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

COMILLAS PONTIFICAL UNIVERSITY - MASTER THESIS - MASTER´S DEGREE IN SMART GRIDS
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Collaborating Entity: Dreamfit®.

***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 project will enable the production of almost 200 MWh of clean per year while avoiding the annual emission of more than 50 tonnes of carbon dioxide to the atmosphere.**

***Index Terms*—Photovoltaic (PV) Energy, PV Plant, Self-Consumption, Distributed Energy Resource (DER), Renewable Energy, PV Module.**

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I. Introduction

THE global energetic context is currently focused on a decarbonisation economy fostered through diverse political measurements intended to boost renewable energies [1]. In the particular case of Spain, where this project will be developed, the major regulatory examples are RITE [2], which determines minimum efficiency requirements and establishes the minimum renewable contribution for Sanitary Hot Water, and Royal Decree 244/2019 [3], 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 [4]. Then, this project consists of the design of a whole engineering project to include a photovoltaic plant for self-consumption in a Spanish sports facility.

I.I. CURRENT STATUS

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 voltage generating facilities [5], or the publication of the Technical Specifications of Grid-Connected Facilities [6] as well as the new electricity tariffs that came into force the first of June of 2021.

I.II. CONTEXT OF THE MASTER THESIS

Dreamfit® [7] 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:

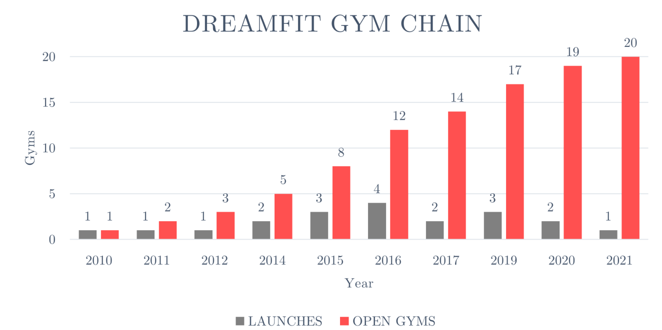


Fig. 1: Dreamfit Gym Chain launches in the period 2010-2021.

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 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.

I.III. 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 and aligned with the Dreamfit core value of insisting on the highest standards:

- Self-consuming more than 150 $MWh/year$, what would represent more than a 35% of the whole energy demanded yearly by the gym.
- Avoiding the emission of more than 50 $t_{eq\ CO_2}/year$.

II. Methodology

II.I. 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 [8]. 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.

II.I.A. 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 [9]. 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 Watts 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 [10]. 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:

$$e\_pv(i) = PSH(i) \cdot \ pp \cdot pr \tag{1}$$

Where:

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

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:

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

Once the code is executed, the **optimal PV peak power** to install is returned by the program. 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[2] $[kWh]$.

[1]In this case: Performance Ratio $pr = 0.887 \rightarrow$ Source PVsyst®.
[2]Either through the PV plant or through the DSO network.

- **PV Production**. Energy generated by the DER $[kWh]$.
- **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 $[kWh]$.

II.I.B. 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 *tfm.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 $\rightarrow 100,395.22$€.
- **Annual Maintenance Cost** [€]. The maintenance fee has been also offered by Elecnor® $\rightarrow 5,000$€$/year$.
- **Annual Power Attenuation of PV Modules** $[\%]$. Obtained from the PV modules data sheet $\rightarrow 0.55\%/year$.
- **Consumer Price Index (CPI)** $[\%]$. Previous 25 years database of the National Institute of Statistic [11] $\rightarrow 2.02\%/year$.
- **Power and Energy Prices** [€$/kW$, €$/kWh$]. Prices per period for the 3.0TD tariff have been consulted to a professional company devoted to energy services: *Symelec Renovables®*.
  - Power: $[0.054, 0.038, 0.019, 0.017, 0.012, 0.007]$ €$/kW$.
  - Energy: $[0.208, 0.184, 0.153, 0.130, 0.108, 0.110]$ €$/kWh$.
- **Surplus Energy Price** [€$/kWh$]. The compensated energy price and the annual surplus depreciation rate have also been consulted to *Symelec Renovables®* $\rightarrow 0.05$€$/kWh$ 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 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 equation:

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

Where:

- $F_{EP} \rightarrow$ Monthly excessive demanded power charge [€].
- $K_i \rightarrow$ Pricing coefficient per period *i* [€$/kW$].
- $P_{d_j} \rightarrow$ 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} $[kW]$.

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 hour, day, week, 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 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 [€].

II.II. 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 [12]:

- **Project Memory**. Including 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 economically assess the project.
- **Plans**. Required to graphically represent and define the project.

II.II.A. 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 Trinasolar Vertex TSM-DE18M(II) PV monofacial modules with a peak power of 505 W_p [13].
- **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 [14].

Then, next table presents the configuration of the PV system:

TABLE I: Configuration of the photovoltaic System.

PHOTOVOLTAIC SYSTEM	
PV modules manufacturer	Trinasolar
PV modules model	TSM-DE18M-(II)-505
N^{er} of PV modules	220 PV modules
PV module peak power	505 W_p
PV system peak power	111.1 kW_p
Inverter manufacturer	HUAWEI
Inverter model	SUN2000-100KTL-M1-400Vac
N^{er} of inverters, strings	1 inverter, 20 strings (10 MPPTs)
Inverter rated power	100 kW_r
PV system rated power	100 kW_r

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%.

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 [15]. 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.

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 [16]:

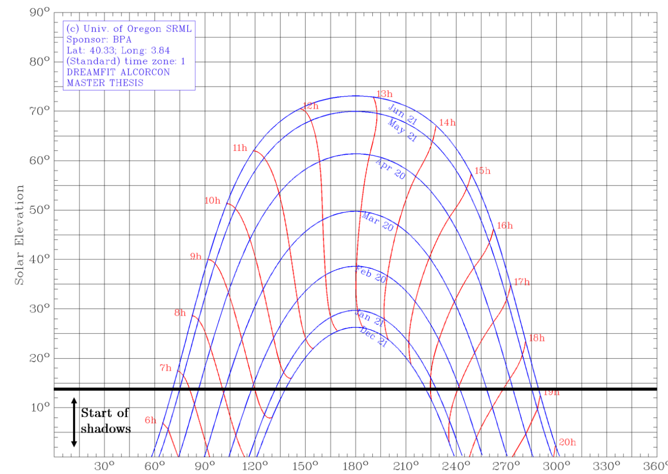


Fig. 2: Sun path chart of Dreamfit Alcorcón.

Then, in order to maximise production:

- **Tilt Angle**: $\beta_{opt} = 33.5°$ with respect to the horizontal plane.
- **Azimuth Angle**: $\alpha_{opt} = 0°$.
- **Distance between the First PV Row and the Edge**: 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 $< 1.5\%$.
  - Two poles: $2 \cdot 6\ mm^2$.
- **AC Side**. Voltage Drop $< 1.5\%$.
  - Three phases and neutral: $4 \cdot 70\ mm^2$ and $4 \cdot 120\ mm^2$.
- **Sections**. 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 [17], Royal Decree 1699/2011 [18] and the Spanish Electrotechnical Regulation for Low Voltage (REBT) [19].

Moreover, the existing grounding system of the building will be used for the PV facility to ensure equipotentiality. Additional coated copper wires between $6-60\ mm^2$ are going unify the earth of all the metallic elements following ITC-BT-08 and ITC-BT-18 [20], [21].

TABLE II: Qualitative summary of the utilised protections.

PROTECTION	TYPE OF PROTECTION	DC	AC
DIRECT CONTACTS	ACTIVE ELEMENTS	INSULATION CLASS II	
	BARRIERS, ENCLOSURES AND OBSTACLES	TUBES, IP65	TUBES
	OUT OF REACH LOCATIONS	FACILITIES ZONE	FALSE CEILING, FACILITIES ZONE
INDIRECT CONTACTS	RESIDUAL CURRENT	INSULATION CLASS II, INVERTER	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	

Table II presents a qualitative summary of the protections included at the Dreamfit Alcorcón PV plant.

The electrical canalisation has been computed respecting the current regulation in terms of canalisation tubes and therefore following ITC-BT-21 [22]. 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^2.

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 as shown in figure 3.

II.II.B. 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 [23].

II.II.C. 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 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 [24], Royal Decree 485/1997 [25], Royal Decree 773/1997 [26] or Royal Decree 614/2001 [27].

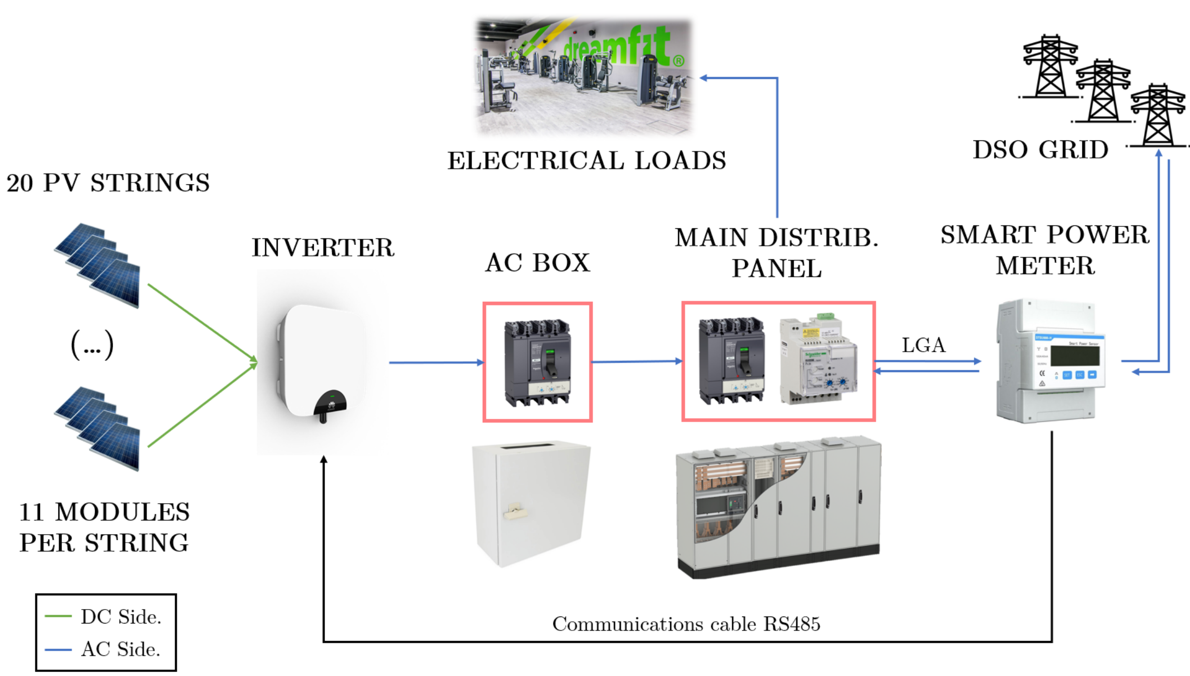


Fig. 3: Interconnection schema of Dreamfit Alcorcón PV plant.

II.II.D. Project Budget

The project budget has been developed by means of the professional software Presto® [28] 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 6 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 required to ensure safety.
5) **Waste Management**. Following the order 2726/2009 [29].
6) **Commissioning**. Including the legalisation of the facility.

→ Total cost of the project: 100,395.22€ (VAT not included).

II.II.E. Project Plans

The five plans that graphically define the project have been designed through the professional software Autocad® [30]:

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.

III. Results

This section presents the results obtained after applying the developed model at Dreamfit Alcorcón. Therefore, the results of the production and economic studies of the pilot project are included.

III.I. RESULTS OF THE PRODUCTION STUDY

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 in table IV.

TABLE IV: 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 IV:

- **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 annual energy consumed by Dreamfit Alcorcón will be generated through the PV plant.

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.

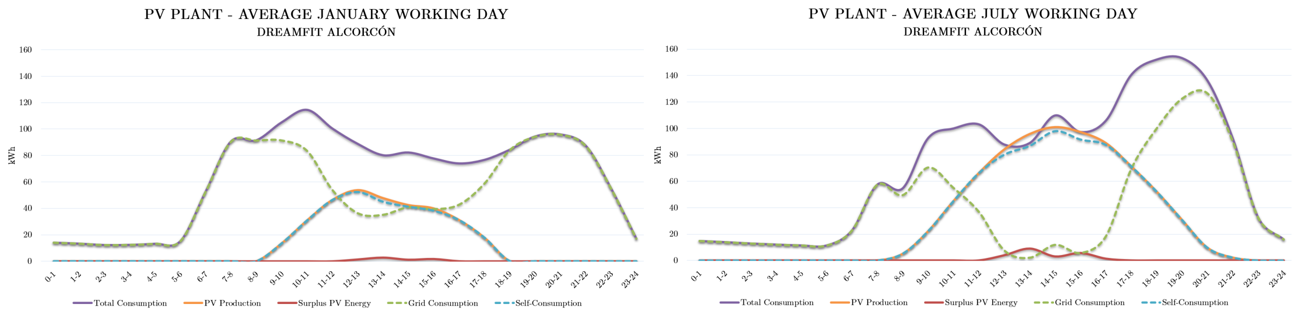
In addition, table III is included as a main results overview, representing a numerical monthly summary of the production study for the first year of the project.

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. Thus, the power attenuation has been considered for the economic study.

Finally, figure 4 compares the performance of the PV plant by contrasting the average working day of the most sunny month against the most cloudy month. Analysing both graphics 4(a) and 4(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.

TABLE III: 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
YEAR	**2,020.15**	**447,567.75**	**198,897.59**	**29,733.28**	**278,403.45**	**169,164.30**



(a) Average January working day.

(b) Average July working day.

Fig. 4: PV plant performance - Most sunny versus most cloudy day.

III.II. RESULTS OF THE ECONOMIC STUDY

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[3]:

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

Additionally, figure 5 presents the annual allocation of total consumption, PV production and self-consumption along the six periods of the 3.0TD tariff of Dreamfit Alcorcón.

At this point, the profitability of the project is assessed through the Internal Rate of Return (IRR) and the PayBack Period (PB).

Hence, the IRR of the 25-year project is computed through the Cash Flows (CF):

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

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:

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

Furthermore, the payback period is evaluated graphically in figure 6. The figure assesses the summation of cash flows considering CPI index as well as any other economical rate mentioned in subsection II, id est, the graphic shows also the project Net Present Value (NPV).

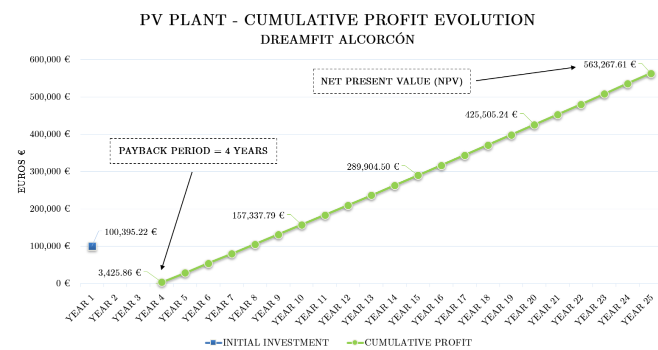


Fig. 6: Economic study - Cumulative profit evolution.

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

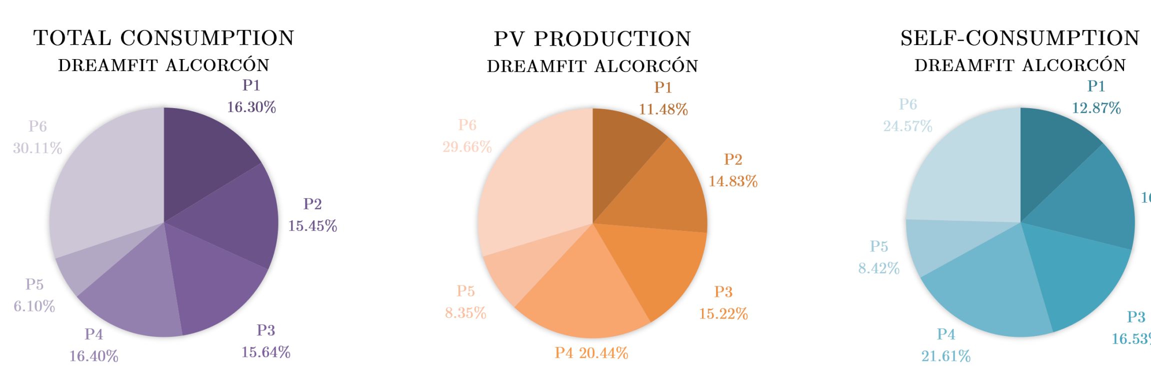
$$\boxed{IRR = 25.96\%} \quad \boxed{Payback\ Period = 4\ years} \tag{6}$$

III.III. TESTING THE PV MODEL

The accuracy of the model developed in MATLAB has been contrasted with a simulation developed through the professional photovoltaic software PVsyst® [31].

The production and economic studies have been replicated under the same hypothetical constraints, parameters and assumptions.

[3]Necessarily $P_1 \leq P_2 \leq P_3 \leq P_4 \leq P_5 \leq P_6$ for tariff 3.0TD.



(a) Total consumption.

(b) PV Production.

(c) Self-consumption.

Fig. 5: Economic study - Consumption and production allocation per 3.0TD tariff periods.

TABLE V: 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%

The comparison between the results obtained by MATLAB and PVsyst are included in table V:

- **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 adjusted.

Delving into the finance results, PVsyst supposes a single-period energy price to perform the economic study. This price has been established considering the gym consumption distribution per period.

Then, the six periods have been given a weight according to the consumption distribution presented in figure 5(a). Every period weight has been obtained multiplying the consumption percentage by the energy price per period utilised for the economic study.

IV. Conclusions

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

- Regarding table V, 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 the roof of **any Dreamfit gym** in the short or the medium term.
- The model has been applied to Dreamfit Alcorcón developing a **whole engineering pilot 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 [32].
- **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*.

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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, *Regulation of Administrative, Technical and Economic Conditions of Self-Consumption*, URL visited on 19/08/2021.
[4] IDAE, *Technological and Economical Evolution of Renewable Energies*, URL visited on 19/08/2021.
[5] BOE, *ITC-BT-40*, URL visited on 19/08/2021.
[6] IDAE, *Technical Specifications of Grid-Connected Facilities*, URL visited on 19/08/2021.
[7] Dreamfit, *Low Cost Gym Chain*, URL visited on 19/08/2021.
[8] Mathworks, *Matlab & Simulink*, URL visited on 19/08/2021.
[9] European Commission, *PVGIS TMY Tool*, URL visited on 19/08/2021.
[10] Circutor, *CVM-MINI Series*, URL visited on 19/08/2021.
[11] INE, *Consumer Price Index*, URL visited on 19/08/2021.
[12] UNE, *UNE 157001:2014*, URL visited on 19/08/2021.
[13] Trinasolar, *Vertex TSM-DE18M(II) modules*, URL visited on 19/08/2021.
[14] Huawei, *Smart PV Controller DC/AC Inverter SUN2000-100KTL-M1*, URL visited on 19/08/2021.
[15] Huawei, *Fusion Solar Smart PV Management System*, URL visited on 19/08/2021.
[16] University of Oregon, *Solar Radiation Monitoring Laboratory*, URL visited on 19/08/2021.
[17] BOE - Royal Decree 1663/2000, *Connection of Photovoltaic Plants to the Low Voltage Grid*, URL visited on 19/08/2021.
[18] BOE - Royal Decree 1699/2011, *Grid Interconnection of Reduced Power Generation Plants*, URL visited on 19/08/2021.
[19] BOE - Royal Decree 842/2002, *Electrotechnical Regulation for Low Voltage*, URL visited on 19/08/2021.
[20] BOE, *ITC-BT-08*, URL visited on 19/08/2021.
[21] BOE, *ITC-BT-18*, URL visited on 19/08/2021.
[22] BOE, *ITC-BT-21*, URL visited on 19/08/2021.
[23] BOE - Royal Decree 413/2014, *Regulation of Energy Generation through Renewable Sources*, URL visited on 19/08/2021.
[24] BOE - Law 31/1995, *Labour Risk Prevention*, URL visited on 19/08/2021.
[25] BOE - Royal Decree 485/1997, *Minimal Provisions related to Occupational Health and Safety Signs*, URL visited on 19/08/2021.
[26] BOE - Royal Decree 773/1997, *Minimal Health and Safety Provisions related to the Usage of Personal Protective Equipment*, URL visited on 19/08/2021.
[27] BOE - Royal Decree 614/2001, *Minimal Health and Safety Provisions related Electrical Risk*, URL visited on 19/08/2021.
[28] RIB Spain, *Presto iTWO*, URL visited on 19/08/2021.
[29] Community of Madrid, *Order 2726/2009*, URL visited on 19/08/2021.
[30] Autodesk, *Autocad*, URL visited on 19/08/2021.
[31] PVsyst, *Photovoltaic Software*, URL visited on 19/08/2021.
[32] IEA, *Spain - Countries & Regions*, URL visited on 19/08/2021.

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