection casing.
- Machines and tools not electrically protected by double insulation must have the protective casings connected to the earth network as well as to the differential circuit breakers of the general electrical distribution panel of the construction work.
- Leaving power tools with cutting or drilling capabilities abandoned on the ground or in motion, even with residual movement is prohibited in order to avoid accidents.

**Personal protective equipment:**

- Workwear.
- Leather gloves.
- Safety footwear.
- Certified protective helmet.
- Hearing protectors.
- Anti-glare safety glasses.

### 3.4.8 Electrical Welding

**Most frequent risks:**

- Fall of people from height.
- Fall of people from the same height level.
- Entrapment between objects.
- Hands crushing due to heavy objects.
- The risks derived from the radiation of the electric arc.
- The risks derived from the inhalation of metallic vapours.
- Skin burns.
- Direct and indirect electrical contacts.
- Fire or explosion.
- Projection of particles.

**Preventive measures:**

- The electrode holders of the welding groups to be used in this construction work will be electrically insulated.
- The personnel in charge of welding must be specialised in these tasks.
- In order to avoid electrocution risk, the soldering process cannot be initiated without the welding group protection.
- Before initiating any soldering, it must be reviewed that the welding group is connected to the ground system.
- In case of actuation of the differential circuit breaker, the casing of the welding group cannot be disconnected from the ground system. In that case the welding group has to be repaired or substituted.
- The welding group must be totally disconnected during breaks.
- The electrical hoses used for the welding group must be linked by means of watertight and outdoor connections. Direct electrical connections through insulated tapes will be avoided.
- The electrode holder clamps and the terminals of the welding groups used in the construction work must be properly insulated.

**Personal protective equipment:**

- Workwear.
- Welding mask.
- Manual support welding screen.
- Leather gloves.
- Safety footwear.
- Certified protective helmet.
- Safety belt.
- Safety glasses to provide protection against electric arc radiation.

## 3.5 Risks and Prevention Measures: Auxiliary Resources

### 3.5.1 Hand Ladder

#### Preventive measures:

- It must be checked that the crossbars have no splices, that no rung is missing and that there are no broken or loose rungs, nor replaced bars nor protruding nails.
- Before starting the rise, it must be ensured that the soles of the footwear do not have mud, grease, or any other substance that can cause slipping.
- The ladder shall have enough length to exceed in at least one meter the surface height intended to reach.
- The maximum length of manual ladders cannot exceed five meters without intermediate support points, and seven meters with intermediate support points. If higher heights have to be reached, special ladders shall be used.
- Ladders shall not be placed over moving mechanisms or bare electrical conductors. If necessary, the moving mechanism must be stopped previously or the cable power must be turned off.
- Ladders cannot be used by more than one worker at the same time.
- Works at a height greater than 3.5 meters which require dangerous movements or efforts for the stability of workers will only be carried out if a seat belt is used or under alternative protection measures approved by the construction project manager.

### 3.5.2 Accessories: Stirrups, Cables, Chains and Hooks

#### Preventive measures:

- The technical conditions of the accessories used must be properly reviewed and a load test has to be carried out.
- Any work developed at heights greater than two meters require the usage of safety belts.
- The Royal Decree 1215/1997 and the Royal Decree 2177/2004 related to safety and health requirements related to works at height shall be followed.
- Loads transported suspended in the air will always be at sight in order to avoid accidents due to lack of visibility of the load path.
- The permanence of works or operators in areas under the path of suspended loads is forbidden.
- The lifting machines to be used in this construction work will be equipped with a limiter for both carriages and hooks.
- The cables used directly or auxiliary to transport suspended loads will be inspected at least once a week by the security guard, who will notify every revision to the construction project manager.
- The fastening or support hooks will be made of steel or wrought iron and will include a security latch.
- All load lifting machines to be used will have the maximum load visibly specified.
- All machines powered by electricity will be connected to the ground system.

Document IV

# PROJECT BUDGET



# Project Budget Explanation

The project budget has been developed by means of Presto® [93]. Presto is an integrated cost management program specialised for construction projects.

Then, the budget document has been divided into six chapters:

- **Chapter 1 - Main Equipment.** Including the PV modules, the inverter, the mounting structure and the power analyser.
- **Chapter 2 - Protection and Wiring.** Considering both DC and AC sides.
- **Chapter 3 - Auxiliary Services.** Covering the civil works assistance and the crane required to raise the construction materials to the roof of Dreamfit Alcorcón.
- **Chapter 4 - Health and Safety.** Including all the Personal Protective Equipment.
- **Chapter 5 - Waste Management.** Following the order 2726/2009 (Comm. of Madrid).
- **Chapter 6 - Commissioning.** Including the legalisation of the facility.

Once the measurements and the requirements of the PV project were defined, all the information was sent to different engineering companies in order to obtain several offers. The information provided to obtain the offers can be summarised as follows:

- **Measurements of the Project.** The project budget without unitary prices.
- **Technical Specifications of the Project.**
- **Data Sheets.** The PV modules data sheet and the inverter data sheet.
- **Plans.** The plans of the project.
- **Current Status.** Images of the current status of the roof of Dreamfit Alcorcón:



(a) East view.



(b) North view.

Figure 1. Current status of the roof of Dreamfit Alcorcón.

All in all, next four pages include the project budget developed with the professional software Presto considering the unitary prices offered by Elecnor® [65].

→ **TOTAL COST OF THE PROJECT: 100,395.22€ (VAT NOT INCLUDED).**

# PROJECT BUDGET – MASTER THESIS

Adrián Cecilio Benito - Dreamfit Alcorcón PV Plant



CODE	SUMMARY	QUANTITY	UNITARY PRICE	COST
<b>CHAPTER 01 MAIN EQUIPMENT</b>				
01.01	<p><b>unit PHOTOVOLTAIC MODULE 505 W<sub>p</sub></b></p> <p>Supply, installation and assembly of 220 Trinasolar monocrystalline photovoltaic modules model TSM-DE18M(II) of 505 W<sub>p</sub> and 26.5 kg of weight, with 35 mm of anodized aluminium frame and front cover of tempered glass, high transmissivity microstructure with 3.2 mm of thickness and IP 68 connection box. Designed and certified according to the standards IEC 61215, IEC 61730, IEC 61701, IEC 62716, ISO 9001, ISO 14001, ISO 14064 and ISO 45001. Including the MC4 EVO2/TS4 connecting hoses.</p>	220.00	186.40€	41,008.00€
01.02	<p><b>unit DC/AC INVERTER 100 kW<sub>n</sub></b></p> <p>Supply, installation and assembly of Huawei inverter model Smart String Inverter SUN2000-100KTL-M1 of 100 kW<sub>n</sub> and 90 kg of weight for self-consumption and grid connection purposes. The device counts with single-phase DC input and three-phase AC output at 400V/50Hz without transformer requirements. No-fuses design, IP 66 protection, 10 MPPTs included and the possibility of connecting two strings per MPPT. Designed and certified according to the standards EN 62109-1/-2, IEC 62109-1/-2, EN 0530, IEC 62116, IEC 61727, IEC 60068 and IEC 61683. Fully installed with the necessary fixing and anchoring accessories, including the Huawei mounting bracket and a ventilated weather protection box to be approved by the Construction Project Manager.</p>	1.00	7,342.72€	7,342.72€
01.03	<p><b>unit MOUNTING STRUCTURE</b></p> <p>Supply, installation and assembly of support structure of extruded aluminium profiles for photovoltaic modules brand Solarstem or similar. Modular system with adjustable height in each row of photovoltaic modules to avoid shading due to the inclination of the roof. Adjustable tilt system to guarantee an angle of 33.5 degrees with respect to the horizontal plane in each row of PV modules. Even cross bracing system in the rear supports of the structure for the module rows with bigger structure requirements according to the manufacturer recommendations. Structure completely anchored to the metal roof of the building, including a panel fastening system compatible with the Trinasolar photovoltaic modules and guaranteeing the impermeability of the roof and the stability of the whole PV system.</p>	220.00	59.13€	13,008.60€
01.04	<p><b>unit BIDIRECTIONAL POWER ANALYSER</b></p> <p>Supply, installation and assembly of a bidirectional network analyser Huawei model Smart Power Sensor DTSU666-H 250A/50mA located upstream the Dreamfit Alcorcón main LV electrical distribution panel. Three-phase device that enables the obtention of real-time data of the self-consumed energy and the relation between the energy injected and the energy absorbed from the network, with class 1 measurement precision, LCD screen and mounting on a DIN rail. Fully configured and connected, including supply and assembly of RS485 communications cable in shielded canalisation tube between the power analyser and the inverter.</p>	1.00	868.56€	868.56€
<b>TOTAL CHAPTER 01 MAIN EQUIPMENT .....</b>				<b>62,227.88€</b>

# PROJECT BUDGET – MASTER THESIS

Adrián Cecilio Benito - Dreamfit Alcorcón PV Plant



CODE	SUMMARY	QUANTITY	UNITARY PRICE	COST
<b>CHAPTER 02 PROTECTION AND WIRING</b>				
02.01	<p><b>unit ALTERNATING CURRENT BOX</b></p> <p>Supply, installation and assembly of an outdoor alternating current panel located downstream the inverter output. Includes Schneider circuit breaker model NSX250F TM200D 4P4R or similar, mounting on DIN rail, with circuit breaker protection of 200 A nominal current and 36 kA of adjustable breaking capacity, designed and certified according to standards IEC 60664-1, IEC 60529 and IEC 62262.</p>			
		1.00	1,934.24€	1,934.24€
02.02	<p><b>unit ADAPTATION OF THE EXISTING MAIN LV PANEL</b></p> <p>Modification of the existing LV panel for the interconnection of the generating installation. Includes Schneider circuit breaker model NSX250F TM200D 4P4R or similar, mounting on DIN rail, with circuit breaker protection of 200 A of nominal current and 36 kA of adjustable breaking capacity, designed and certified according to standards IEC 60664-1, IEC 60529 and IEC 62262. Includes ABB residual current switch model RD3 or similar, mounting on DIN rail, with sensitivity of at least 30 mA, nominal current greater than 200 A and with the corresponding toroid with an internal section greater than 480 square millimetres, designed and certified according to the standard UNE-EN 60947-2.</p>			
		1.00	813.12€	813.12€
02.03	<p><b>m DC WIRING 6 mm<sup>2</sup></b></p> <p>Supply and installation under canalisation tube of the wiring required for the direct current side of the facility that interconnects the photovoltaic strings with the DC/AC inverter. Topsolar PV DC conductor model ZZ-F 0.6/1kV for photovoltaic purposes or similar, with 6 square millimetres of conductor section, made of flexible class 5 tinned electrolytic copper according to the standard EN 60228, halogen-free thermoset insulation and specially designed for outdoor applications. Including the proportional part of canalisation tube required for the deployment of the wiring, as well as the necessary pieces and connection boxes.</p>			
		1,876.00	4.20€	7,879.20€
02.04	<p><b>m AC WIRING 70 mm<sup>2</sup></b></p> <p>Supply and installation under canalisation tube of the wiring required for the alternating current side of the facility that interconnects the inverter with the AC box of the generation PV plant. Copper conductor, 70 square millimetres of conductor section (3F + N), specially designed for its usage outdoors, flame retardant, thermoset insulation and halogen free, type RZ1-K(AS) 0.6/1kV and designed as well as certified according to the UNE-HD 603-0:2007 standard. Including the proportional part of canalisation tube required for the deployment of the wiring, as well as the necessary pieces and connection boxes.</p>			
		100.00	14.66€	1,466.00€
02.05	<p><b>m AC WIRING 120 mm<sup>2</sup></b></p> <p>Supply and installation under canalisation tube of the wiring required for the alternating current side of the facility that interconnects the AC box of the PV plant with the main AC electrical distribution panel of the gym. Copper conductor, 120 square millimetres of conductor section (3F + N), specially designed for its usage outdoors, flame retardant, thermoset insulation and halogen free, type RZ1-K(AS) 0.6/1kV and designed as well as certified according to the UNE-HD 603-0:2007 standard. Including the proportional part of canalisation tube required for the deployment of the wiring, as well as the necessary pieces and connection boxes.</p>			
		140.00	24.09€	3,372.60€
02.06	<p><b>m GND WIRING 6 mm<sup>2</sup></b></p> <p>Supply, installation and assembly of grounding coated copper cable, with a section of 6 mm<sup>2</sup> for the equipotential connection of the photovoltaic structure and the PV modules, as well as any other existing metallic element between the modules and the PV inverter. Including any connecting part or item required.</p>			
		950.00	4.96€	4,712.00€

# PROJECT BUDGET – MASTER THESIS

Adrián Cecilio Benito - Dreamfit Alcorcón PV Plant



CODE	SUMMARY	QUANTITY	UNITARY PRICE	COST
02.07	<b>m GND WIRING 35 mm<sup>2</sup></b> Supply, installation and assembly of grounding coated copper cable, with a section of 35 mm <sup>2</sup> for the equipotential connection of the PV inverter and the AC box, as well as any other existing metallic element between the PV inverter and the AC box. Including any connecting part or item required.			
		30.00	9.55€	286.50€
02.08	<b>m GND WIRING 60 mm<sup>2</sup></b> Supply, installation and assembly of grounding coated copper cable, with a section of 60 mm <sup>2</sup> for the equipotential connection of the AC box of the PV plant and the main AC electrical distribution panel of the gym, as well as any other existing metallic element upstream of the AC box. Including any connecting part or item required.			
		40.00	16.68€	667.20€
	<b>TOTAL CHAPTER 02 PROTECTION AND WIRING .....</b>			<b>21,130.86€</b>

# PROJECT BUDGET – MASTER THESIS

Adrián Cecilio Benito - Dreamfit Alcorcón PV Plant



CODE	SUMMARY	QUANTITY	UNITARY PRICE	COST
<b>CHAPTER 03 AUXILIARY SERVICES</b>				
03.01	<b>unit CIVIL WORKS ASSISTANCE</b> Execution of the necessary hole in the Dreamfit Alcorcón facilities area to connect the generation installation from the AC box to the gym's main AC electrical distribution panel through the existing utility ducts and false ceilings.			
		1.00	630.00€	630.00€
03.02	<b>unit CRANE</b> Crane required to raise the construction materials to the roof of the building. The crane must have the proper features for the corresponding placement of any PV module and the mounting structure.			
		1.00	1,120.00€	1,120.00€
<b>TOTAL CHAPTER 03 AUXILIARY SERVICES .....</b>				<b>1,750.00€</b>
<b>CHAPTER 04 HEALTH AND SAFETY</b>				
04.01	<b>unit PERSONAL PROTECTIVE EQUIPMENT</b> Supply of the required Personal Protective Equipment (PPE) to ensure the safety of the construction employees. Including protective certified polyethylene helmets, workwear, wetsuits, leather and insulating protective gloves, safety footwears, anti-vibration belts, anti-glare safety glasses, safety harnesses, hearing protectors, anti-dust facemasks with replaceable filter, welding masks as well as any other PPE required to guarantee the safety of all the workers directly or indirectly related to the construction of the PV plant. All the equipment has to be properly certified, approved both by the Construction Project Manager and by the Health and Safety Coordinator, and must comply with the current Spanish regulation such as the RD 773/1997 and the RD 1215/1997.			
		1.00	4,736.26€	4,736.26€
<b>TOTAL CHAPTER 04 HEALTH AND SAFETY .....</b>				<b>4,736.26€</b>
<b>CHAPTER 05 WASTE MANAGEMENT</b>				
05.01	<b>unit TREATMENT AND MANAGEMENT OF CONSTRUCTION WASTE</b> Waste Management according to the current regulation established by the order 2726/2009 (Community of Madrid). Including the waste management of residues from both stony and non-stony nature, the potentially hazardous waste, rentals and shipping of containers and tanks, machinery and headcount required to separate and classify the waste as well as any auxiliary service required.			
		1.00	6,630.22€	6,630.22€
<b>TOTAL CHAPTER 05 WASTE MANAGEMENT .....</b>				<b>6,630.22€</b>
<b>CHAPTER 06 COMMISSIONING</b>				
06.01	<b>unit LEGALISATION AND COMMISSIONING</b> Implementation of all the administrative procedures and the required management with the Distribution System Operator for the legalisation of the PV facility. Including the Construction Project Management and the complete commissioning of the PV plant. Totally installed and properly working, one year of maintenance included. Also including the procurement and contract review by a competent body when applicable.			
		1.00	3,920.00€	3,920.00€
<b>TOTAL CHAPTER 06 COMMISSIONING .....</b>				<b>3,920.00€</b>
<b>TOTAL .....</b>				<b>100,395.22€</b>

# PROJECT BUDGET – MASTER THESIS

Adrián Cecilio Benito - Dreamfit Alcorcón PV Plant



CODE	SUMMARY	QUANTITY	UNITARY PRICE	COST
<b>DREAMFIT ALCORCÓN PV PLANT BUDGET:</b>				
	TOTAL CHAPTER 01 MAIN EQUIPMENT .....			62,227.88€
	TOTAL CHAPTER 02 PROTECTION AND WIRING .....			21,130.86€
	TOTAL CHAPTER 03 AUXILIARY SERVICES .....			1,750.00€
	TOTAL CHAPTER 04 HEALTH AND SAFETY .....			4,736.26€
	TOTAL CHAPTER 05 WASTE MANAGEMENT .....			6,630.22€
	TOTAL CHAPTER 06 COMMISSIONING .....			3,920.00€
	<b>TOTAL DF ALCORCÓN PV PLANT .....</b>			<b>100,395.22€</b>

VAT NOT INCLUDED



**Master Thesis.**  
**Adrián Cecilio Benito.**

**Document V**

**PLANS**



# Plans List

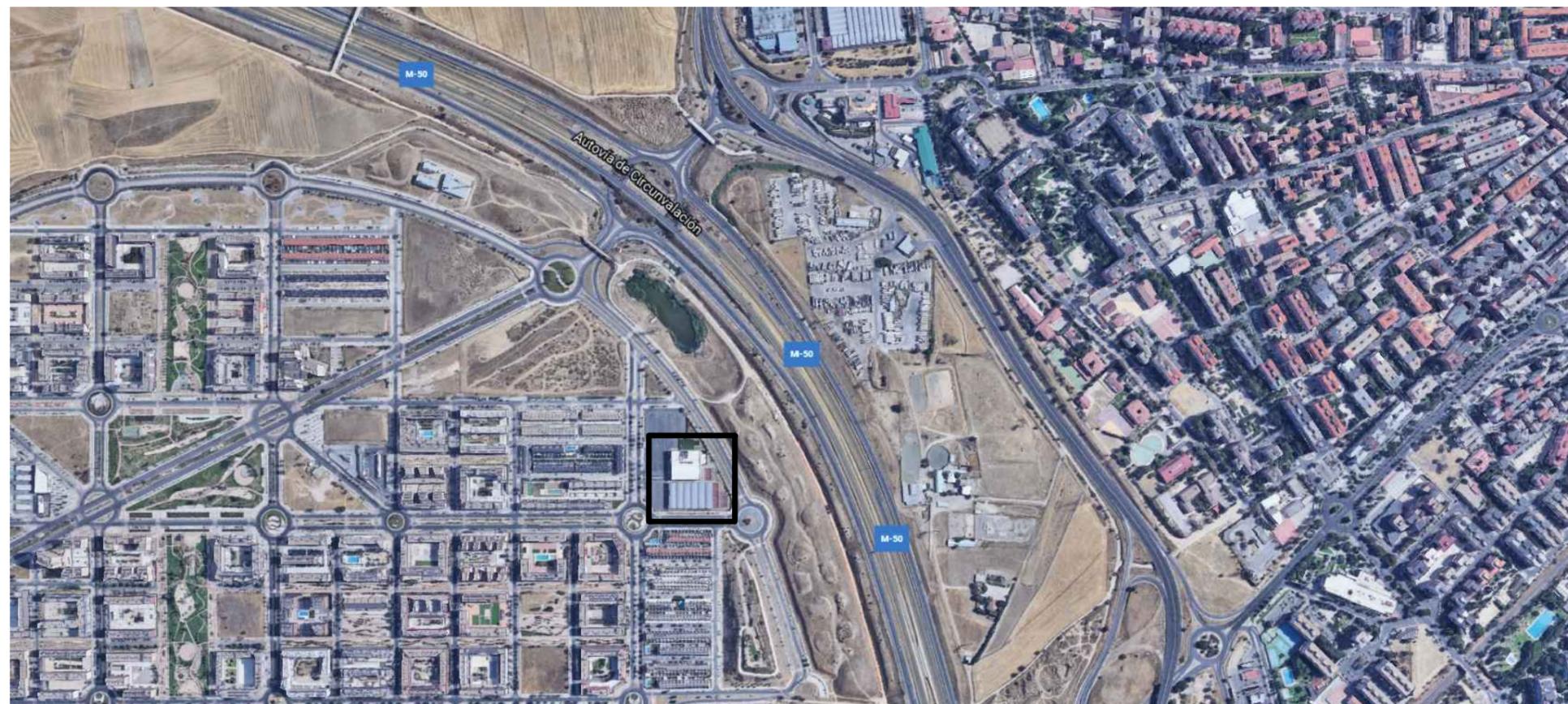
The plans developed for the project have been designed by means of Autocad® [46]:

1. Situation and Location of the PV Project.
2. General Distribution - Plan View of Dreamfit Alcorcón Roof.
3. Electrical Canalisation.
4. Photovoltaic Mounting Structure.
5. Electrical Schematic of the Dreamfit Alcorcón PV Plant.

DESIGN OF A DISTRIBUTED  
GENERATION RESOURCE:  
PHOTOVOLTAIC PLANT FOR  
SELF-CONSUMPTION  
IN A SPORTS FACILITY

DREAMFIT ALCORCÓN SL  
NIF: B40257990  
C/LOS ROBLES, S/N 12B  
28922 ALCORCÓN, MADRID

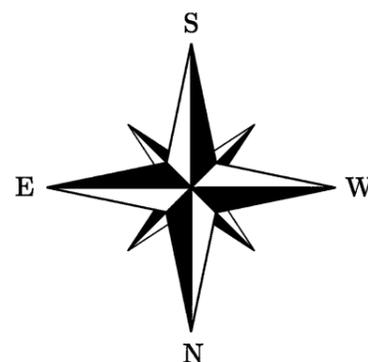
SITUATION



LAND REGISTER REFERENCE: 8549101VK2684N0001PO



LOCATION



PHOTOVOLTAIC SYSTEM

PV modules manufacturer	
PV modules model	TSM-DE18M-(II)-505
N <sup>ct</sup> of PV modules	220 PV modules
PV module peak power	505 W <sub>p</sub>
PV system peak power	111.1 kW <sub>p</sub>
Inverter manufacturer	
Inverter model	SUN2000-100KTL-M1-400Vac
N <sup>ct</sup> of inverters	1 inverter
Inverter rated power	100 kW <sub>r</sub>
PV system rated power	100 kW <sub>r</sub>

DATE: AUGUST 2021

AUTHOR: ADRIÁN CECILIO BENITO

MASTER THESIS

PROJECT: DREAMFIT ALCORCÓN PV PLANT

SCALE: 1:1

COMILLAS PONTIFICAL UNIVERSITY & UNIVERSITY OF STRATHCLYDE

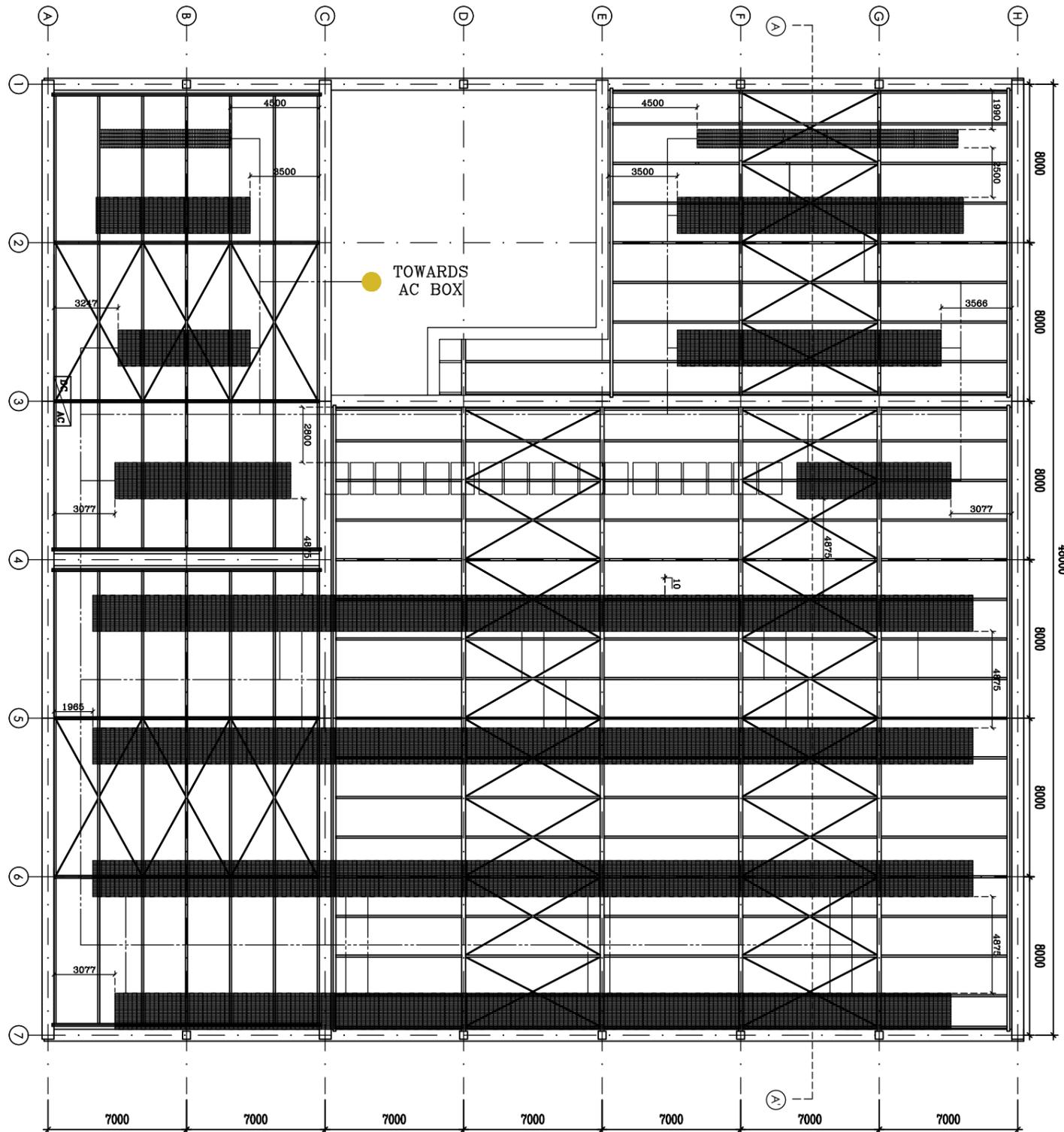
PLAN NUMBER:

PLAN DESIGNATION:

1

SITUATION AND LOCATION

SOUTH

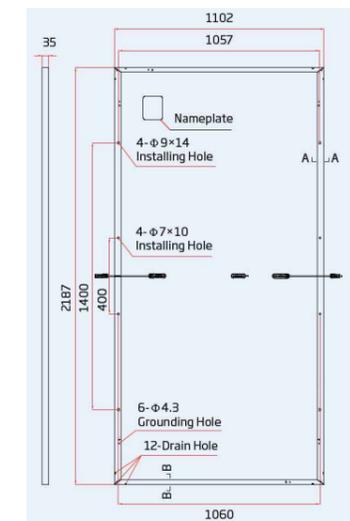
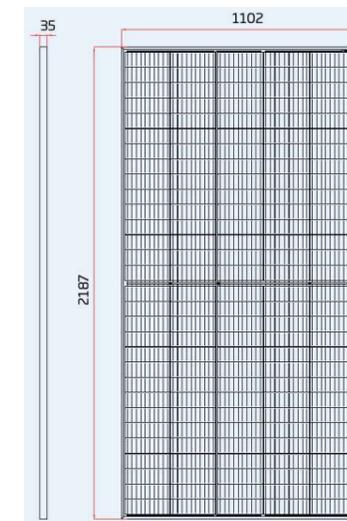


PV GENERAL DISTRIBUTION	
	Horizontal PV Module
	Vertical PV Module
	Thermal PV Panel
	Canalisation Tube
	Huawei DC/AC Inverter

DETAIL OF THE PV MODULES:

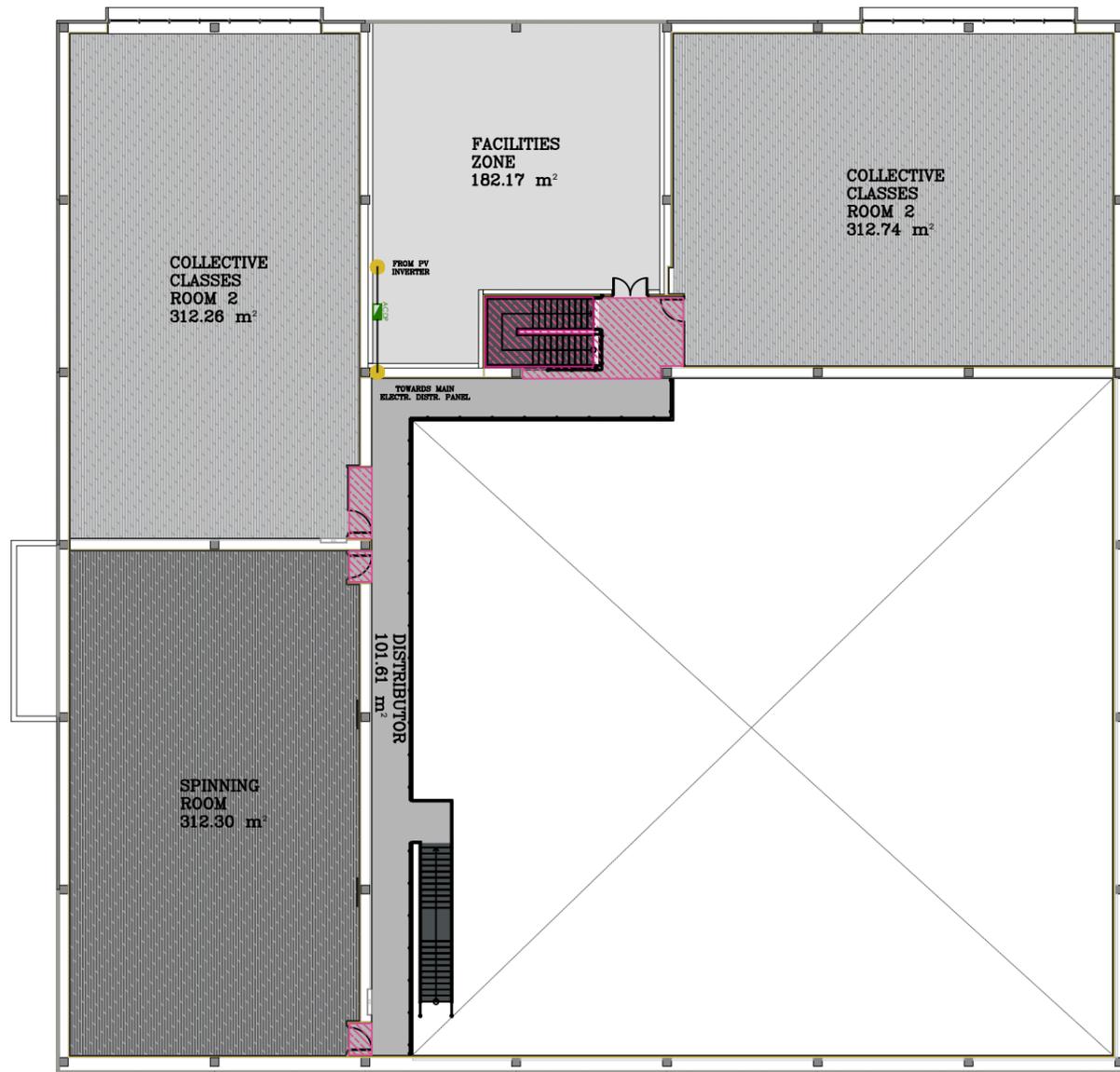
FRONT:

BACK:



DATE: AUGUST 2021	AUTHOR: ADRIÁN CECILIO BENITO	MASTER THESIS
PROJECT: DREAMFIT ALCORCÓN PV PLANT		
SCALE: 1:1	COMILLAS PONTIFICAL UNIVERSITY & UNIVERSITY OF STRATHCLYDE	
PLAN NUMBER: 2	PLAN DESIGNATION: GENERAL DISTRIBUTION	

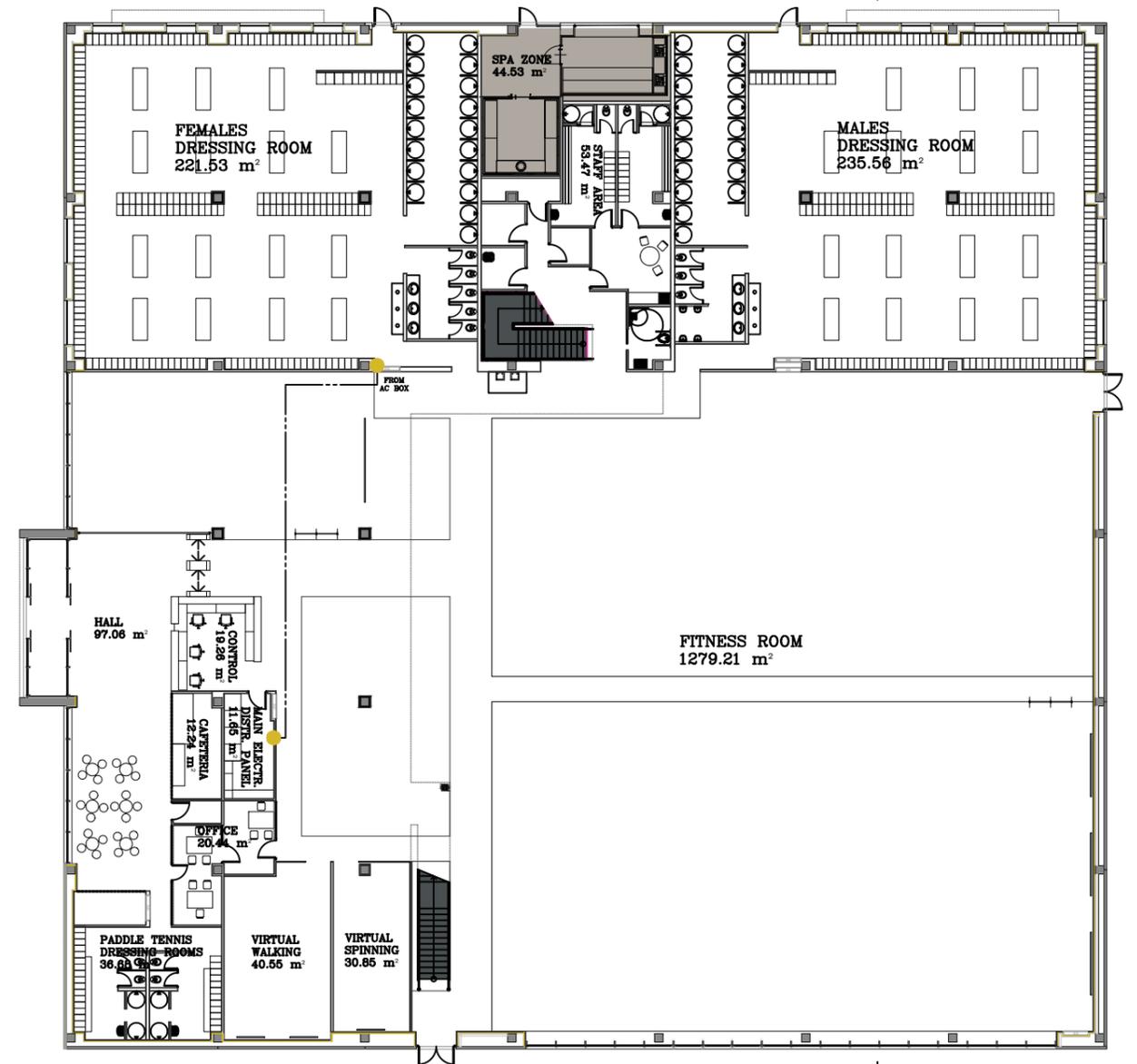
SOUTH



UPPER FLOOR

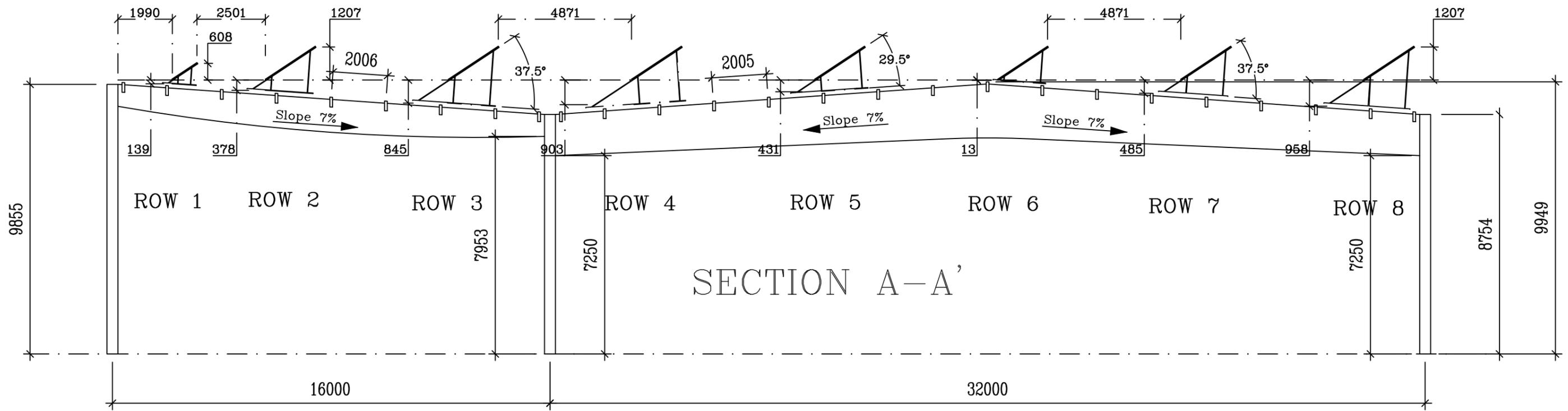
PV CANALISATION	
	Canalisation Tube
	AC Box

SOUTH



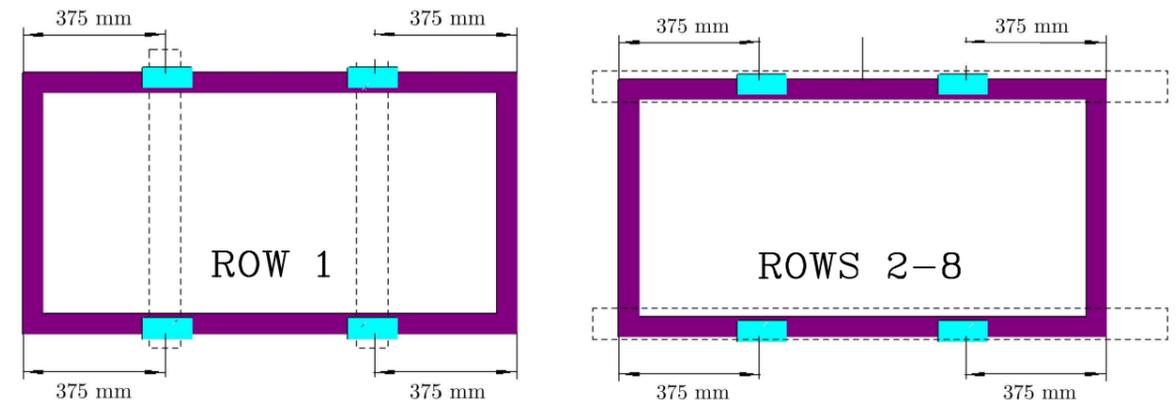
GROUND FLOOR

DATE: AUGUST 2021	AUTHOR: ADRIÁN CECILIO BENITO	MASTER THESIS
PROJECT: DREAMFIT ALCORCÓN PV PLANT		
SCALE: 1:1	COMILLAS PONTIFICAL UNIVERSITY & UNIVERSITY OF STRATHCLYDE	
PLAN NUMBER: 3	PLAN DESIGNATION: CANALISATION	

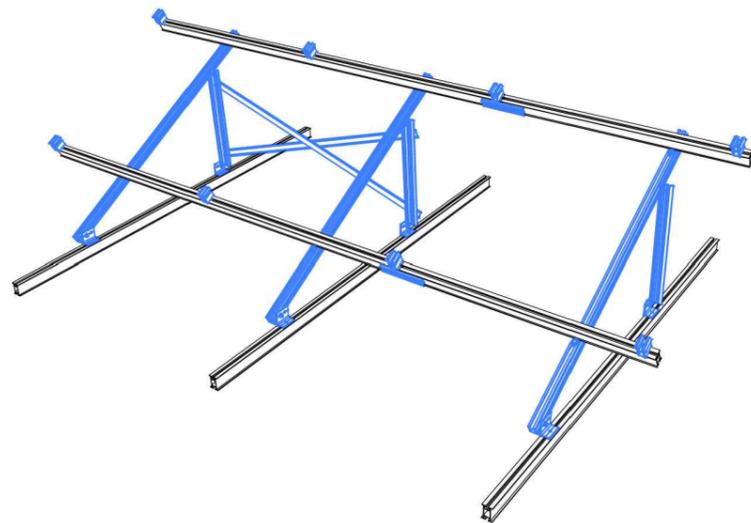


PV MOUNTING STRUCTURE	
Maximum Facilities Load Withstood	25 kg/m <sup>2</sup>
PV Structure Maximum Load	22.70 kg/m <sup>2</sup> ✓

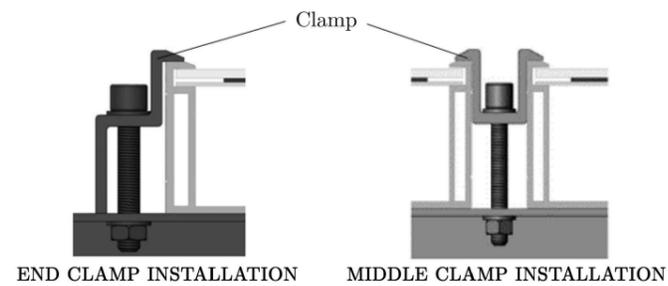
DETAIL OF THE MOUNTING RAILS:



DETAIL OF THE MOUNTING STRUCTURE:

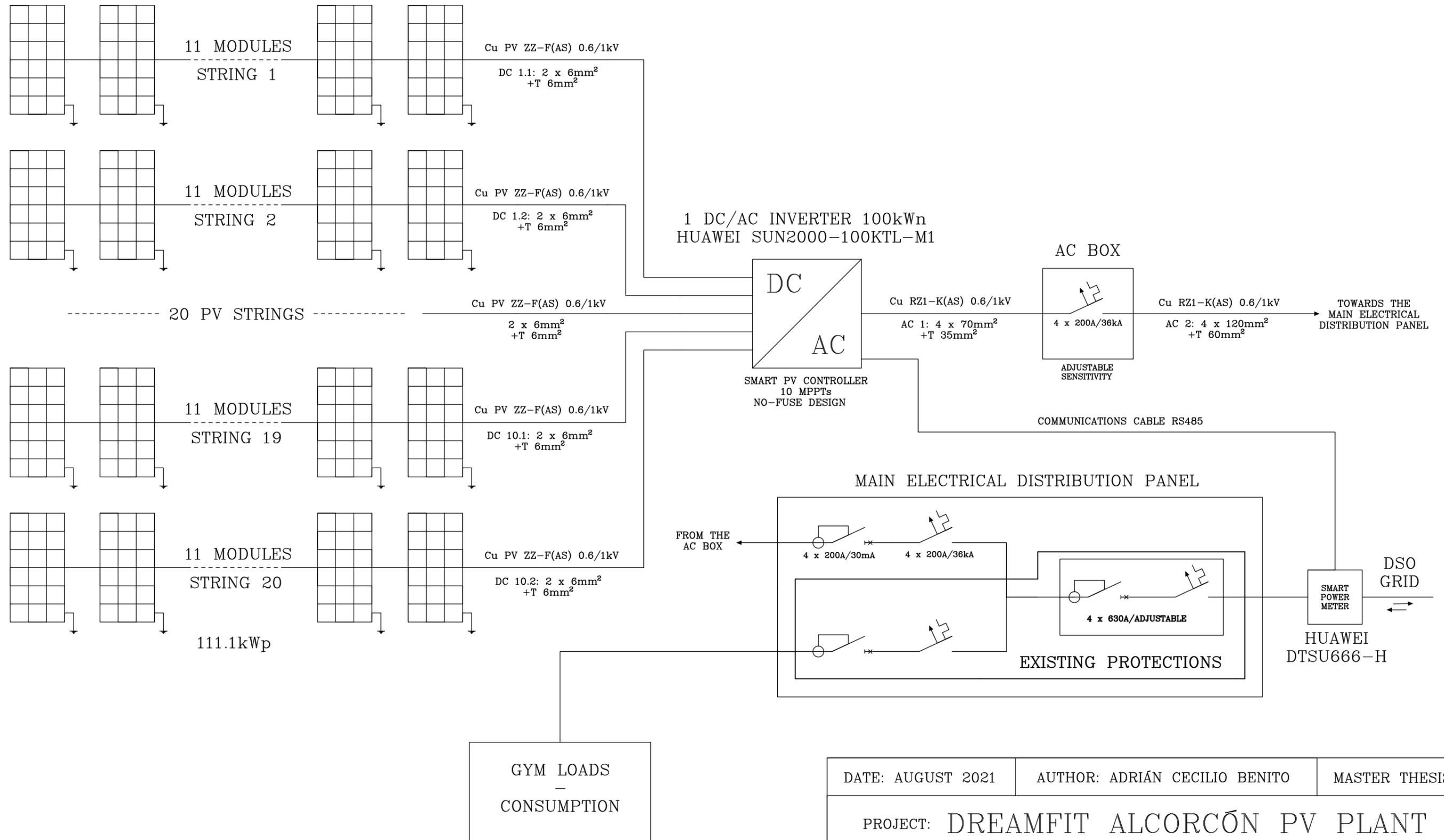


DETAIL OF THE ANCHORING:



DATE: AUGUST 2021	AUTHOR: ADRIÁN CECILIO BENITO	MASTER THESIS
PROJECT: DREAMFIT ALCORCÓN PV PLANT		
SCALE: 1:1	COMILLAS PONTIFICAL UNIVERSITY & UNIVERSITY OF STRATHCLYDE	
PLAN NUMBER: 4	PLAN DESIGNATION: MOUNTING STRUCTURE	

220 PV MODULES TRINASOLAR TSM-DE18M(II) 505Wp



DATE: AUGUST 2021	AUTHOR: ADRIÁN CECILIO BENITO	MASTER THESIS
PROJECT: DREAMFIT ALCORCÓN PV PLANT		
SCALE: 1:1	COMILLAS PONTIFICAL UNIVERSITY & UNIVERSITY OF STRATHCLYDE	
PLAN NUMBER: 5	PLAN DESIGNATION: ELECTRICAL SCHEMATIC	

# Bibliography

- [1] IRENA. *Future of Solar Photovoltaic*. URL: [https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA\\_Future\\_of\\_Solar\\_PV\\_2019.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Future_of_Solar_PV_2019.pdf) (visited on 07/17/2021).
- [2] Dreamfit. *Disfruta de tu Gimnasio Dreamfit*. URL: <https://www.dreamfit.es/> (visited on 05/08/2021).
- [3] IDAE. *Evolución Tecnológica y Prospectiva de Costes de las Energías Renovables*. URL: [https://www.idae.es/uploads/documentos/documentos\\_11227\\_e2\\_tecnologia\\_y\\_costes\\_7d24f737.pdf](https://www.idae.es/uploads/documentos/documentos_11227_e2_tecnologia_y_costes_7d24f737.pdf) (visited on 07/17/2021).
- [4] Google Earth. *Dreamfit Alcorcón*. URL: <https://earth.google.com/web/@40.32973328,-3.84305487,679.75123792a,239.40997632d,35y,39.11148612h,59.99867576t,0r> (visited on 05/08/2021).
- [5] IDAE. *Inicio*. URL: <https://www.idae.es/> (visited on 05/09/2021).
- [6] BOE - Real Decreto 244/2019. *Condiciones Administrativas, Técnicas y Económicas del Autoconsumo de Energía Eléctrica (article 3, instruction h)*. URL: <https://www.boe.es/boe/dias/2019/04/06/pdfs/BOE-A-2019-5089.pdf> (visited on 06/06/2021).
- [7] Trinasolar. *Energía Solar Fiable e Inteligente*. URL: <https://www.trinasolar.com/es/product> (visited on 07/17/2021).
- [8] Huawei. *Solución Inteligente Fusion-Solar*. URL: <https://solar.huawei.com/es/> (visited on 07/17/2021).
- [9] Trinasolar. *Vertex TSM-DE18M(II) Triple Corte, MBB, 480-505W*. URL: <https://www.trinasolar.com/es/product/VERTEX-DE18MII> (visited on 07/18/2021).
- [10] Trinasolar. *Trinasolar Recognised as Top Performer Module Manufacturer by PVEL and DNV GL*. URL: <https://www.trinasolar.com/eu-en/resources/newsroom/eu-trinasolar-recognized-top-performer-module-manufacturer-pvel-dnv-gl-fifth-time> (visited on 07/18/2021).
- [11] PVEL. *Bankability Testing for the Solar Industry*. URL: <https://www.pvel.com/> (visited on 07/18/2021).
- [12] DNV. *When Trust Matters*. URL: <https://www.dnv.es/> (visited on 07/18/2021).
- [13] Energías Renovables. *¿Por Qué la Tecnología PERC se Está Haciendo un Hueco en la Fotovoltaica?* URL: <https://www.energias-renovables.com/fotovoltaica/por-que-la-tecnologia-perc-se-20180306> (visited on 07/18/2021).
- [14] Huawei. *Huawei Wins Intersolar AWARD at Intersolar 2019*. URL: [https://solar.huawei.com/na/news/en\\_20190516](https://solar.huawei.com/na/news/en_20190516) (visited on 07/18/2021).
- [15] Huawei. *Solución Inteligente de Fotovoltaica Fusion-Solar Comercial*. URL: <https://solar.huawei.com/es/Commercial> (visited on 07/19/2021).
- [16] Huawei. *SUN2000-100KTL-M1 User Manual*. URL: <https://support.huawei.com/enterprise/es/doc/EDOC1100127828> (visited on 06/29/2021).

- [17] Huawei. *Huawei Fusion-Solar Youtube Channel*. URL: <https://www.youtube.com/channel/UCqY5WCjAYp2LyogA28vsyeg> (visited on 07/19/2021).
- [18] Huawei. *DTSU666-H 100A and 250A Smart Power Sensor User Manual*. URL: <https://support.huawei.com/enterprise/en/doc/ED0C1100020898/426cffd9/about-this-document> (visited on 07/20/2021).
- [19] BOE - Real Decreto 842/2002. *Reglamento Electrotécnico para Baja Tensión (REBT)*. URL: <https://www.boe.es/boe/dias/2002/09/18/pdfs/A33084-33086.pdf> (visited on 05/23/2021).
- [20] TÜV Rheinland. *Certification and Auditing Services for Batteries, Cells and Accumulators*. URL: <https://www.tuv.com/united-kingdom/en/batteries-cells-accumulators.html?verbid=131> (visited on 07/20/2021).
- [21] BOE - Real Decreto 1699/2011. *Conexión a Red de Instalaciones de Producción de Energía Eléctrica de Pequeña Potencia (article 14)*. URL: <https://www.boe.es/boe/dias/2011/12/08/pdfs/BOE-A-2011-19242.pdf> (visited on 05/22/2021).
- [22] Trinasolar. *User Manual Vertex Series Modules*. URL: [https://static.trinasolar.com/sites/default/files/AP\\_Vertex%5C%20Series\\_User\\_Manual\\_Apr2021.pdf](https://static.trinasolar.com/sites/default/files/AP_Vertex%5C%20Series_User_Manual_Apr2021.pdf) (visited on 06/22/2021).
- [23] Solarstem. *Perfiles de Aluminio sin Mecanizar*. URL: [https://solarstem.com/wp-content/uploads/2015/06/IC-032-3-SP\\_PERFILES\\_PS\\_DIRECT\\_ESTRUCTURAS\\_FOTOVOLTAICAS.pdf](https://solarstem.com/wp-content/uploads/2015/06/IC-032-3-SP_PERFILES_PS_DIRECT_ESTRUCTURAS_FOTOVOLTAICAS.pdf) (visited on 07/25/2021).
- [24] IDAE. *Pliego de Condiciones Técnicas de Instalaciones Aisladas de Red (point 2)*. URL: [https://www.idae.es/uploads/documentos/documentos\\_pliego\\_condiciones\\_tecnicas\\_instalaciones\\_aisladas\\_red\\_843370f2.pdf](https://www.idae.es/uploads/documentos/documentos_pliego_condiciones_tecnicas_instalaciones_aisladas_red_843370f2.pdf) (visited on 06/01/2021).
- [25] IDAE. *Pliego de Condiciones Técnicas de Instalaciones Aisladas de Red (figures 3-4)*. URL: [https://www.idae.es/uploads/documentos/documentos\\_pliego\\_condiciones\\_tecnicas\\_instalaciones\\_aisladas\\_red\\_843370f2.pdf](https://www.idae.es/uploads/documentos/documentos_pliego_condiciones_tecnicas_instalaciones_aisladas_red_843370f2.pdf) (visited on 06/01/2021).
- [26] IDAE. *Pliego de Condiciones Técnicas de Instalaciones Aisladas de Red (table 3)*. URL: [https://www.idae.es/uploads/documentos/documentos\\_pliego\\_condiciones\\_tecnicas\\_instalaciones\\_aisladas\\_red\\_843370f2.pdf](https://www.idae.es/uploads/documentos/documentos_pliego_condiciones_tecnicas_instalaciones_aisladas_red_843370f2.pdf) (visited on 06/01/2021).
- [27] PVsyst. *Photovoltaic Software*. URL: <https://www.pvsyst.com/> (visited on 06/01/2021).
- [28] IDAE. *Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red (figure 4)*. URL: [https://www.idae.es/sites/default/files/documentos\\_5654\\_FV\\_pliego\\_condiciones\\_tecnicas\\_instalaciones\\_conectadas\\_a\\_red\\_C20\\_Julio\\_2011\\_3498eaaf.pdf](https://www.idae.es/sites/default/files/documentos_5654_FV_pliego_condiciones_tecnicas_instalaciones_conectadas_a_red_C20_Julio_2011_3498eaaf.pdf) (visited on 06/01/2021).
- [29] MathWorks. *Matlab-Simulink*. URL: <https://www.mathworks.com> (visited on 06/04/2021).
- [30] European Commission. *Photovoltaic Geographical Information System (PVGIS)*. URL: <https://ec.europa.eu/jrc/en/pvgis> (visited on 06/04/2021).
- [31] European Commission. *PVGIS TMY Generator*. URL: <https://ec.europa.eu/jrc/en/PVGIS/tools/tmy> (visited on 06/04/2021).
- [32] L. Ubaldo Yancachajlla T. Quispe-Huaman and O. A. Vilca-Huayta. *Evaluation of the Peak-Sun Hour on a Tilted Surface in the City of Juliaca*. URL: <https://ieeexplore.ieee.org/document/9220191> (visited on 06/04/2021).
- [33] MathWorks. *Command Xlsread*. URL: <https://uk.mathworks.com/help/matlab/ref/xlsread.html> (visited on 06/06/2021).

- [34] MathWorks. *Command Xlswrite*. URL: <https://uk.mathworks.com/help/matlab/ref/xlswrite.html> (visited on 06/06/2021).
- [35] Circutor. *CVM-MINI Series*. URL: <http://circutor.es/en/products/measurement-and-control/fixed-power-analyzers/power-analyzers/cvm-mini-series-detail> (visited on 06/04/2021).
- [36] IDAE. *Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red (subsection 7.2.4)*. URL: [https://www.idae.es/sites/default/files/documentos\\_5654\\_FV\\_pliego\\_condiciones\\_tecnicas\\_instalaciones\\_conectadas\\_a\\_red\\_C20\\_Julio\\_2011\\_3498eaaf.pdf](https://www.idae.es/sites/default/files/documentos_5654_FV_pliego_condiciones_tecnicas_instalaciones_conectadas_a_red_C20_Julio_2011_3498eaaf.pdf) (visited on 06/06/2021).
- [37] IDAE. *Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red (subsection 7.2.3)*. URL: [https://www.idae.es/sites/default/files/documentos\\_5654\\_FV\\_pliego\\_condiciones\\_tecnicas\\_instalaciones\\_conectadas\\_a\\_red\\_C20\\_Julio\\_2011\\_3498eaaf.pdf](https://www.idae.es/sites/default/files/documentos_5654_FV_pliego_condiciones_tecnicas_instalaciones_conectadas_a_red_C20_Julio_2011_3498eaaf.pdf) (visited on 06/06/2021).
- [38] Huawei. *Smart PV Controller SUN2000-100KTL-M1 (circuit diagram)*. URL: <https://solar.huawei.com/en-GB/download?p=%5C%2F-%5C%2Fmedia%5C%2FSolar%5C%2Fattachment%5C%2Fpdf%5C%2Feu%5C%2Fdatasheet%5C%2FSUN2000-100KTL-M1.pdf> (visited on 06/08/2021).
- [39] Agencia Estatal de Meteorología. *Valores Extremos-Getafe*. URL: [http://www.aemet.es/es/serviciosclimaticos/datosclimatologicos/efemerides\\_extremos\\*w=0&k=mad&l=3200&datos=det&x=3200&m=13&v=todos](http://www.aemet.es/es/serviciosclimaticos/datosclimatologicos/efemerides_extremos*w=0&k=mad&l=3200&datos=det&x=3200&m=13&v=todos) (visited on 06/09/2021).
- [40] IDAE. *Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red (equation 2)*. URL: [https://www.idae.es/sites/default/files/documentos\\_5654\\_FV\\_pliego\\_condiciones\\_tecnicas\\_instalaciones\\_conectadas\\_a\\_red\\_C20\\_Julio\\_2011\\_3498eaaf.pdf](https://www.idae.es/sites/default/files/documentos_5654_FV_pliego_condiciones_tecnicas_instalaciones_conectadas_a_red_C20_Julio_2011_3498eaaf.pdf) (visited on 06/09/2021).
- [41] IDAE. *Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red (annex III, page 44)*. URL: [https://www.idae.es/sites/default/files/documentos\\_5654\\_FV\\_pliego\\_condiciones\\_tecnicas\\_instalaciones\\_conectadas\\_a\\_red\\_C20\\_Julio\\_2011\\_3498eaaf.pdf](https://www.idae.es/sites/default/files/documentos_5654_FV_pliego_condiciones_tecnicas_instalaciones_conectadas_a_red_C20_Julio_2011_3498eaaf.pdf) (visited on 05/25/2021).
- [42] IDAE. *Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red (figure 7)*. URL: [https://www.idae.es/sites/default/files/documentos\\_5654\\_FV\\_pliego\\_condiciones\\_tecnicas\\_instalaciones\\_conectadas\\_a\\_red\\_C20\\_Julio\\_2011\\_3498eaaf.pdf](https://www.idae.es/sites/default/files/documentos_5654_FV_pliego_condiciones_tecnicas_instalaciones_conectadas_a_red_C20_Julio_2011_3498eaaf.pdf) (visited on 05/25/2021).
- [43] University of Oregon. *Solar Radiation Monitoring Laboratory*. URL: <http://solardat.uoregon.edu/SunChartProgram.html> (visited on 05/26/2021).
- [44] IDAE. *Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red (annex III, point 5)*. URL: [https://www.idae.es/sites/default/files/documentos\\_5654\\_FV\\_pliego\\_condiciones\\_tecnicas\\_instalaciones\\_conectadas\\_a\\_red\\_C20\\_Julio\\_2011\\_3498eaaf.pdf](https://www.idae.es/sites/default/files/documentos_5654_FV_pliego_condiciones_tecnicas_instalaciones_conectadas_a_red_C20_Julio_2011_3498eaaf.pdf) (visited on 05/25/2021).
- [45] IDAE. *Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red (annex III, point 2)*. URL: [https://www.idae.es/sites/default/files/documentos\\_5654\\_FV\\_pliego\\_condiciones\\_tecnicas\\_instalaciones\\_conectadas\\_a\\_red\\_C20\\_Julio\\_2011\\_3498eaaf.pdf](https://www.idae.es/sites/default/files/documentos_5654_FV_pliego_condiciones_tecnicas_instalaciones_conectadas_a_red_C20_Julio_2011_3498eaaf.pdf) (visited on 06/03/2021).
- [46] Autodesk. *Autocad - 3D Design, Engineering and Construction Software*. URL: <https://www.autodesk.es/> (visited on 06/03/2021).

- [47] IDAE. *Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red (figure 5)*. URL: [https://www.idae.es/sites/default/files/documentos\\_5654\\_FV\\_pliego\\_condiciones\\_tecnicas\\_instalaciones\\_conectadas\\_a\\_red\\_C20\\_Julio\\_2011\\_3498eaaf.pdf](https://www.idae.es/sites/default/files/documentos_5654_FV_pliego_condiciones_tecnicas_instalaciones_conectadas_a_red_C20_Julio_2011_3498eaaf.pdf) (visited on 06/03/2021).
- [48] IDAE. *Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red (table V-1)*. URL: [https://www.idae.es/sites/default/files/documentos\\_5654\\_FV\\_pliego\\_condiciones\\_tecnicas\\_instalaciones\\_conectadas\\_a\\_red\\_C20\\_Julio\\_2011\\_3498eaaf.pdf](https://www.idae.es/sites/default/files/documentos_5654_FV_pliego_condiciones_tecnicas_instalaciones_conectadas_a_red_C20_Julio_2011_3498eaaf.pdf) (visited on 06/03/2021).
- [49] IDAE. *Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red (annex III, section 2.4)*. URL: [https://www.idae.es/sites/default/files/documentos\\_5654\\_FV\\_pliego\\_condiciones\\_tecnicas\\_instalaciones\\_conectadas\\_a\\_red\\_C20\\_Julio\\_2011\\_3498eaaf.pdf](https://www.idae.es/sites/default/files/documentos_5654_FV_pliego_condiciones_tecnicas_instalaciones_conectadas_a_red_C20_Julio_2011_3498eaaf.pdf) (visited on 06/03/2021).
- [50] Asociación Española de Normalización. *UNE-EN 60228:2005: Conductors of Insulated Cables*. URL: <https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0033734> (visited on 06/26/2021).
- [51] Asociación Española de Normalización. *UNE 21123-2:2014: Industrial Cables of Rated Voltage 0,6/1 kV. Part 2: XLPE Insulated and PVC Sheathed Cables*. URL: <https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma/?Tipo=N&c=N0053008> (visited on 06/26/2021).
- [52] Ministerio de Industria y Energía. *Instrucción MIE BT-001*. URL: <https://www.jmcpr1.net/NORMATIVA%5C%20COMPLEMENTARIA/27-Rbt/BT001.htm> (visited on 07/04/2021).
- [53] Ministerio de Industria. *ITC-BT-18*. URL: [http://www.f2i2.net/documentos/l5iF2I2/rbt/guias/guia\\_bt\\_18\\_oct05R1.pdf](http://www.f2i2.net/documentos/l5iF2I2/rbt/guias/guia_bt_18_oct05R1.pdf) (visited on 07/05/2021).
- [54] International Electrotechnical Commission IEC. *Conformity Assessment*. URL: <https://www.iec.ch/conformity-assessment> (visited on 07/10/2021).
- [55] Solarstem. *Perfiles Base y Portantes de Aluminio*. URL: <https://solarstem.com/sistemas-de-montaje/soportes-para-paneles-solares/> (visited on 07/10/2021).
- [56] Guillermo Ortego Carretero. *Memoria General del Proyecto Básico y de Ejecución del Centro de Deportes de Raqueta Dreamfit Alcorcón*.
- [57] R. Gonzalez, H. R. Jimenez, and J. M. Huacuz. *Voltage and Power Ratio Effects of Grid-Connected PV Plant's Operation on the Performance Ratio and Total System Efficiency*. URL: <https://ieeexplore.ieee.org/document/4017981> (visited on 07/21/2021).
- [58] PVSyst. *Array Incidence Loss (IAM)*. URL: [https://www.pvsyst.com/help/iam\\_loss.htm](https://www.pvsyst.com/help/iam_loss.htm) (visited on 07/21/2021).
- [59] BOE - Resolución de 18 de marzo de 2021 de la CNMC. *Valores de los Peajes de Acceso a las Redes de Transporte y Distribución de Electricidad de Aplicación a Partir del 1 de Junio de 2021*. URL: <https://www.boe.es/boe/dias/2021/03/23/pdfs/BOE-A-2021-4565.pdf> (visited on 07/22/2021).
- [60] BOE - Real Decreto 1164/2001. *Tarifas de Acceso a las Redes de Transporte y Distribución de Energía Eléctrica*. URL: <https://www.boe.es/buscar/doc.php?id=BOE-A-2001-20850> (visited on 07/22/2021).
- [61] Symelec Renovables. *Energy and Cost Saving*. URL: <http://www.symelec-renovables.com/en/index.html> (visited on 07/22/2021).
- [62] Somenergia. *La Cooperativa de Energía Verde*. URL: <https://www.somenergia.coop/es/> (visited on 07/24/2021).

- [63] Instituto Nacional de Estadística. *Índice de Precios de Consumo - Últimos Datos*. URL: [https://www.ine.es/dyngs/INEbase/es/operacion.htm?c=Estadistica\\_C&cid=1254736176802&menu=ultiDatos&idp=1254735976607](https://www.ine.es/dyngs/INEbase/es/operacion.htm?c=Estadistica_C&cid=1254736176802&menu=ultiDatos&idp=1254735976607) (visited on 07/24/2021).
- [64] BOE - Real Decreto 1110/2007. *Reglamento Unificado de Puntos de Medida del Sistema Eléctrico (article 5)*. URL: <https://www.boe.es/buscar/pdf/2007/BOE-A-2007-16478-consolidado.pdf> (visited on 05/23/2021).
- [65] Elecnor. *Infrastructure, Renewable Energies and New Technologies*. URL: <https://www.elecnor.com/home-en> (visited on 07/24/2021).
- [66] PVSyst. *Carbon Balance Tool*. URL: [https://www.pvsyst.com/help/carbon\\_balance\\_tool.htm](https://www.pvsyst.com/help/carbon_balance_tool.htm) (visited on 07/25/2021).
- [67] International Energy Agency. *Spain - Countries and Regions*. URL: <https://www.iea.org/countries/spain> (visited on 07/25/2021).
- [68] Asociación Española de Normalización. *UNE 157001:2014: General Criteria for the Drawing-Up of the Documents which Make Up a Technical Project*. URL: <https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0052985> (visited on 08/15/2021).
- [69] United Nations. *Sustainable Development Goals, 17 Goals to Transform Our World*. URL: <https://www.un.org/sustainabledevelopment/> (visited on 06/20/2021).
- [70] The Guardian. *Outdoor Air Pollution Cuts Three Years from Human Lifespan*. URL: <https://www.theguardian.com/environment/2020/mar/03/outdoor-air-pollution-cuts-three-years-from-human-lifespan-study> (visited on 06/20/2021).
- [71] Gobierno de España - Presidencia del Gobierno. *NextGenerationEU*. URL: <https://www.lamoncloa.gob.es/temas/fondos-recuperacion/Paginas/fondos-europeos.aspx> (visited on 06/20/2021).
- [72] Asociación Española de Normalización. *UNE-HD 60364-7-712:2017: Low-Voltage Electrical Installations - Part 7-712: Requirements for Special Installations or Locations - Photovoltaic (PV) Systems*. URL: <https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0057935> (visited on 05/20/2021).
- [73] BOE - Reglamento Electrotécnico para Baja Tensión. *ITC-BT 19 (table 3)*. URL: <https://www.boe.es/buscar/act.php?id=BOE-A-2002-18099#ib-19> (visited on 05/20/2021).
- [74] Megger. *Electrical Testing Solutions Built for your Application Needs*. URL: <https://us.megger.com/> (visited on 05/20/2021).
- [75] BOE - Reglamento Electrotécnico para Baja Tensión. *ITC-BT 19 (section 2.2.4)*. URL: <https://www.boe.es/buscar/act.php?id=BOE-A-2002-18099#ib-19> (visited on 05/22/2021).
- [76] BOE - Reglamento Electrotécnico para Baja Tensión. *ITC-BT 20*. URL: <https://www.boe.es/buscar/act.php?id=BOE-A-2002-18099#ib-20> (visited on 05/22/2021).
- [77] IDAE. *Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red (section 5)*. URL: [https://www.idae.es/sites/default/files/documentos\\_5654\\_FV\\_pliego\\_condiciones\\_tecnicas\\_instalaciones\\_conectadas\\_a\\_red\\_C20\\_Julio\\_2011\\_3498eaaf.pdf](https://www.idae.es/sites/default/files/documentos_5654_FV_pliego_condiciones_tecnicas_instalaciones_conectadas_a_red_C20_Julio_2011_3498eaaf.pdf) (visited on 05/22/2021).
- [78] BOE - Reglamento Electrotécnico para Baja Tensión. *ITC-BT 43 (table 1)*. URL: <https://www.boe.es/buscar/act.php?id=BOE-A-2002-18099#ib-43> (visited on 05/22/2021).

- [79] Asociación Española de Normalización. *UNE-EN 61646:2009: Thin-Film Terrestrial Photovoltaic (PV) Modules - Design Qualification and Type Approval*. URL: <https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0042946> (visited on 05/22/2021).
- [80] TÜV SÜD. *Add Value, Inspire Trust*. URL: <https://www.tuvsud.com/en/about-us> (visited on 05/22/2021).
- [81] European Commission. *Electro-Magnetic Compatibility (EMC) Directive*. URL: [https://ec.europa.eu/growth/sectors/electrical-engineering/emc-directive\\_en](https://ec.europa.eu/growth/sectors/electrical-engineering/emc-directive_en) (visited on 05/22/2021).
- [82] European Commission. *The Low Voltage Directive (LVD)*. URL: [https://ec.europa.eu/growth/sectors/electrical-engineering/lvd-directive\\_en](https://ec.europa.eu/growth/sectors/electrical-engineering/lvd-directive_en) (visited on 05/22/2021).
- [83] Comisión Nacional de los Mercados y la Competencia. *Plantilla Informe CNMC*. URL: [https://www.cnmec.es/sites/default/files/2190303\\_1.pdf](https://www.cnmec.es/sites/default/files/2190303_1.pdf) (visited on 05/22/2021).
- [84] BOE - Reglamento Electrotécnico para Baja Tensión. *Anexo 1: Significado y Explicación de los Códigos IP e IK*. URL: [https://industria.gob.es/Calidad-Industrial/seguridadindustrial/instalacionesindustriales/baja-tension/Documents/bt/guia\\_bt\\_anexo\\_1\\_sep03R1.pdf](https://industria.gob.es/Calidad-Industrial/seguridadindustrial/instalacionesindustriales/baja-tension/Documents/bt/guia_bt_anexo_1_sep03R1.pdf) (visited on 05/22/2021).
- [85] Asociación Española de Normalización. *UNE 21123-1:2017: Industrial Cables of Rated Voltage 0,6/1 kV. Part 1: PVC Insulated and Sheathed Cables*. URL: <https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma/?c=N0057801> (visited on 05/22/2021).
- [86] BOE - Real Decreto 1699/2011. *Conexión a Red de Instalaciones de Producción de Energía Eléctrica de Pequeña Potencia (article 13)*. URL: <https://www.boe.es/boe/dias/2011/12/08/pdfs/BOE-A-2011-19242.pdf> (visited on 05/22/2021).
- [87] BOE - Real Decreto 1110/2007. *Reglamento Unificado de Puntos de Medida del Sistema Eléctrico (article 9)*. URL: <https://www.boe.es/buscar/pdf/2007/BOE-A-2007-16478-consolidado.pdf> (visited on 05/23/2021).
- [88] BOE - Real Decreto 1699/2011. *Conexión a Red de Instalaciones de Producción de Energía Eléctrica de Pequeña Potencia (article 15)*. URL: <https://www.boe.es/boe/dias/2011/12/08/pdfs/BOE-A-2011-19242.pdf> (visited on 05/23/2021).
- [89] BOE - Real Decreto 1699/2011. *Conexión a Red de Instalaciones de Producción de Energía Eléctrica de Pequeña Potencia (article 16)*. URL: <https://www.boe.es/boe/dias/2011/12/08/pdfs/BOE-A-2011-19242.pdf> (visited on 05/23/2021).
- [90] IDAE. *Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red (section 6)*. URL: [https://www.idae.es/sites/default/files/documentos\\_5654\\_FV\\_pliego\\_condiciones\\_tecnicas\\_instalaciones\\_conectadas\\_a\\_red\\_C20\\_Julio\\_2011\\_3498eaaf.pdf](https://www.idae.es/sites/default/files/documentos_5654_FV_pliego_condiciones_tecnicas_instalaciones_conectadas_a_red_C20_Julio_2011_3498eaaf.pdf) (visited on 05/23/2021).
- [91] BOE - Real Decreto 23/2003. *Aspectos de la Venta y Garantía de los Bienes de Consumo*. URL: <https://www.boe.es/boe/dias/2003/07/11/pdfs/A27160-27164.pdf> (visited on 05/23/2021).
- [92] Asociación Española de Normalización. *UNE-EN 60529:2018: Degrees of Protection Provided by Enclosures (IP Code)*. URL: <https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0060015> (visited on 06/13/2021).
- [93] RIB Spain. *Presto iTWO*. URL: [https://www.rib-software.es/presto\\_21](https://www.rib-software.es/presto_21) (visited on 08/08/2021).