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TECHNICAL AND ECONOMIC DESIGN OF AN INDUSTRIAL PHOTOVOLTAIC SYSTEM

Author:

Andrea Gasparella

Director:

Ignacio Espinosa

Supervisor:

Arturo Lorenzoni

Madrid

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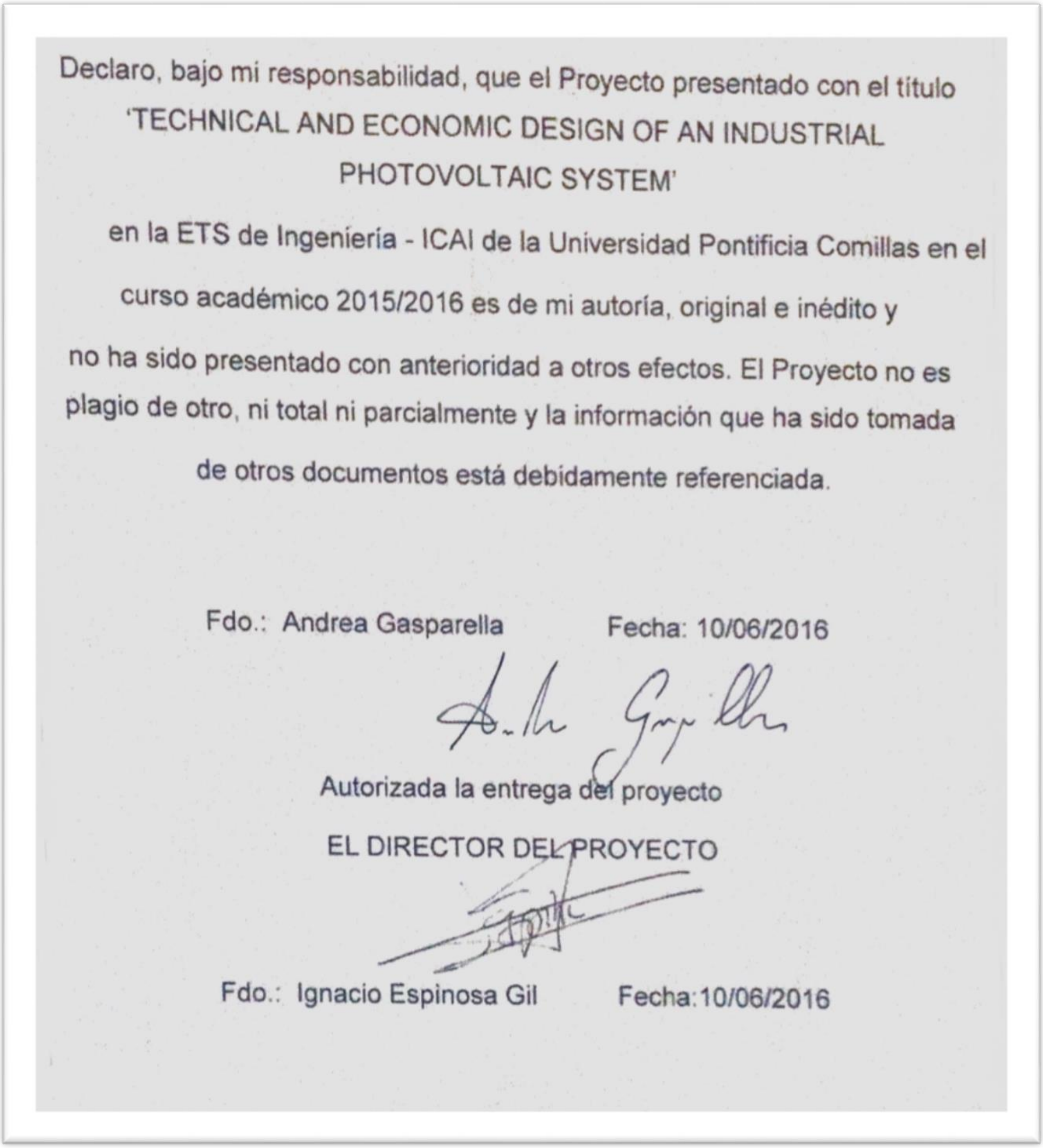

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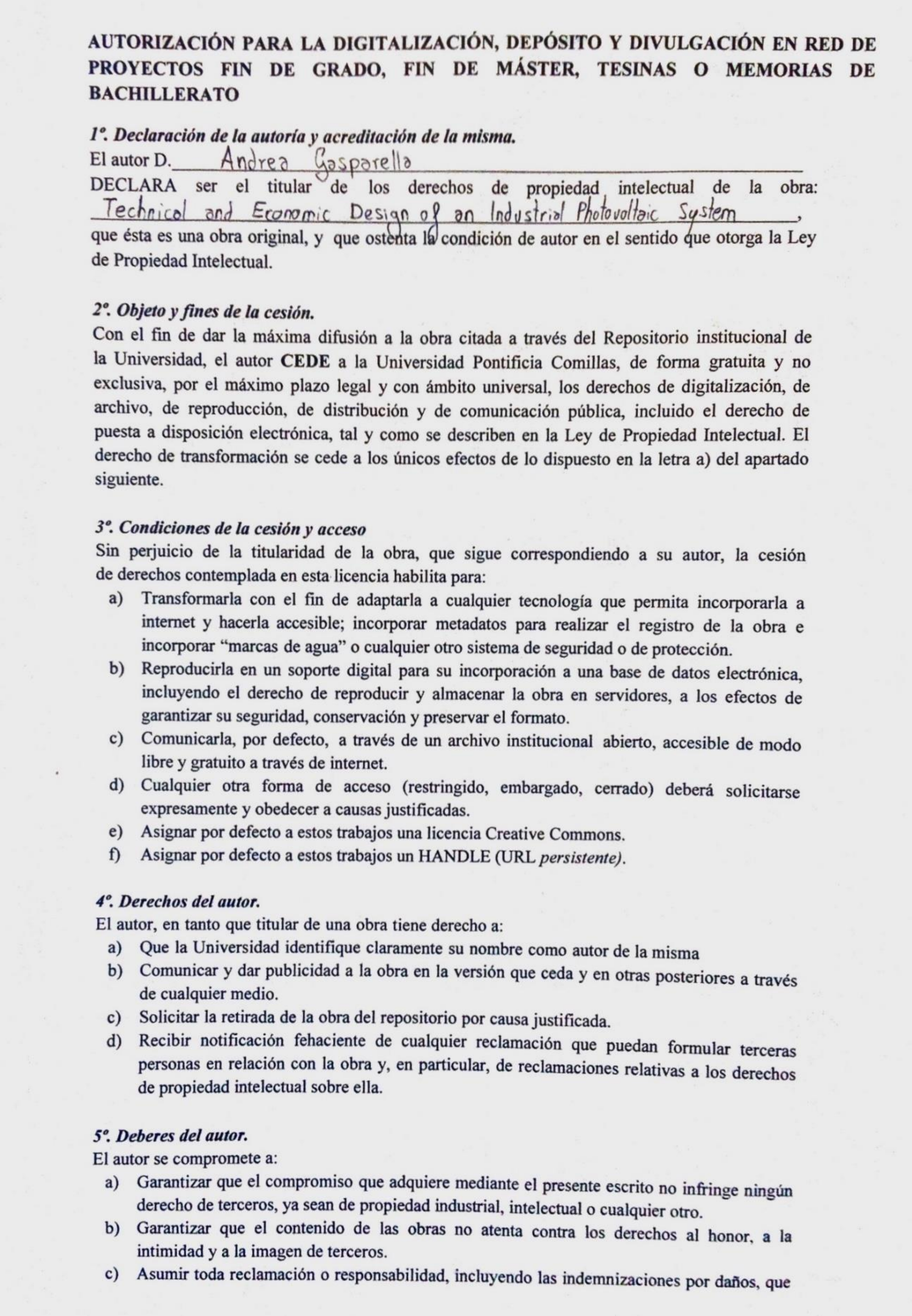

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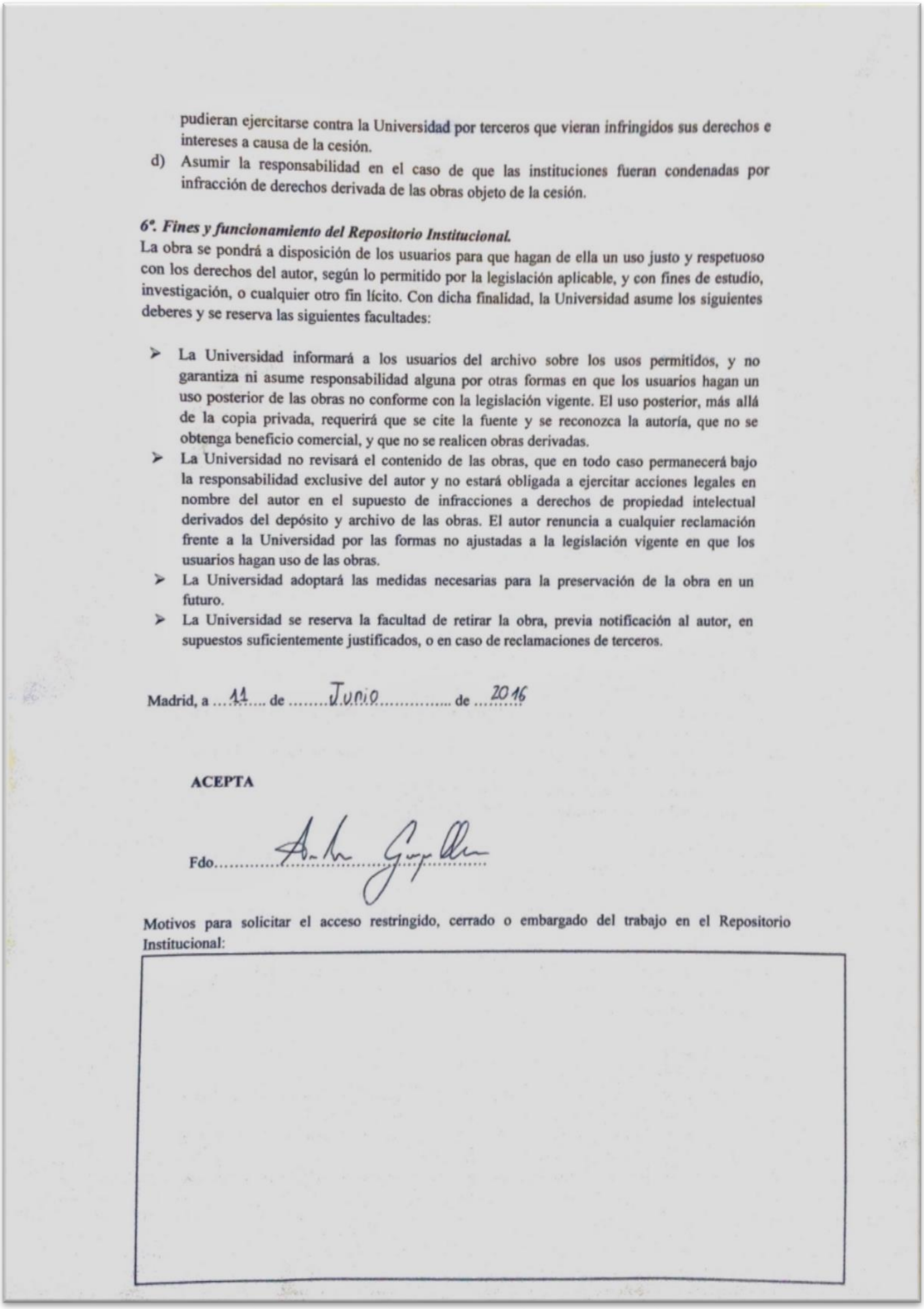

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Project Summary

Introduction

The project analyses a prototype of photovoltaic plant installed in an industrial facility, connected to the grid and set up for the self-consumption. The theoretical illustration of the arguments, the technical and electrical design, as the economic analysis of the system are carried out in order to properly present all the aspects that characterized the photovoltaic plant.

Motivation

The continuous rise of the world's population, together with the substantial development of industry and the raise of living standards has considerably increased the energy consumption. Nowadays, more than 75% of the energy production is made from the combustion of fossil fuels, including oil, natural gas, and coal. However, the depletion of fossil resources and the enormous impact of their usage to the environment, causing rise in noxious gas emissions and other environmental pollutions, have put forward an urgent demand for developing sustainable energy technologies, utilizing renewable energy sources. The sun is a primary energy source that sends each day to the earth an enormous quantity of energy that could cover the electrical demand of all the society. For this reason, the photovoltaic technology has acquired in the last decades an increasing interest as a viable and sustainable way to produce energy. Specifically, as the peak hours of solar production coincide with the peak hours of industrial consumptions, the photovoltaic systems result particularly convenient for this application.

Methodology

The design of the plant is carried out by trying to maximize its affordability and making it a reliable and well integrated energy system for the industrial facility. The project wants to be a realist example of a technical and economic analysis of a photovoltaic plant. For this reason, the normative and legislation is respected both for the technical and economic stages of the project.

Results

The obtained plant presents a nominal installed power of 70 kWn for the photovoltaic array and an AC output of 60 kWn. This installed power is the best compromise respect to the energy demand of the facility for maximising the affordability of the plant. The payback period results of 12 years with a IRR of 8,42 %. Finally, the LCOE is of 11,8 c€/kWh, making the plant a competitive technology for the energy generation.

Chapter 1

This preliminary chapter wants to briefly presents the content of the project by reporting the introduction, the status of the issue, the motivations and the objectives.

1.1 Introduction

Energy is a fundamental element in our modern civilization and the increasing demand for electricity requires new technologies that will allow to produce a greater quantity of energy while respecting the environment. Among all the possible solution, solar energy has a big potential of development for having a significant impact on the near future. This technology is particularly interesting for Spain as it is the country in Europe with the highest irradiation of sun and the market on this field is really progressed. Considering that the peak of energy produced with photovoltaic systems is from 10 am to 3 pm, they can effectively respond to the full load that affected the grid consequently of all the industrial processes. These reasons have led to an increasing interest for the industrial sector and, considering the actual normative in Spain, the self- consumption of energy from the sun has attracted a lot of investments.

This project analyses a prototype of photovoltaic grid connected system, based on the self-consumption, design for the new building of investigation, development and post selling of Yingli Green Energy in San Agustin de Guadalix. The design of the plant is carried out accordingly with the actual normative and the real demand of the facility.

Figure 1.1 - 1 Yingli's facility in San Agostin de Guadalix

1.2 Motivation

During the COP21, held in Paris the month of December 2015, almost 200 chiefs of state were gathered in an historic meeting for negotiate a new agreement over the climate change. The key element is to reduce greenhouse gas emissions by human activity to the same levels that trees, soil and oceans can absorb naturally, beginning at some point between 2050 and 2100. The aim is to controlled and limit the increasing global temperature below 2 °C above pre-industrial times. The challenge is very big and time is running out. Each country needs to take advance of their best resources in order to settle the road and direct toward the goal. Spain has the possibility to gives his contribution to define a sustainable future, and solar energy is definitely going to play an important role on it.

The interest for the solar technology is huge and it is continuously increasing for some principal characteristics. First of all, solar energy it is extremely abundant; each hour the sun sends enough energy to earth to meet the human demand for an entire year. It is the world’s most abundant and accessible source of energy. Secondly, it is an affordable technology with an industry’s learning curve that make it cheaper each year. For the last 30 years, each doubling in global solar panel production has led to a roughly 25% reduction in solar panel prices. Finally, it is a sustainable way to produce energy; silicon solar panels generate electricity without noise or emissions, and are produced with almost all recyclable materials. Moreover, solar plants don’t need water to operate, making it very appetitive for communities that live in arid regions of the world.

In particular, the self-consumption technology is also economically viable. In fact, due to the fact that the maximum production of a solar plant coincides with the peak demand of an industrial facility, it allows to lower effectively the electricity bill. Moreover, another interesting fact is the positive effect on the efficiency of the global system. Smaller quantity of electricity is lost in the grid thanks to the short distant between the production site and the consumption one.

1.3 Status of the issue

The photovoltaic system analysed in the project is installed in an industrial facility connected to the grid producing electricity that is directly consumed by the building. The installed power was established by the demand of the building considering an optimal compromise of 75% electricity self-consumed and a 25% of it delivered to the grid. In our case, the installed power of the facility is design for an average daily power demand of 60 kWh. The study is conducted considering the actual retribution normative, regulated by the Real Decreto 900/2015, that economically penalises with an energy toll the profitability of the facility. However, due to political and international criticisms respect to the decree, it is probable that this normative will change in the near future to allow a greater diffusion of photovoltaic systems.

In general, in a direct self- consumption facility, the electricity generated is directly used by the building, with the exceeding part of it that is injected to the grid. To determine self-consumption, the average consumption of solar energy must be compared with the amount of energy generated by the solar power plants.

Figure 2 show a generic diary trend of an self-consumption plant where it is possible to appreciate the power consumption respect to the power generation from the solar modules. During the peak hours, when the production exceeds the demand, part of the electricity generated is injected to the grid, while at night, energy is imported from the grid to satisfy the demand.

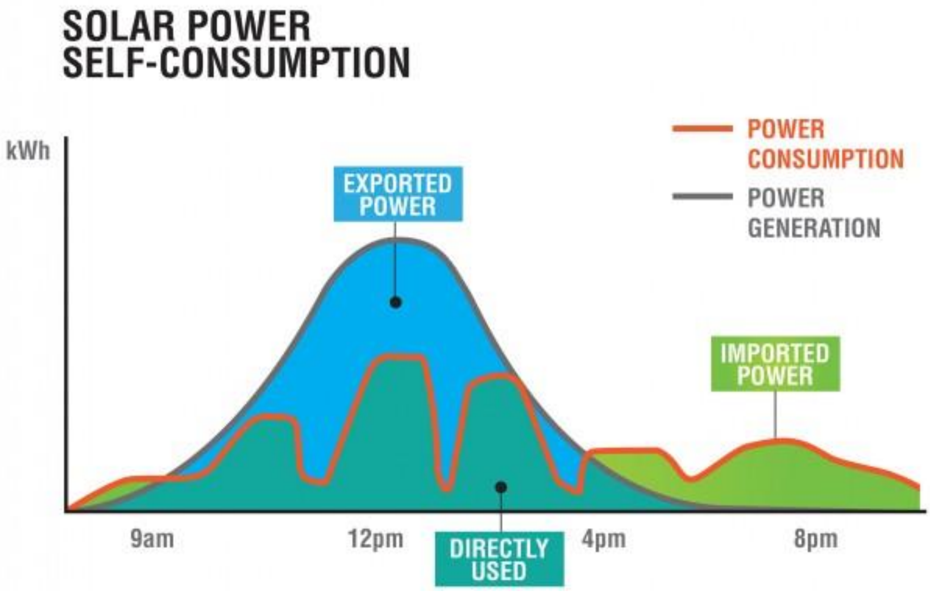


Figure 1.3-2 Diary curve of a solar power self-consumption plant connected to the grid

The other application of self-consumption is by the usage of a mean for storing energy. In this case, the surplus of energy during the peak hours production, from 10 to 15, can be stored and utilised at night or when the production is lower than the demand. In figure 3 it is possible to appreciate the curves' profiles in a generic day.

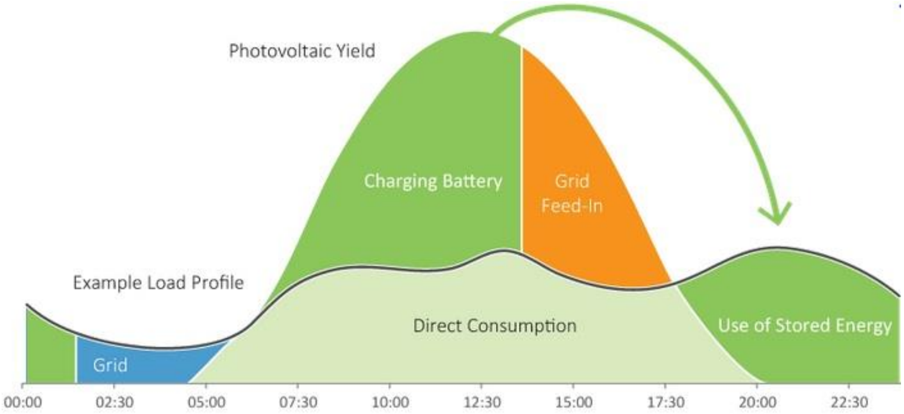


Figure 1.3-3 Diary profile of a solar power self-consumption facility with

1.4 Project goals and objectives

The project aim is to study the technical and economic feasibility of the photovoltaic system, considering all the parameters that affect the different phases of the project. In particular, the major goals are:

1. Designing an innovative photovoltaic system: The aim is to propose a perfect model for the self-consumption technology, showing the advantages of such system in the industrial field. To enhance this purpose, all the technical equipment is chosen from the latest technology available in the market. The plant is easily integrated in the building making it possible to install also on existing facilities.

2. Technical configuration: All the elements that take part in the system are considered with all their technical data and type of connections. Moreover, all the calculations, electrical schemes and tables are specified with the actual normative. The solar plant is designed with PVsyst that is a professional virtual simulator so that all the data are the closest possible to the reality. Moreover, the drawing of the plant is realised with AutoCAD, allowing to make in detail the technical configurations of all the equipment and to set the measure of the necessary wiring.

3. Economic feasibility: The cost of photovoltaic plants and consequently the cost of electricity generated varies accordingly to a large list of factors: country considered, technology developed, local labour, size of the plant, level of maturity of the project, eth. The purpose is to evaluate in detail all the factors that influence the economic feasibility of the plant, considering all the elements that affects it. The analysis is carried out with an advance excel spreadsheet that wants to be the most possible coherent to a real one utilised in energy companies.

4. Environmental impact: Not only the solar energy is economically profitable and technically feasible, but it is also eco-friendly respect to the environment. It helps reducing the production of greenhouse gasses by substitute the usage of fossil fuels. Moreover, the materials that constitute the modules and the majority of the other components are largely recyclable, making them reusable at the end of their operation lifespan.

5. Enhance a political and institutional change: The actual normative in Spain, but also in other European country, penalises by the imposition of tolls the companies or families that want to install a solar plant and contribute to a green future. This causes larger period for the payback, decreases incomes and discourages all the entrepreneurs and private citizens that want to invest on the sector. It is strongly advisable a change in the energy policies to incentivize a diffusion of the technology and an improvement in the solar market.

1.5 Work Methodology

The stages followed for the development of the project are:

1. Definition of the problem and objectives
2. Planning of the roadmap and structure of the report
3. Research and investigation:
    - Energy data of Spain
    - Consultancy of the actual normative
    - Self-consumption systems
    - Solar modules manufactures
    - Inverters and cables’ manufactures
    - Technical normative for the configuration of the plant
    - Weather and irradiance data of the site
    - Economic and financial parameters
    - Legalize cost of electricity for different technologies
    - Pricing of electricity for different time of the day

4. Lecture and bibliographies:
    - Articles from ‘Energy Policy’, journal of the Political, Economic, Planning, Environmental and Social Aspects of Energy
    - Articles from ‘Renewable Energy’, journal of sustainable energies
    - Reports and statistics from Fraunhofer institute, Eurostat
    - Advisable lectures: ‘Solar photovoltaic: fundamental technologies and applications, Solanki’; ‘Planning and installing photovoltaic systems: a guide for installers, architects and engineers’
    - Catalogues from ABB, Sunbeam, SMA
    - Normative for low tension installation

5. Analysis of the information

6. General description of the industrial facility, area available for the plant, orientation etc.

7. Design of the solar plant with PVsys with related calculations
    - Solar gain: Definition of the site and the area of the rooftop, orientation and inclination of the panels, shadows effect
    - Calculation of the electrical demand and variation during the day and season
    - Selection of the PV modules manufacturer
    - Selection of the Inverters and other equipment
    - Design and modules disposition
    - Wiring of the modules
    - Protections and distribution panel

8. Drawing with AutoCAD
    - Building site and area on the rooftop
    - Layout of the disposition of the plant
    - Configuration of the AC and DC grids

9. Energy production results
    - Total energy production
    - Electricity tariff
    - Energy distribution
    - Net energy production

10. Economic study
    - Cost for the materials and equipment
    - Cost for operation and maintenance
    - Tariff and economic parameters
    - LCOE
    - Payback and ROI

11. Considerations and conclusion

1.6 Resources

The software and resources that have been used for the realisation of the project are:

- PVsyst in the design of the plant and the technical configuration; it is a software package for the study, sizing and data analysis of complete PV systems.
- AutoCAD for the drawing of the building integrated with the plant and for the configuration of the system with the schematic of the wiring.
- Meteonorm for the meteorological data of the geographical site
- Microsoft Excel for the realisation of graph, table and calculation.

Chapter 2: Project

This second chapter illustrates the theoretical concepts of the project. In particular, it describes all the different components of the photovoltaic plant.

2.1 Industrial facility

The industrial facility in which is installed the solar plant is in the district of San Augustín de Guadalix in the autonomous province of Madrid. The number of persons working in the building is of around 50. The plant is set on the rooftop that present a total area of 4000 m^2. For the installation is used only the half side lower of the roof, direct to the south. Moreover, the interested area does not present close obstacles or other building that could compromise the production by making shadows on it.

Figure 2.1-1 - Satellite picture of the facility (source: Google earth)

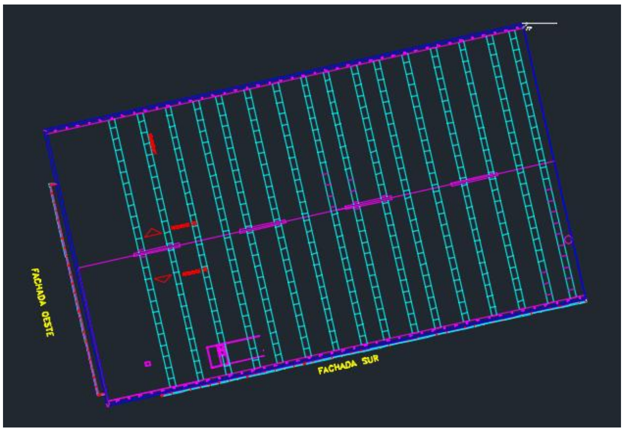


Figure 2.1-2 - AutoCAD schematic of the rooftop

For establishing the correct size of the plant to install, all the data of the electrical consumption was measured by a grid counter that for one year and each 15 minutes has recorded the electricity demand of the building.

Below in figure 6, the consumption demand trend is represented over the year for each month, where the hourly values are an average of the measures of all the days of the month.

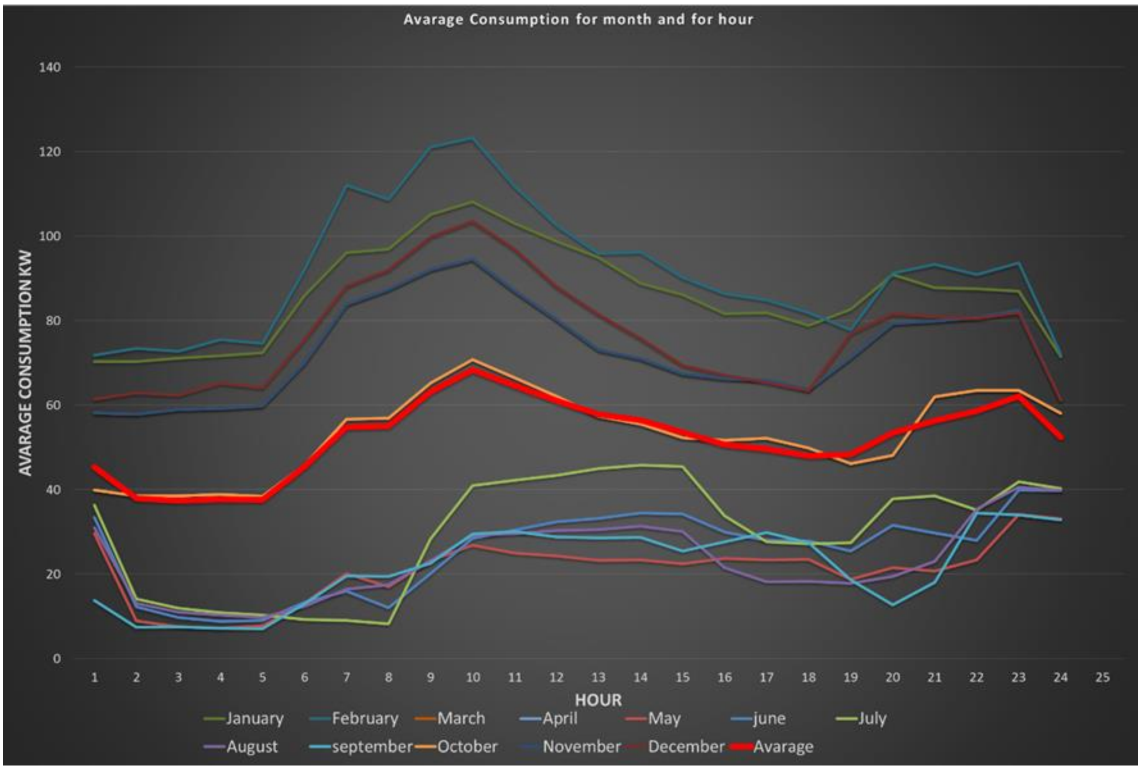


Figure 2.1-3 Power average consumption for month and for hour

The elements that affect the demand in a constant way during all the year are:

- Illumination systems
- Typical office consumptions like mobiles charger, computers, printers, etc.
- Laboratory equipment for conducing analysis test on photovoltaic panels
- Warehouse machinery

On the other hand, the acclimatization system has a big effect on the consumption demand and varies a lot according to the months. The maximum electricity consumptions are registered during winter’s months, particularly January and February, for the intensive use of the heating system. On the other hand, during mild moths the consumption decreases, reaching a minimum during the months of May and June.

Considering the daily curve, the minimum demand is always around 5 am, just before the time when the acclimatization system is activated, while the peak demand is situated around 9 am when the facility and its personals operate at full regime. There is a secondary peak demand around 23 pm because the facility runs a series of tests on photovoltaic modules that require a consistent amount of energy. They are made at this time of the day for the convenient tariff of electricity that allows to save a consistent quantity of money.

From the graph above, it is possible to notice that the average daily consumption is around **60 kWn** and this would be the ideal installed power of the solar plant. Nevertheless, there are a lot of others factors to take into account, so this is taken as a primary approximation to later define the correct size of the photovoltaic system.

2.2 Description of the photovoltaic plant

Following the load profile and the dimensions of the available area, the photovoltaic plant consists of a fixed number of modules that are placed on the rooftop of the facility. The photovoltaic generator, composed by the modules and inverters, is connected directly with the internal system, for the direct consumption, and with the external grid, where is injected the surplus of electricity.

The photovoltaic array is composed by multiples strings of modules connected in series. This generates a direct current that is converted into alternating current by inverters and it is after possible to use it for the self-consumption load or to inject it to the grid in case of a surplus of electricity. Whereas the facility's demand is higher than the production of the plant, the missing energy is absorbed from the public grid. Accordingly with the Real Decreto 900/2015, the internal grid of the facility disposes of two Bi-directional counter for measuring the electricity production and the global energy balance of the facility. Moreover, the system has all a series of elements of control and security, like the general and the automatic switch that allows to separate the generator with the internal grid of the facility, and the electrical insulation for guarantee the safety of the personal and also the reliability and quality of the service.

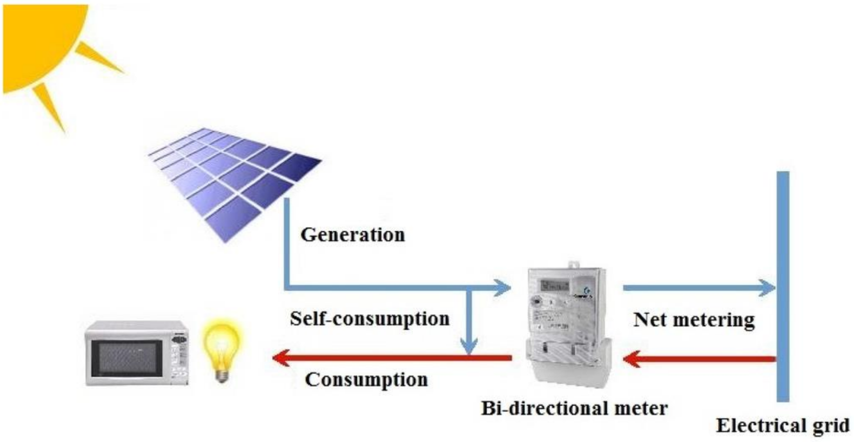


Figure 2.2-1 General schematic of the photovoltaic plant and the grid (source: MDPI energies)

2.3 Applied Normative

For the installation of a photovoltaic project there is a long series of laws and normative that need to be followed and respected. In particular, as the project is design for an industrial facility in Spain, the normative is coherent with the country's legislation, although a lot of them are valid in all Europe. These are the main ones:

- Law 54/1997, concerning the Electric sector
- Normative UNE-EN 62466: Photovoltaic system connected to the grid; Minimum requisites for the documentation, start of the activity and inspection
- Real Decreto 1955/2000, regarding the connexion of photovoltaic plant to low voltage grid
- Resolution of 31 May 2001, establishing the typical contract and facture module for the photovoltaic plants connected to the low voltage grid
- Real Decreto 842/2002, approving the Electrotechnical regulation for low voltage grid
- Real Decreto 314/2006, approving the Technical code for the edification;
- Real decreto 661/2007, regulating the production of electricity in special regime
- Real decreto 1110/2007, approving the the Unified regulation of the measurement points of the grid
- Real decreto 900/2015, regulating the retribution of the production activity of the photovoltaic plants

Above all these main regulations, the last one of them, the Real Decreto 900/2015, deserves a clear analysis and illustration, as it concerns the viability of the plant.

2.4 Real Decreto 900/2015

The analysis proposed here wants to illustrates in a synthetic and simply way the major points of the RD900/15, considering only the parts that affect and have a direct impact on self-consumption plants.

The RD was approved the 9 October 2015 and its aim is to regulate the administrational, technical and economic conditions of the different modalities of suppling and producing electric energy with self-consumption photovoltaic systems. This regulation is only valid for plants that are connected to the grid, so it does not affect that ones that operate isolated from it. Moreover, this normative substitute and partially renew the precedent Real Decreto 1699/2011.

The first important point defined by the RD is the differentiation between self-consumption type 1 and 2. In the table below there is a resume of the principal differences between the two of them:

	Type 1	Type 2
Maximum power limit	100 kW	No
Installed power higher than the contracted one	No	No
Normative	RD1699/2011	P ≤100 kW RD1699/11; P≥100 kW RD1955/2000
Request for a connexion point to the electric company	yes	yes
Production plant's owner is also the consumer	Yes	No (but only 1 to 1)
Subjects of the system	Consumer	Consumer and producer
Retribution for the exceed energy	No	Yes
Generation toll	No	Yes
Generation tax	No	Yes

Table 2.2-1 Schematic resume of Real Decreto 900/2015

Clarification type 1:

- The installed power must be always equal or lower than the contracted one before installing the photovoltaic system. For example, if a house had a contracted power of 6,6 kW, the possible maximum power of the photovoltaic plant is the same amount.

- Production plant's owner is also the consumer: This is one of the most criticised point of the RD because it does not allow the installation of a plant that can be use by a community of neighbours.

- Metering equipment: It is mandatory to install an equipment for the generated energy, and another independent one that measures the energy imported from the grid. Alternatively, it is possible to install a single unit that measures the total energy consumption, although it could be very expensive.

Clarification type 2:

- In this case, the consumer and the producer can be two different entities. This opens the door to companies offering energy service to supply self-consumption systems to industrial or public facilities.

- Metering equipment: For installation with a power ≤ 100 kWp it is necessary to displace a bidirectional counter for measuring the neat energy production, and another for the imported and exported energy from the grid. Alternatively, it is possible to install a single unit for the measurement of the total energy consumption. For installation with a power greater than 100 kWp, it is mandatory to displace one bidirectional equipment for the generation and another unit for the total consumption of the consumer.

Another important point that deserves a clarification is the Sun tax, that is the toll imposed to all the facilities that have installed a photovoltaic system for the self-consumption. The tax’s aim is to pay for the charges of the electrical system and for its services. In particular, it is composed by two terms, a fixed and a variable one. The first one gives the consumer the right to consume the contracted power whenever he requires it. The second one depends from the installed capacity of the plant, it is included on the energy’s price (around 10 %) and its scope is to pay the electric central that operate at peak hours’ demand.

For both type of self-consumption, the installation of a battery system is allowed for storing the exceed energy. However, it is not say that the system is more economically affordable and gives a better result of the payback of the plant. This is due to the fact that also a system with a storing capacity needs to pay all the taxes that are applied to a normal system (Sun tax), without giving any type of incentive or discount.

Finally, all the facilities that don’t respect the above normative, are finable by the government authorities that have the right to disconnect them from the grid.

The photovoltaic plant design and installed in this project is included in the category ‘type 2’, so it will have to respect all the conditions imposed and regulated by the coherent part of the Real Decreto. Accordingly, the exceed energy production will be sold to the grid to increase incomes, even thought that means that the plant will be submitted to a higher fiscal detraction.

2.5 Solar resource

The solar resource is the primary energy source that comes from the sun in the form of electromagnetic radiation. The energy is generated in the sun's core through the fusion of hydrogen atoms into helium, where part of the mass of the hydrogen is converted into energy. Only a tiny portion of this energy reaches the earth due to the enormous distance to the sun, although it still remains a huge quantity of energy. It is considered that each hour the sun sends to the earth enough energy to meet the human demand for an entire year.

The intensity of solar radiation outside of the earth's atmosphere depends upon the distance between the sun and the earth, and this varies during the year and the latitude considered. From the figure below it is possible to see the value of the global irradiance in kWh/m^2/day, varying for the latitude considered. The maximum values are registered at central latitudes, whereas the lowest ones are close to the poles.

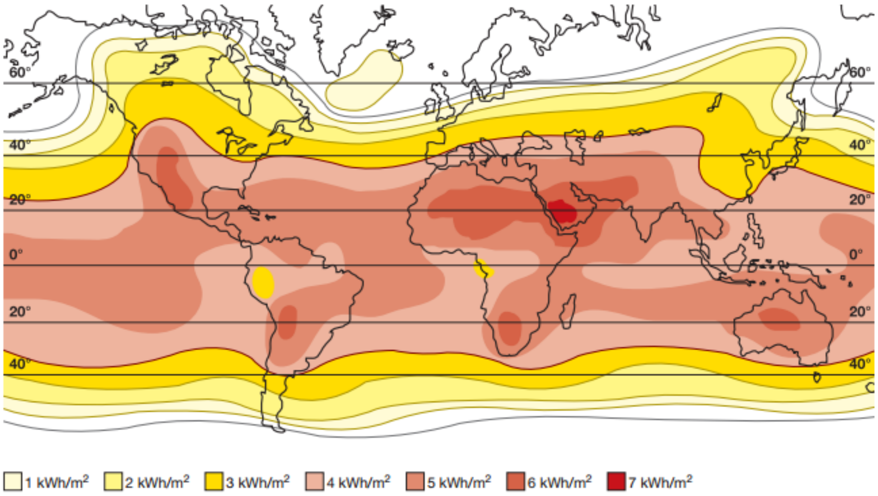


Figure 2.5-1 Worldwide average daily irradiance [kWh/m^2/day] (source: ABB)

Moreover, the atmosphere reduces the insolation through reflexion, absorption and scattering. The atmosphere caused that the sunlight arrives to the earth in different types of forms, in particular a direct radiation and a diffuse one. The direct one arrives from the direction of the sun and has a big energy's quantitative. On the other hand, the diffuse radiation is scattered from the elements of the atmosphere, presenting a no defined direction and a lower energy's potential. The percentages of them can vary a lot during the day and the year, and depends strongly on the weather conditions. For example, while in a sunny day the direct radiation is predominant, in a cloudy day, the diffuse one is the most abundant.

The photovoltaic technologies capture this electromagnetic radiation and convert it to electric energy thanks to the photovoltaic effect.

2.6 Photovoltaic technology

Photovoltaic technologies use the photoelectric effect to generate electricity from sunlight. This effect consists that some materials absorb photons of light and release electron that if they are captured, it results in an electric current that can be used as electricity.

The main material that are used for this purpose are semiconductors as amorphous silicon and microcrystalline silicon, copper indium or cadmium telluride. These materials are used to manufacture the solar cells that are constituted by an n-type layer which can emit electrons (emitter) and a p-type layer which can absorb electro (base). At the boundary interface between the two layers (p-n junction) an electric field is formed, which separates the light generates charge carriers. A voltage corresponding to the electric field is produced at the terminal contacts of the cell.

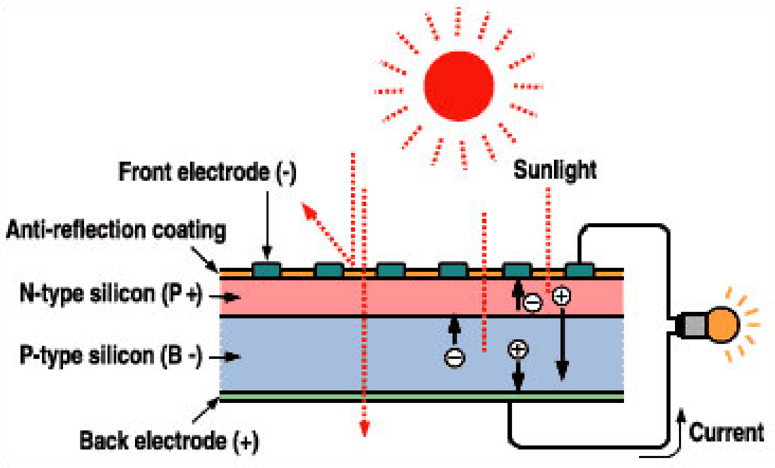


Figure 2.6-1 The Photovoltaic effect (source: Solarphotovoltaic blog)

Many types of solar cells have been developed to increase efficiency and reduce costs. In particular, five of these are used commercially today and play a role in the market that depends from the plant dimensions and configuration. The fundamental difference between them is the semiconductor material used and their crystal structure. Moreover, photovoltaic technologies can be divided into three generations: the first one is based on crystalline silicon; the second one uses thin-film technology; the third and last one is based on new technologies which have not yet reached the commercial market, and that uses mainly organic solar cells.

- **Crystalline silicon cells**: These cells consist of a mono or polycrystalline silicon wafer approximately 180 micro meters thick. In order to increase its conductivity, the crystal structure is doped, I. e. foreign atoms are added to the material in a specific manner. The p-type conductive layer is formed by doping the structure with boron while the n-type conductive layer with phosphorous. On the front side of the cell, the electrical contact fingers that conduct charges away form a lattice structure of conductors which meet in a wide metallic strip. Monocrystalline cells have a perfectly regular crystal structure while polycrystalline cells consist of silicon crystals with grains (just few millimetres), where the grain boundaries represent crystal defects. Monocrystalline cells have higher efficiency (15-18%) respect polycrystalline ones (13-16%), however for manufacturing high purity silicon cells is required a large amount of energy and they result more expensive.

- **Thin-film modules:** Thin-film modules are photovoltaic modules with an active photoelectric layer only a few micro meters thick, which is deposited in an area of at least one meter square, surpassing enormously the area of a silicon solar cell. These thing layers are not self-supporting so they need to be mounted on a substrate, generally glass or flexible plastic. This module is less efficient (11-15%) than those made with crystalline cells but has some concrete advantages: First of all, the energy payback period is shorter, due to the lower amount of materials and energy used; Secondly, the manufacturing process can be automated for large area modules; Finally, flexible substrates open up new areas of use and integration.

- **Organic solar cells:** The use of organic semiconductors represents a promising approach as they can be processed into large-area, thin layers on flexible films using simple print and film coating. This allows more cost-effective production processes. Organic solar cells convert light in a process that is similar to the way in which photosynthesis converts the radiant energy from sunlight into chemical energy. Even though this technology can offers some very interesting applications, its efficiency and life durability are still too low to be commercialised.

A single solar cell generates only a tiny quantity of electricity and at very low voltage. It is for this reason that several cells are linked together to create solar modules with a higher voltages and energy outputs. Modules are generally connected in series to form a string that can be connected in parallel with other strings to achieve any voltage requirement. The choice between crystalline modules and thin-film ones is made considering the available space. If the space is limited and costly, it is better an installation with crystalline modules for their higher efficiency. Instead, if the area is not so valuable and the disposition space is hard to made for a standard configuration, the flexible and more integrated structure of thin-film modules can give a lot of advantages.

For the specific case of this project, considering the plane of the rooftop, that present a bigger area of the one required by the plant, the best compromise is the polycrystalline cells technology, that have a good efficiency/cost ratio.

2.7 Selection of the photovoltaic module

In the decision of the photovoltaic module there are a lot of parameters that need to be taken into consideration. Above all, the reliability and expertise of the manufacturer, the guarantee of the product, the cost, the service provided, etc.

The decision of Yingli Solar, as the manufactures of the modules, is driven by the fact that the enterprise is one of world's leading seller, giving a certain level of quality, reference and sustainability of the product. Secondly, it gives a good guaranteed of 10 years at 91.2% of the minimal rated power output and 25 years at 80.7% of the minimal rated power output. Finally, it combines products with a competitive price that make them economically affordable. The module chosen is YL310P-35b that is a multicrystallin silicon panel composed of 72 cells. The front cover is composed of low-iron tempered glass while the frame is done with an anodized aluminium alloy. The main positive aspects that characterized the performance is the high transmission and textured glass that deliver an efficiency of up to 16.2%, minimizing installation costs and maximizing the kWh output of the system per unit area. Concerning the reliability, tests by independent laboratories prove that the Yingli modules are fully conform to certification and regulatory standards. Moreover, they can withstand wind loads of up to 2.4kPa and snow loads of up to 5.4kPa, confirming mechanical stability. Finally, they successfully endure ammonia and salt-mist exposure at the highest severity level, ensuring their performance in adverse conditions

The main electrical and physical properties are reported below on the tables [x]:

Electrical properties at Standard Test Condition (STS)	
Power output	310 W
Module efficiency	**15,9 %**
Voltage at PMAX	36,9 V
Current at PMAX	8,41 A
Open-circuit voltage	46,4 V
Short-circuit current	8,98 A

Table 2.7-1 – Electrical properties

Physical Properties	
Length	**1970 mm**
Width	990 mm
Height	50 mm
Weight	26.8 kg
Open-circuit voltage	46,4 V
Short-circuit current	8,98 A

Table 2.7-2 – Physical properties

The electrical properties are given for the Standard Test Condition, accordingly with the normative EN 61215) that refers at ideal conditions of 1000 W/m^2 of irradiance, a temperature of 25 °C of the module and a wind's velocity of 1,5m/s.

2.8 Modules disposition

The photovoltaic modules are disposed on the rooftop in the lower part of the plane and as the building is orientated toward the south the Azimuth angle is 0°. For the decision of the inclination angle of the plane, also called Tilt, the software PVsyst gives the best compromise considering the geographical coordinates that were set. From the picture 2.8-1 it is possible to appreciate the optimization graphs for the azimuth and for the Tilt. In particular, these graphs indicate the actual choice by a violet dot on the curves, showing the set positioned by respect to the optimum. It results clear that the minor production losses are achieved for an angle of around 30 degrees. In this case was chosen an angle of 33°, obtaining a yearly solar yield of 1877 kwh/m^2.

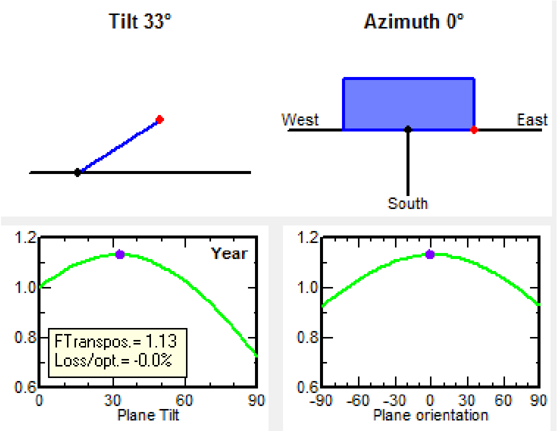
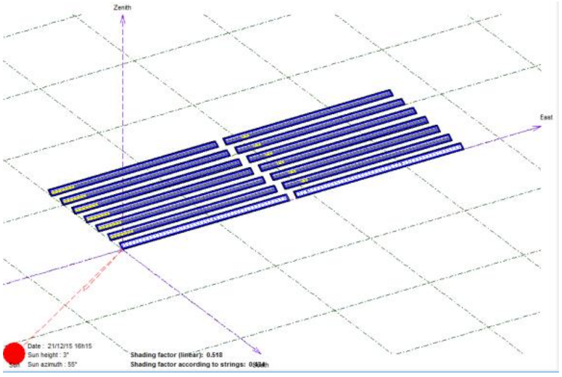


Figure 2.8-1 PVsyst optimization for the Azimuth and the Tilt (source: PVsyst)

The second criterion for the disposition of the photovoltaic array is the consideration of the possible presence of shadow that can decrease the solar yield. Considering that there are not close buildings or external obstacles that obscure the rooftop, the only shadows that need to be considered are produced by the same disposition of the panels, being inclined respect to the plane. For making an accurate calculation of the losses caused by this effect it is important to calculate the minimum distance between two consecutive rows for collocate the module in the most convenient way.



Date : 21/12/15 16h15
Sun height : 3°
Sun azimuth : 55°
Shading factor (linear): 0.518
Shading factor according to strings:

Figure 2.8-2 Pre design of the modules' disposition (source: PVsyst)

2.9 Selection of the Inverters

The invert converts direct current of the PV modules into grid-compliant alternating current and feeds this into the public grid. At the same time, it controls and monitors the entire plant. This way, it ensures on the one hand that the PV modules always operate at their radiation and temperature-dependent maximum power. On the other, it continually monitors the power grid and is responsible for the adherence to various safety criteria.

In detail, the tasks of a PV inverter are:

1. Low-loss conversion: One of the most important characteristic of an inverter is its conversion efficiency. This value indicates what proportion of the energy “inserted” as direct current comes back out in the form of alternating current.

2. Power optimization: The power characteristics curve of a PV module is strongly dependent on the radiation intensity and the temperature of the module – in other words, on values that continually change over the course of the day. For this reason, the inverter must find and continually observe the optimal operating point on the power characteristics curve, in order to “bring out” maximum power from the PV modules in every situation.

3. Monitoring and securing: It analyses the energy yield of the PV plant and signals if there is any problems. On the other, it also monitors the power grid that it is connected to. Thus, in the event of a problem in the power grid, it must immediately disconnect the plant from the grid for reasons of safety or to help support the grid. In addition, in most cases the inverter has a device that can safely interrupt the current from the PV modules.

4. Communication: these interfaces on the inverter allow control and monitoring of all parameters, operational data, and yields.

5. Temperature management: The temperature in the inverter housing also influences conversion efficiency. If it rises too much, the inverter has to reduce its power. Under some circumstances the available module power cannot be fully used. On the one hand, due to the fact that the installation location affects the temperature, a constantly cool environment for its disposition is ideal.

A large number of PV inverters are available on the market and the devices are classified on the basis of three important characteristics: power, DC-related design, and circuit topology. In our case, the maximum power required by the PV plant is of 70,7 KWp. The DC-related design referred to the module wiring and for this project the modules are connected in multi string, where a string is a series of modules. Finally, the circuit topology regards the distinction between one- and three-phase inverters, and between devices with and without transformers.

Considering all the cited factors, the manufacturer selected is SMA, being one of the world's leading fabricator and guarantying good performance. In particular, the inverter elected is the Sunny Tripower 20000TL that is the ideal inverter for large-scale commercial and industrial plants. Not only it delivers extraordinary high yields with an efficiency of 98.4%, but it also offers enormous design flexibility and compatibility with many PV modules thanks to its multistring capabilities and wide input voltage range. The multistring capability helps to reduce the problem of mismatching, that is caused when not all the modules of the generator are operating at the maximum power point. This effect can be due to minor differences in the fabrication of the PV module, voltage drops resulting from the DC wiring or different modules temperature. Losses increase with the number of modules connected in series, so dividing them in different strings allow to maximise the production of each one of the string without affecting the other ones. The main technical and electrical features are reported above on the tables:

Sunny Tripower 20000TL

Technical features: INPUT	
Max. DC power (cosϕ= 1)	20440 W
Max. input voltage	1000 V
Min. input voltage	150/188 V
Max. input current	33A/11A
Number of independent Mpp input	2
String per MPP input	3

Technical features: OUTPUT	
Rated power	20000 W
Max AC apparent power	20000 W
AC nominal voltage	3 phase, 220/380
AC voltage range	180 V to 380 V
Max output current	29 A
String per MPP input	3
Max. efficiency	98.4/98.0 %

General data	
Dimensions (W / H / D)	661/682/264 mm
Weight	61 Kg
Operating temperature range	-25 to +60 °C
Self- consumption at night	1 W
Topology	transformerless
Cooling concept	Opticool
Warranty	5 y

Table 2.9-1 Main data of the inverter

2.10 Modules configuration

In this section the number of modules and the way they are connected to the inverters are defined. Considering all the characteristics of the plant and the energy demand of the building, the ideal configuration is to install the total number of 228 modules for a nominal PV power of 70 KWn. This power is slightly oversize respect the average demand of the facility as the actual production is then lower due to climate conditions and technical and electrical losses. For this power requirement, the decision is to dispose three inverters of 20 KWn each, for a total AC output power of 60 KWn. The modules are connected in series of 19 units forming 12 strings, 4 for each inverter.

The inverter power sizing is a delicate and debate problem and most inverters providers recommend that the ratio between Pnon inverter/array should be of the order of 1,0 or 1,1. However, there are some factors to take into accounts: Firstly, the Pnom array is defined for the STC, while in real conditions the relative values are rarely attained and are usually lower; Secondly, the power distribution is strongly dependant on the plane orientation, obtaining values that are almost always minor than the maximum ones. Considering these elements, a lot of providers suggest it is better to propose over-sizing inverters, arguing that when the Pmpp [1] of the array overcomes its PnonDC limit, the unit will stay at its safe nominal power by displacing the operation point in the I/V curve of the PV array, figure 2.10-1. Therefore, it will not undertake any overpower, simply the potential power of the array is not produced. There is no power to dissipate, no overheating and therefore no ageing of the devise. This overload is not dangerous for the invert until its tension remain lower than the maximal one, that with this configuration is obtained at a module’s temperature of -10 °C, table 6. However, considering the weather conditions in Madrid, it is an unlikely situation, while the normal temperature conditions will be a lot higher.

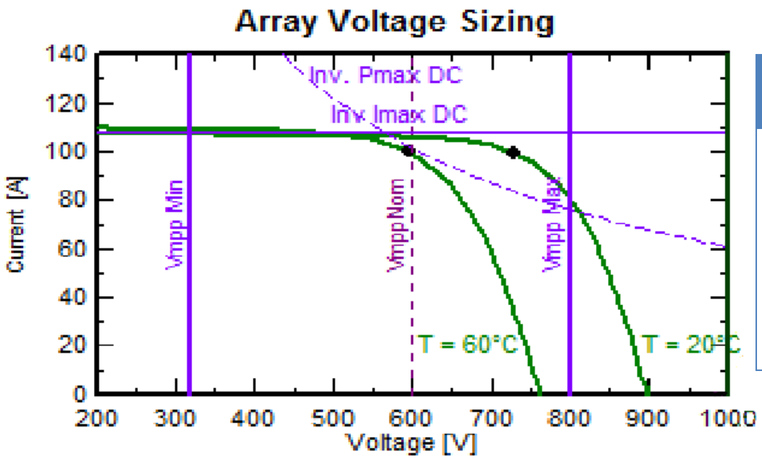


Figure 2.10-1 Array voltage sizing (source PVsyst)

Inverter operating conditions	
Overload loss	0,2 %
Pnon ratio	1.18
Vmpp 60 °C	595 V
Vmpp 20 °C	730 V
Vmpp -10 °C	994 V

Table 2.10-1

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[1] Pmpp, Maximum Power under STC

In this condition, the energy loss due to the overload is the difference between the array Pmpp and the inverter Pnom**DC** limit values. On the power distribution diagrams, figure 2.10-2, it is possible to appreciate that even when the inverter's power is a little bit under the maximum powers attained by the array in real operation, this results in very little power losses (violet steps by respect to the green ones).

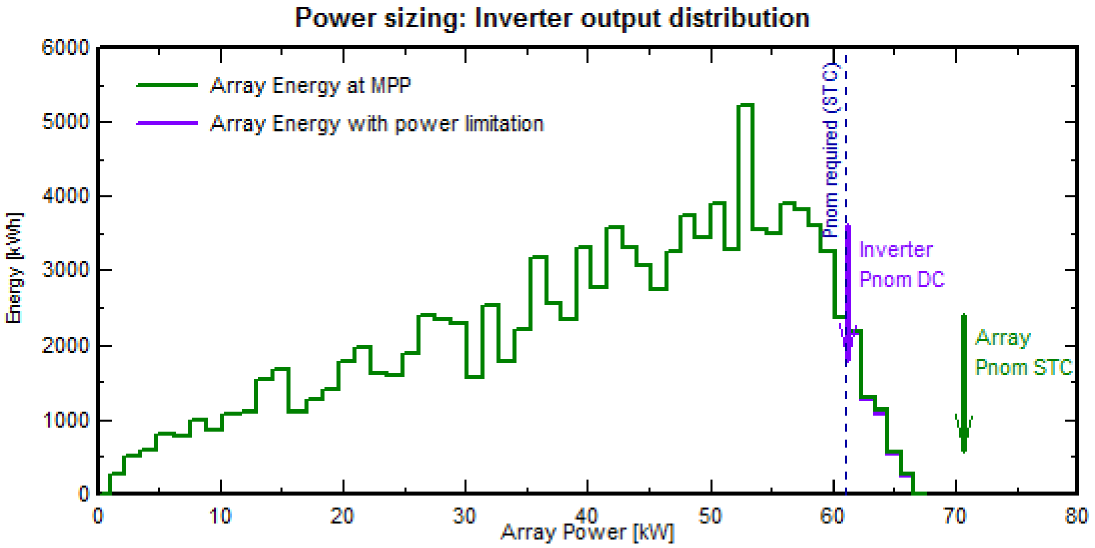

Figure 2.10-2 Power sizing: Inverter Pnom DC respect to the array Pnon STC (source: PVsyst)

The simulation, and the analysis of the overload loss, is therefore a very good mean for assessing the size of an inverter. For an economical optimization, the final overpower losses are to be put in balance with the price difference with an inverter of higher power. These considerations often lead to very undersized inverters by respect to the manufacturer's recommendations (Pnom ratio of the order of 1.25 for optimal 30° south planes).

To sum up, the main data of the final configuration are:

Configuration features	
Number of modules	228
Number of inverters	3
Modules in series	19
Number of string	12
Nominal PV power	70.7 KWp
Maximum PV power	67.6 KWdc
Nominal AC power	60.0 KWac

Table 2.10-2 Configuration data

2.11 Cabling

A PV plant’s electrics consist of the DC cables between modules, the generator junction box (GJB) and inverter, and the AC cable running from inverter to grid. The cables and wires must be laid in such a way to ensure that they are ground-fault and short-circuit proof. Cables connect individual modules to the PV generator where module’s cables are connected into a string which leads into the GJB and a main DC cable connects it to the inverter.

The DC cables are usually laid outside submitted to the weather conditions. For this reason, they need to be characterized by a series of features so that they can resist for the lifetime of the plant and avoid any type of technical and electrical trouble. First of all, they need to present a water proof insulation that is also resistant to UV irradiance and salt corrosion. This protection should not only sustain thermal load, but also permit to withstand mechanical ones. Secondly, for avoiding electrical accidents, the positive and negative cables, each with double insulation, need to be laid separately. Moreover, when laying them to the ground, it is important to fix them in a durable and sufficient manner. Finally, it would be advisable that they dispose of a fire-resistant coat to avoid, in a fire scenario, the spreading of the flame. Concerning the dimensions, the cross-section of the cables should be proportioned such that voltage losses are never over 1,5 %.

The cable used for the wiring of the modules in DC is the model ‘**Topsolar PV ZZ-F / H1Z2Z2-K**’ of the manufacturer Top Cable. The main characteristics of the cable are:

- Electrical performance: Low voltage 0,6/1kV - CC: 1,8 kV
- Chemical performance: UV, chemical and oil, grease and mineral oil resistance
- Thermal performance: Max/min service T 120 °C/-40°C
- Fire performance: Flame non propagation, low smoke emission
- Lifetime: estimated 30 years based on UNE-EN 60216-2.

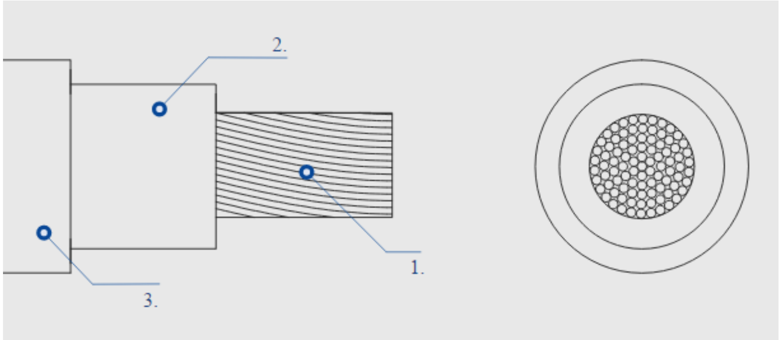

Figure 2.12-1 Schematic of the DC cable (source: Top Cable)

1- **Conductor**: Class 5, flexible tinned copper

2-**Insulation**: Low smoke zero halogen rubber

3- **Outer sheath**: Low smoke outer halogen rubber

The cable used for the wiring of the modules in the AC part of the plant is the model '**POWERFLEX RV-K**' that is suitable for all types of low voltage industrial-type connections, in urban grids, building installations, etc. Its high flexibility makes the installation process substantially easier and, as a result, is particularly suitable for use in difficult layouts. The main characteristics of the cable are:

- Electrical performance: Low voltage 0,6/1kV
- Chemical performance: UV, chemical and oil
- Thermal performance: Max/min service T 90 °C/-40°C
- Fire performance: Flame non propagation, reduced smoke emission
- Lifetime: estimated 30 years based on UNE-EN 60216-2.

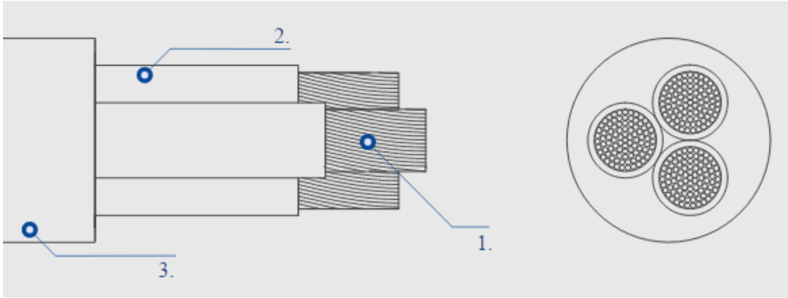

Figure 2.12-2 Schematic of the AC cable (source: Top Cable)

1- Conductor: Class 5, electrolytic copper, flexible

2-Insulation: Cross-linked polyethylene3-

3-**Outer sheath**: Flexible PVC

For the collocation of the cables the normative that will be followed are the ITC-BT-07, ITC-BT-21, ITC-BT-22, ITC-BT-23, ITC-BT-24.

2.12 Grounding

Highly excessive voltages and currents can threaten the operation of a PV plant. Such surges are mainly caused by lightning strikes, but also by faults in the grid. Ensuring a path to earth for any lightning or currents caused by overvoltage is an extremely important factor in PV plant protection. The grounding installation follows the normative 'Real Decreto 1663/2000' (art. 12) for the conditions of grounding in photovoltaic plant connected to low tension grid. All the units of the photovoltaic plant, both from the DC and AC sections, are connected to a unique grounding that is isolated respect the neuter of the electrical provider, accordingly with the normative for low tension. The grounding grid is disposed through the grounding system of the facility, firstly by the copper conductors placed on the rooftop and then by the cable tray, until the grounding made outside the building. It is important that the different units of the plant are stably connected, considering the dynamic load that are generated in case of a short circuit scenario.

2.13 Protections and distribution panel

The protection devises are regulated and defined by two major normative:

- ‘Real Decreto 1663/2000’, that referred to all the photovoltaic installation connected to a low voltage grid.
- ‘Real Decreto 842/2002’ and its complementary technical instructions.

According with the RD 1663/2000 the system needs to displace the following equipment:

- Automatic differential interrupter: its aim is to protect the personal in case there is a fault and there is the shunt of some electrical elements of the direct current part of the plant. This is a delicate part of the protection system, since even with the action of the interrupter, the tension on the PV arrays remain until there is solar light, creating a situation of danger.
- General manual interrupter: it is a magneto-thermal switch with a current intensity higher than the one of short circuit indicated, in the connexion point, by the distribution enterprise. This interrupter needs to be always accessible to the distribution company, so that it is always possible to disconnect the plant when it is required.
- Automatic cut-off switch: it needs to support the maximal short circuit intensity in the connexion point. It enables to isolate the inverter to the PV generator.
- Automatic interrupter for the interconnexion: Its aim is to disconnect and reconnect the PV plant if there is a variation on the frequency or voltage. The reconnection of the facility must be automatic when their values return normal.
- Protection equipment disposed for each phase to guarantee the maximum and minimum frequencies (51 and 49 Hz) and the maximum and minimum tensions (1,1 Um and 0,85Um). These functions are usually integrated in the inverter.

Concerning the photovoltaic modules, that constitute the electrical generator during the day, there are some more aspects to take into considerations:

- The strings of modules are protected by fuses in the string boxes.

- The positive and negative conductor that leave each of the string are isolated between themselves and respect the earth. In this way, if one of the wire makes an electrical contact with a structural metallic part, that has a grounding system, the wire and the structure present the same electrical voltage, avoiding any time of current’s flows.

With these additional dispositions the DC part of the plant results also secure and protected in case of faults or short circuit's events that can affect the grid.

2.14 Metering Equipment

According with RD900/2015 for installation with a power ≤ 100 KWp, for this project it is necessary to displace two bidirectional counter, one for measuring the neat energy production, and another for the imported and exported energy from the grid. All the components of the two units must be sealed by the grid provider and they need to be displaced in a market place and easy to consult. Moreover, each unit needs to specify if is measuring the energy of the energy provider or the energy of the internal plant.

The meters need to be regulated to the actual normative and their precision needs to be at least of Catergory2, fixed by the 'Real Decreto 809/2006[2]'.

2.15 Plant Monitoring

In order to determine whether a PV plant is producing optimal yields, the plant data needs to be measured continually, and preferably compared with the actual radiation values. This is due to the fact that currents and voltages, and consequently feed-in capacities, constantly change depending on meteorological conditions. The operator can only determine whether or not the PV plant's operational data indicate optimal functioning by directly comparing them with insolation data. Solar radiation is measured using either pyranometers or PV sensors.

Yield losses can generally be attributed to three causes of faults: component faults, installation faults and faults caused by external influences.

- Component faults are more frequently found in inverters than modules. These can be due to production faults, aging or thermal overload of the inverters. Such faults often lead to the complete failure of either the PV plant or the part of the generator connected to the defective inverters.
- Installation faults rarely result in complete plant failure but only in partial yield reduction. Sometimes, installation faults only start to take effect after a certain time, which means that they are recognized far too late.

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[2] RD809/2006: Decree that approved the model and verification of metering units of category2, with direct connexion, with simple or multiple tariff. Intended for monophasic or multiphasic energy system at 50 Hz.

- External influences primarily affect PV modules. Over the decades, UV radiation from the sun will lead to light aging. The darkening of the plastic film (browning) can lead to a reduction in module output (degradation).

For these main faults, it is strongly advisable to install equipment for the continuous measurement of voltage and current at the entrance of the inverter. Moreover, also the monitoring of the voltages of the phases of the grid and the total output power of the inverter can help to avoid and preventing some of them.

2.16 Mounting structure

The modules are displaced on the rooftop on a metallic ground structure that separate the inferior extreme of the modules some centimetres from the ground. This structure is design to support the weight of the modules and the eventual overload due to climate conditions as wind, rain or snow, conformably with the normative CTE. The structure need to be of galvanized steel and aluminium so that it is not affected by corrosion effects. Moreover, the design and sizing of the montage does not have to transmit any kind of tension due to thermic dilatation to the modules.

An example of ground structure is the model ‘Schletter PV Max’ commercialised by Wind and Sun. It is a modular system for mounting large PV arrays in open areas. Made with high quality components, it allows easy to erect economical systems with long lifetimes. Sturdy aluminium supports are fastened to these which carry aluminium crossbeams to which the PV modules are fastened. All materials are made from durable aluminium or stainless steel. Strong cross beams permit large span lengths. Usually concrete strip foundations are used that can consist either of pre-cast concrete blocks or can be made on site. From the picture below it is possible to see the module’s disposition on the support’s structure.

Figure 2.16-1 Mounting structure Schletter PV Max (source: Wind&Sun)

2.17 Conclusion

This second chapter wanted to illustrate the theoretical concepts behind the development of the project and to describe the elements that compose the photovoltaic plant. The rooftop of the industrial building, the disposition of the modules, as the devises of the grid, will be shown in detail in the technical plans, Annex B, drawn with AutoCAD. Moreover, the technical features and specifications of the components are reported on the catalogues of the respective manufacturers, Annex C.

Chapter 3: Calculation

This chapter reports the calculation done for resolving some technical parts of the project as the losses estimation, the grounding system, the protection equipment and the cables section requirement. The data obtained were useful for the correct and safe design of the PV plant, accordingly with the normative and the technical standards.

3.1 Total losses

The losses of a photovoltaic plant can be defined as all the events which penalise the available array output energy by respect to the PV-module nominal power as stated by the manufacturer for STC conditions. This ideal yield is diminished by the following losses:

1. Optical losses (shading, orientation)
2. Array losses (temperature, module quality, mismatching, ohmic wiring)
3. Global inverter losses (regulation, AC ohmic losses)
4. Ohmic loss in the wiring system

1- Optical losses: Shading and orientation losses affected heavily on the performance of the module by reducing the total solar irradiation that reach and is then captured by the solar cells. These losses will be calculated analytically in the next sections of the chapter.

2- Array losses: Thermal losses are due to the fact that the standard test conditions are specified for a cell temperature of 25°C, but the modules are usually working at much higher temperatures. The module quality is the parameter that take into consideration the real performance of the panel respects the ideal one given by the manufacturer. Mismatching losses are due to the fact that not all the modules of a string produce the same amount of energy. This can be caused by dirt on the pv-modules or by partial shading. Ohmic wiring losses are the ones that are caused by the wiring ohmic resistance of the module that affect the final power that is available at the terminals of the array.

3- **Global inverter:** Regulation loss is the energy potentially available from the PV array, but which cannot be used by the system. In MPP applications, this could be the array potential PV production outside the inverter input voltage limits, or during power overloads. AC ohmic losses are due to the resistance in the cables that goes from the inverters to the injection points of the grid.

4- **Ohmic** loss in the wiring system: All the losses due to resistance of the cable.

Considering all these components, in fig. 3.1-1 it is possible to appreciate the global losses of the photovoltaic plant, as calculated by the simulator PVsyst, that is of **17.5%**. For each loss effect the behaviour of the array system is displayed on the I/V curve.

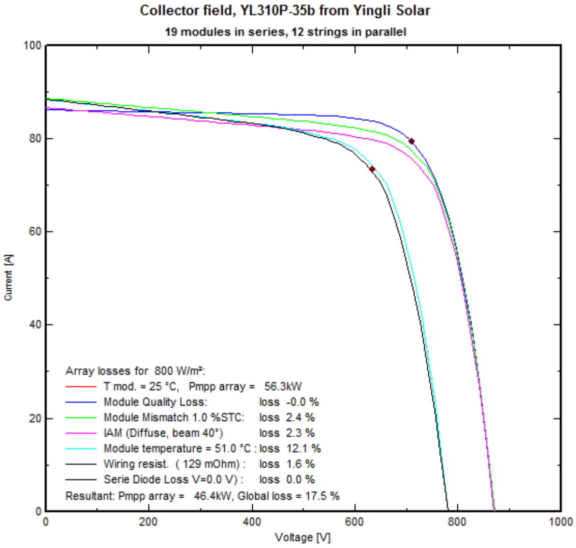


Figure 3.1-1 PV array behaviour for each loss effect (source: PVsyst)

Finally, in figure 3.1-2, there is a resume of the losses flows as calculated by the simulator PVsyst. The diagram needs to be considered only for the losses percentages as the energy production will be calculated with a more precise method in the next chapter.

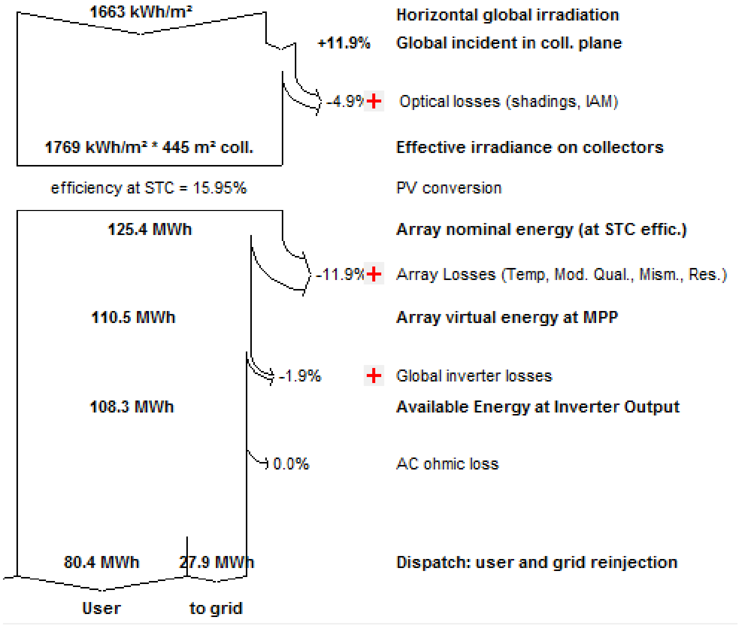


Figure 3.1-2 System loss flow chart (source: PVsyst)

3.2 Loss for orientation and inclination

The losses of sun radiation due to the orientation and the inclination of the modules' disposition on the rooftop are affected by two main parameters:

- Inclination angle β, also called tilt, is the angle that forms the module's surface whit the horizontal plane. Its value is 0° for horizontal modules, while its 90° for vertical ones.
- Azimut angle α, defined as the angle between the projection on the horizontal plane of the normal to the surface of the module and the meridian of the site. Typical values are 0° for a southern orientation, -90° for the east and 90 for the west.

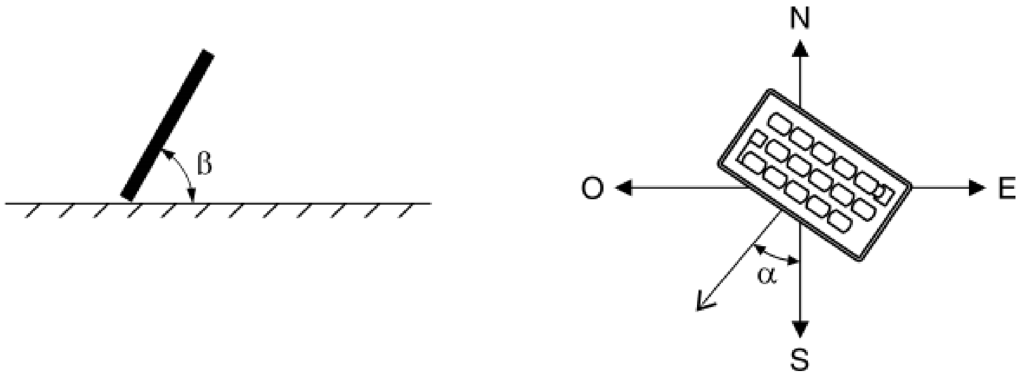


Figure 3.2-1 Inclination and orientation angles (source: IDAE)

On the rooftop the modules are disposed with a southern disposition so α is equal to 0°. The orientation angle was given by the program PVsyst with an optimum value of 33°. With the analytical calculations it is possible to verify the values. Accordingly to IDAE[3], the formula for the calculation of the losses for 15°≤β ≤90° is:

$$Loss\ (\%) = 100 * [1{,}2 * 10^{-4} * (\beta - \phi + 10)^2 + 3{,}5 * 10^{-5} * \alpha^2]$$

where ϕ is the values of the latitude of the site, that in our case is 40° 39' 20''.

For example, the calculation for a value of 15 ° or 30 ° the results obtained are:

$$Loss15°\ (\%) = 100 * [1{,}2 * 10^{-4} * (25 - 4{,}39 + 10)^2 + 3{,}5 * 10^{-5} * \alpha^2] = 2{,}842\%$$

$$Loss30°\ (\%) = 100 * [1{,}2 * 10^{-4} * (35 - 4{,}39 + 10)^2 + 3{,}5 * 10^{-5} * \alpha^2] = 0{,}001\%$$

---

[3] IDAE, Institute for Diversification and Saving of Energy

Iterating the formula in excel the results obtained are displayed in fig. 3.2-2; it is possible to appreciate that the minimum value is for an inclination angle close to 30 °.

Angle	Loss %
15°	2,842
20°	1,295
30°	0,001
40°	1,108
50°	4,614

Table 3.2-1 Results

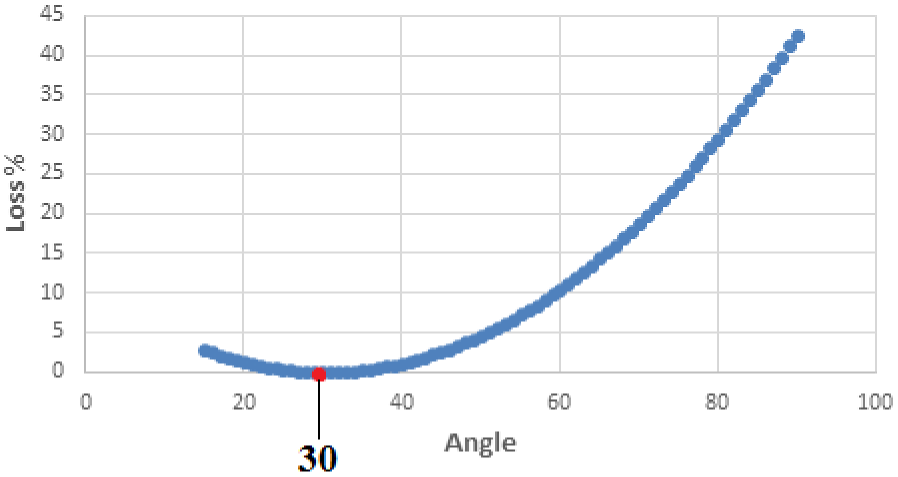


Figure 3.2-2 Loss and inclination curve

3.3 Loss for shading

In this section, is calculated the loss of sun radiation caused by the shadows due to the module's disposition in rows. As it is possible to appreciate from fig. 3.3-1, once the inclination of the modules is fixed, the value of this loss depends from the inclination of the sun irradiance and the distance between different rows.

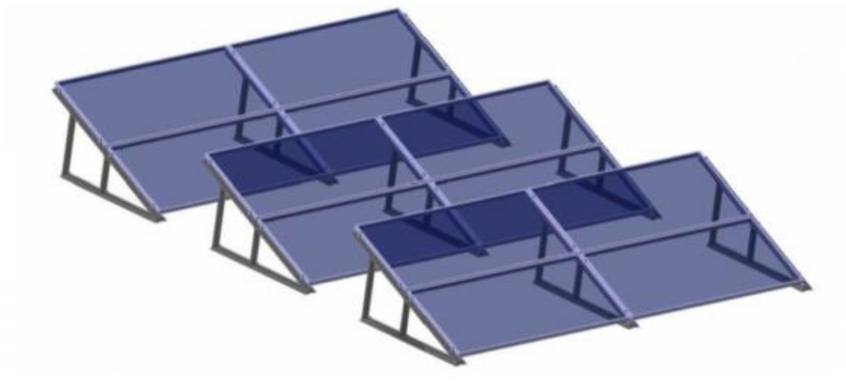


Figure 3.3-1 Simplify schematic of the modules

The calculation is done considering the optimal inclination value of 33°. First of all, it is necessary to establish the minimum distance between consecutive rows, as illustrated in figure 16. According to IDAE, the minimum distance d, between two modules of height h, needs to guarantee a minimum of 4 hours of sun's incidence during the winter solstice. The value is calculated as:

$$dmin = \frac{h}{\tan(61° - \phi)}$$

where ϕ is the latitude and the coefficient h/tan(61- ϕ) is an adimensional parameter indicated with k.

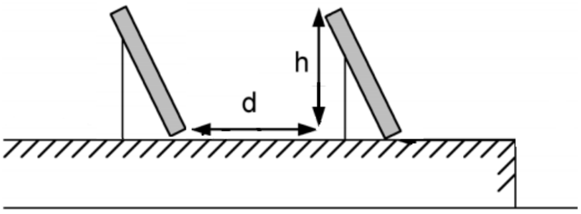


Figure 3.3-2 Profile of the disposition

Considering the dimension of the module of 1,99 x 0,99 meters and that the module is dispose horizontally, h is equal to: $h = 0{,}99 * sen(33) = 0{,}54\,m$.

So finally the value is:

$$dmin = \frac{0{,}54}{\tan(61° - 40{,}39)} = 1{,}43\,m$$

The distance between two homologue points is: $1{,}43 + 0{,}99 * \cos(33) = 2{,}26\,m$

The method applied for the calculation of the loss consist on comparing the profile of the obstacle (the modules) that affect the interested surface with the one of the sun's trajectory. For comparing the first profile to the second one, it is necessary to calculate the shading angle γ:

$$\gamma = \arctan\frac{h}{d} = \arctan\left(\frac{0{,}54}{1{,}43}\right) = 20{,}69\,°$$

In figure 18, is shown the shading profile that affect the projection of the sun during all the year. The orange line represents the effect of the shading angle while the yellow area is the solar irradiation that is lost due to its effect. The profile is divided in sub-area defined with a letter and a number and delimited by the solar hours, negative before midday and positive after it.

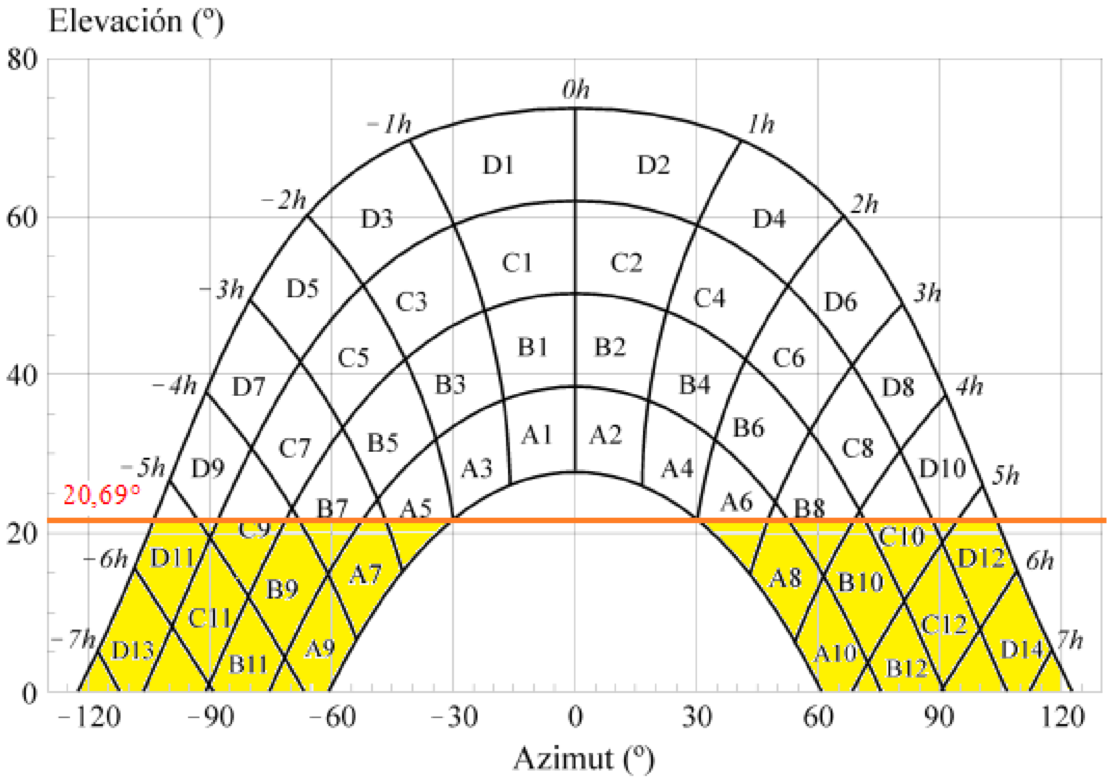


Figure 3.3-3 Shading profile on the sun projection (source IDAE)

The second stage is to select the most appropriate table of reference for the shading effect from the technical manual for pv plant from IDAE. In this particular case, with an azimuth angle α of 0° and an inclination β of 33° the most similar table of reference is the one in fig. 17.

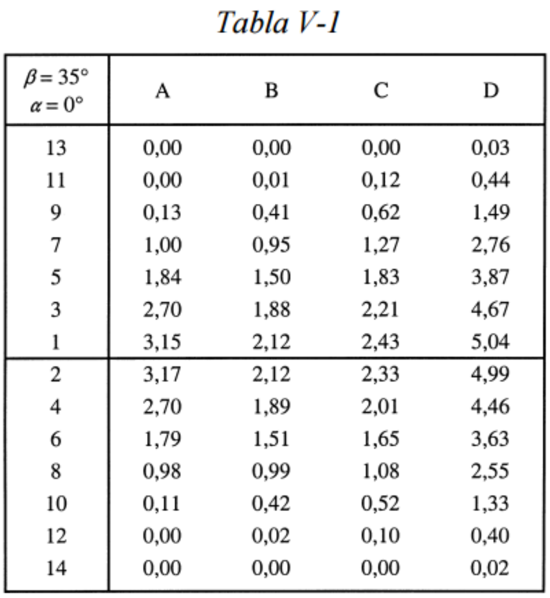


Tabla V-1

$\beta = 35°$ $\alpha = 0°$	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

Figure 3.3–4 Reference shading table (source: IDAE technical manual)

This table gives for each sub-area of the shading area the value, in percentile, of the lost irradiation if the sub-area is below the line of the shading angle. For the sub-area that are partially below it, is used the coefficient closest to the values: 0.25, 0.50, 0.75 or 1.

For the particular case of this project the calculation is:

$$loss\ (\%\ of\ total\ annual\ solar\ radiation) = \mathrm{D13} + \mathrm{C11} + \mathrm{B11} + \mathrm{B9} + \mathrm{A9} + 0.75 * \mathrm{D11} + 0.5 * \mathrm{C9} + 0.25 * \mathrm{B7} + 0.75 * \mathrm{A7} + 0.25 * \mathrm{A5} + 0.5 * \mathrm{A6} + 0.25 * \mathrm{B8} + 0.5 * \mathrm{C10} + 0.75 * \mathrm{D12} + 0.25 * \mathrm{D10} + \mathrm{B10} + \mathrm{A10} + \mathrm{C12} + \mathrm{B12} + \mathrm{D14} =$$

$$= 0.03 + 0.12 + 0.01 + 0.41 + 0.13 + 0.75 * 0.44 + 0.5 * 0.62 + 0.25 * 0.95 + 0.75 * 1 + 0.25 * 1.84 + 0.5 * 1.79 + 0.25 * 0.99 + 0.5 * 0.52 + 0.75 * 0.4 + 0.25 * 1.33 + 0.42 + 0.11 + 0.10 + 0.02 + 0.02 = \mathbf{5.4925}\ \%$$

This is the reference loss due to shading accordingly to CTE and IDAE.

3.3 Cables section

According with REBT[4] the choice of the cable's section is made by respecting two main technical parameters: The loss of tension and the maximum admissible current. The cables used for connecting the modules to the inverters and the ones for connecting the inverters to the grid have a session that varies from the distance and from the current intensity passing through it. The bigger the distance between the two units and the thicker need to be the cable in order to avoid energy losses and overheating. Nevertheless, the commercially available sizes for the cable's section of the two elected products range between 2 to 25 mm^2, with a cost that increases proportionally with the section.

The installation is design for a maximal loss tension of 1,5 % that is an advisable value given by many manufacturers.

The first step for the calculation of the required section is to measure the distance of the cables that need to be disposed in the system. For the DC cables the distance is measure from the AutoCAD 'Rooftop – PV array' plane, calculating respectively the distance of each string of modules.

From the distance and the maximal admitted intensity, a first sizing of the cable is done respecting the maximal tension loss of 1,5 %. The applied formula for the DC part is:

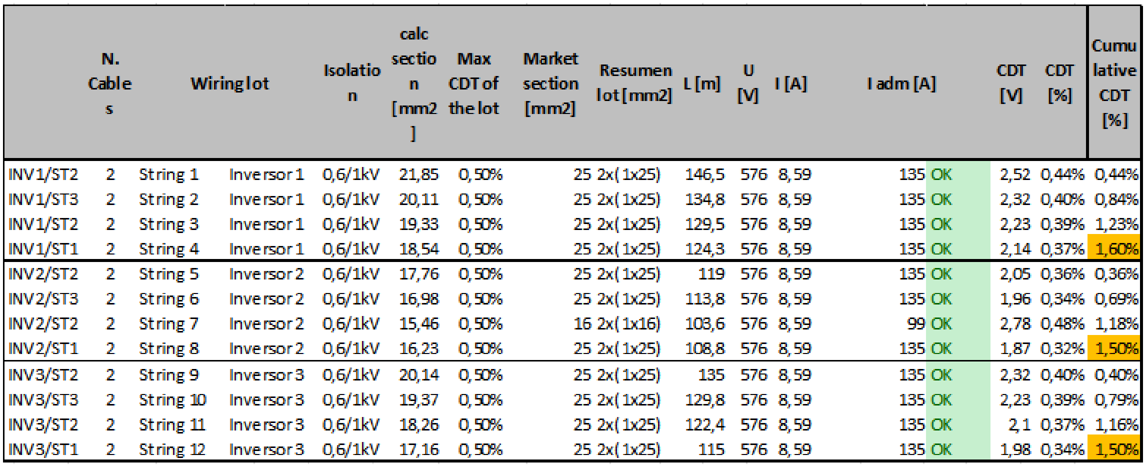
$$S\ [mm^2] = \frac{2 * L[m] * I[A]}{\Delta V * \gamma_{120°}}$$

According with REBT, the values of $\gamma_{120°}$ is taken as 40.

---

[4] Electrical regulation for low tension

Iterating the process in an excel spreadsheet the results are:



	N. Cables	Wiring lot		Isolation	calc section [mm2]	Max CDT of the lot	Market section [mm2]	Resumen lot [mm2]	L [m]	U [V]	I [A]	I adm [A]		CDT [V]	CDT [%]	Cumulative CDT [%]
INV1/ST2	2	String 1	Inversor 1	0,6/1kV	21,85	0,50%	25	2x(1x25)	146,5	576	8,59	135	OK	2,52	0,44%	0,44%
INV1/ST3	2	String 2	Inversor 1	0,6/1kV	20,11	0,50%	25	2x(1x25)	134,8	576	8,59	135	OK	2,32	0,40%	0,84%
INV1/ST2	2	String 3	Inversor 1	0,6/1kV	19,33	0,50%	25	2x(1x25)	129,5	576	8,59	135	OK	2,23	0,39%	1,23%
INV1/ST1	2	String 4	Inversor 1	0,6/1kV	18,54	0,50%	25	2x(1x25)	124,3	576	8,59	135	OK	2,14	0,37%	1,60%
INV2/ST2	2	String 5	Inversor 2	0,6/1kV	17,76	0,50%	25	2x(1x25)	119	576	8,59	135	OK	2,05	0,36%	0,36%
INV2/ST3	2	String 6	Inversor 2	0,6/1kV	16,98	0,50%	25	2x(1x25)	113,8	576	8,59	135	OK	1,96	0,34%	0,69%
INV2/ST2	2	String 7	Inversor 2	0,6/1kV	15,46	0,50%	16	2x(1x16)	103,6	576	8,59	99	OK	2,78	0,48%	1,18%
INV2/ST1	2	String 8	Inversor 2	0,6/1kV	16,23	0,50%	25	2x(1x25)	108,8	576	8,59	135	OK	1,87	0,32%	1,50%
INV3/ST2	2	String 9	Inversor 3	0,6/1kV	20,14	0,50%	25	2x(1x25)	135	576	8,59	135	OK	2,32	0,40%	0,40%
INV3/ST3	2	String 10	Inversor 3	0,6/1kV	19,37	0,50%	25	2x(1x25)	129,8	576	8,59	135	OK	2,23	0,39%	0,79%
INV3/ST2	2	String 11	Inversor 3	0,6/1kV	18,26	0,50%	25	2x(1x25)	122,4	576	8,59	135	OK	2,1	0,37%	1,16%
INV3/ST1	2	String 12	Inversor 3	0,6/1kV	17,16	0,50%	25	2x(1x25)	115	576	8,59	135	OK	1,98	0,34%	1,50%

Figure 3.3-1 Section result table

Considering the table, it is possible to appreciate that the parameter that mostly affects the section of the cable is the loss of tension along the wiring. In general, the technical standard limit of 1,5 % of tension loss is respected for all the inverters except the first one where the cumulative loss if of 1,6 %. However, considering the fact that the results were obtained by setting the parameters of U [V] and I[A] of maximum power output for the strings, in normal operation condition the loss will be lower and it will not compromise the correct functions of the plant

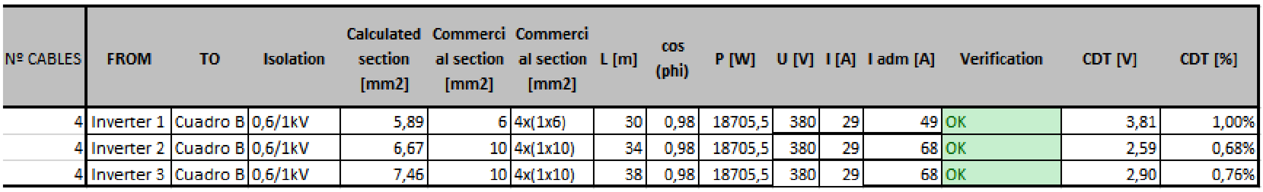
For the DC wiring the cable elected is the model 'Topsolar PV ZZ-F / H1Z2Z2-K' that will be disposed with a section of 25 mm^2 (diameter 10,8 mm) in each lot of the system. Even though for a string of the system the cable could be of just 16 mm^2, it is advisable to choose the same section so that it is not necessary to install changing section panel and also the price for a single section will be cheaper.

For the AC wiring the formula that is applied for the correct sizing is the following:

$$S\,[mm^2] = \frac{\sqrt{3} * L[m] * I[A] * \cos(\varphi)}{\Delta V * \gamma_{90^\circ}}$$

According with the manufacturer of the inverter the value of cos (φ) is taken as 0,98.

For the AC part of the system the results obtained are:



Nº CABLES	FROM	TO	Isolation	Calculated section [mm2]	Commercial section [mm2]	Commercial section [mm2]	L [m]	cos (phi)	P [W]	U [V]	I [A]	I adm [A]	Verification	CDT [V]	CDT [%]
4	Inverter 1	Cuadro B	0,6/1kV	5,89	6	4x(1x6)	30	0,98	18705,5	380	29	49	OK	3,81	1,00%
4	Inverter 2	Cuadro B	0,6/1kV	6,67	10	4x(1x10)	34	0,98	18705,5	380	29	68	OK	2,59	0,68%
4	Inverter 3	Cuadro B	0,6/1kV	7,46	10	4x(1x10)	38	0,98	18705,5	380	29	68	OK	2,90	0,76%

Figure 3.3-2 AC wiring results

In this case, the distance of the cables is calculated from the inverter to the Electrical Panel B, displaced before the connexion with the grid. The required section is of 6 mm^2 for the first inverter, closer to the panel, and a section of 10 mm^2 for the other two. Nevertheless, in the first case with a section of 6 mm^2 the tension loss in the lot would be of 1% and if it is sum up with the other two the final value exceeds 1,5%. For this reason and also for avoiding different section orders, the cable 'POWERFLEX RV-K' is selected with a section of 10 mm^2 for each of the inverter. This will guarantee that the current is lower than the maximal admissible and also that the tension loss remain very small.

3.3 Protection system

The protection's system is divided into the DC and AC parts of the photovoltaic plant.

For the DC electrical panel displaced before the invert the protection's equipment is:

- 1 fuse disposed for each pole of the string with an intensity of 15 A (considering that each inverter has 4 strings of modules, the number of fuses are 8 for each inverter)
- 1 direct current switch of 50 A > Isc = 1,25 x Isc[5] x n. string = 1,25 x 9 x 4 = 45 A
- 1 overvoltage arrester of class 1 and 2

For the AC electrical panel displaced after the invert:

- 1 bipolar magnetothermic switch for each invert. The intensity from which the thermic protection needs to operate is calculate from the power of the inverter. Considering the model 'Sunny Tripower 20000TL' the result is:

$$I_N[A] = \frac{P}{\sqrt{3} * V * 0{,}85} = \frac{20000}{\sqrt{3} * 400 * 0{,}85} = 34\ A$$

The value 0,85 is the tension coefficient and it takes into account that the invert stays connect to the grid until the tension is higher than the 85% of the nominal one.

---

[5] Short circuit current

- 1 differential switch for each inverter of 34 A with a sensibility of 300/1KA

The protection system is appreciable in the Annex B in the AutoCAD sketch ‘Single line diagram’ that represents all the elements that constitute the electrical system.

3.4 Grounding resistance

The value of the grounding resistance needs to guarantee that no elements of the plant can achieve a contact tension of 24 V, as stated in the regulation for low voltage system. Every circuit disposes of a protection based on a differential switch with a sensibility of 300 mA, so that the biggest possible resistance can be bigger than:

$$R_{max} = 24/0,3 = 80\ \Omega$$

The grounding system of the photovoltaic plant needs to be connected with the grounding system of the building. Moreover, the modules are connected to the mounting system so that the two elements stay at the same potential.

Chapter 4: Production Results

This chapter reports the results of the electric energy production of the photovoltaic plant. The results will be displayed for month of the year and for electrical tariff.

4.1 Meteorological Data

For the calculation of the solar yield the data of the solar irradiance was taken from the program Meteonorm v.7.0, that allows to choose the closest possible site to the one interested. In the case of this project, the locality was established as Madrid Barajas airport, not only for the closeness to the Yingli's facility but also for the abundance of data. The database of the program allows to choose between various period of time. For this project was chosen the most recent period for the temperature as for the irradiance. The program also allows to set the inclination angle of the plant, so that the irradiance data are most possible coherent.

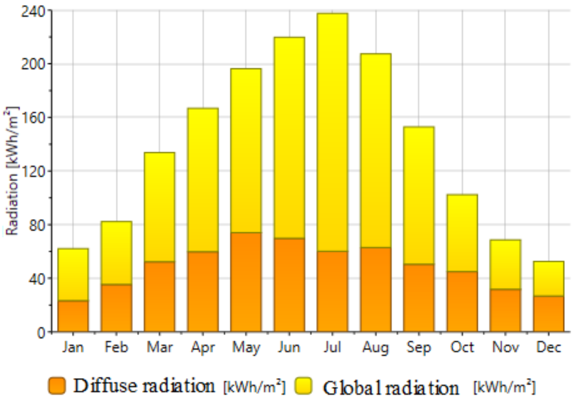


Figure 4.1-1 Annual total radiation [kWh/m^2/y] (source: PVsyst)

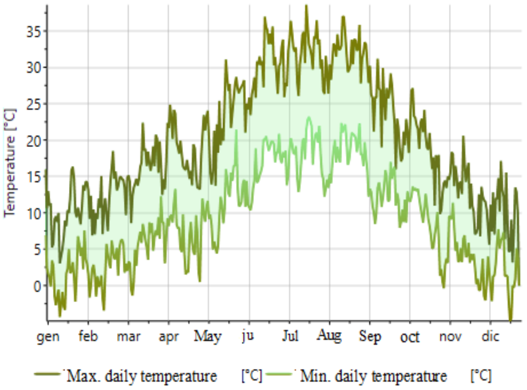


Figure 4.1-2 Annual temperature (source: PVsyst)

Month	Global Radiation [kWh/m^2]
Jenuary	62
February	82
March	134
April	167
May	196
June	220
July	238
August	207
September	153
October	102
November	69
December	53
Total	**1680**

Table 4.1-1 – Annul global radiation

4.2 Ideal energy production

The calculation of the total yearly energy production is carried out by introducing the data of the solar irradiance in an excel spreadsheet. According with the PV plant’s inclination and orientation it is possible to calculate and obtain the average production in each hour of each month. All this data is defined for kwh/m^2, so by multiplying them for the Peak power of the plant, the final output production is obtained. The values that are reported for this phase are the maximum obtainable values for the solar yield and the specified nominal power of the plant of 70,7 KWh multiply by the performance factor of 0,824, that depend on the sizing of the inverters and was given by the simulator PVsyst.

Below the schematic of the daily production along the year, figure 4.1-1, and a table with the monthly average production, figure 4.1-2, are reported.

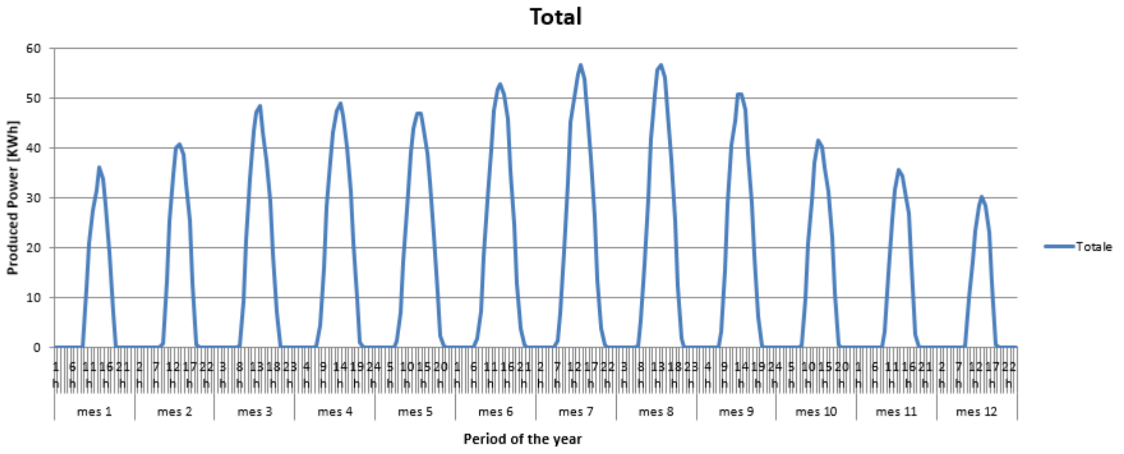


Figure 4.1-1 Monthly average production

Month	Average energy production for hour [kWh]	Total energy production for month [kWh/m]
January	9,36	6966,73
February	11,47	7710,15
March	14,73	10961,37
April	16,25	11700,88
May	16,55	12314,28
June	18,28	13168,05
July	19,52	14527,75
August	18,87	14037,71
September	16,24	11694,15
October	12,10	9003,52
November	9,64	6943,41
December	7,51	5587,09
Total	**14,23**	**124615,111**

Table 4.2-1 Production values

4.3 Production and consumption chart

This section wants to show the energy production's trend respect the consumption's one. The year is divided into two main seasons that are:

- Winter: January, February, March, October, November; December
- Summer: April, May, June. July, August, September

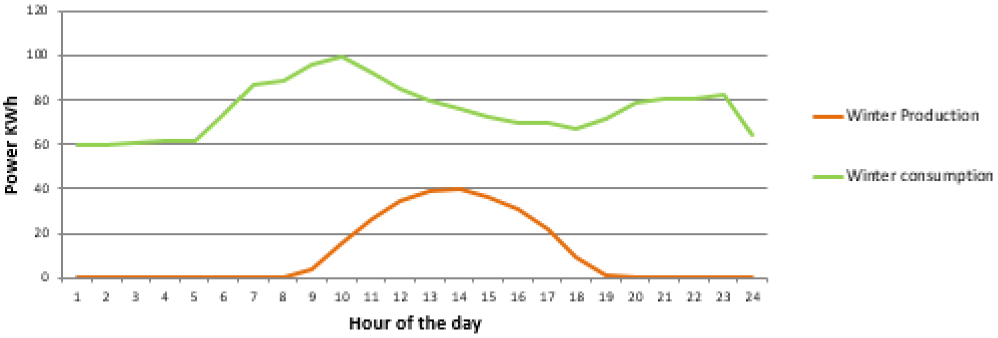


Figure 4.3-1 Production/Consumption Winter chart

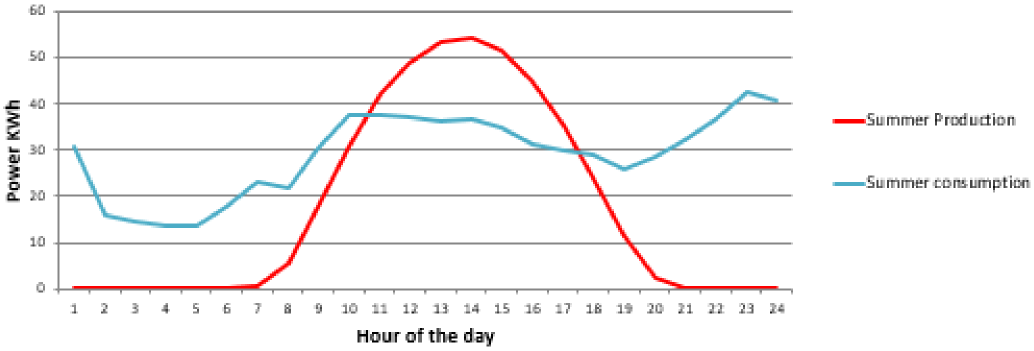


Figure 4.3-2 – Production/consumption Summer chart

From the above graphs, it is possible to appreciate that during the winter's season the consumption demand is always higher than the production. For this reason, there is not energy excess from the photovoltaic plant and the percentage of self-consumption is of 100 %, since no energy is injected to the grid.

On the other hand, during summer's months, the production overpasses the energy demand from 10 am to 17 pm, so that the system will inject part of the total energy to the grid. During the summer's season the percentage of self-consumption is of 79,2 % with a roughly 20 % of the energy that is sold to the grid.

4.4 Tariff and tolls

The tariff and tools applied to the energy consumption of the facility is regulated by the Tariff 3.0A that correspond to a category with a contracted power greater than 15 KW in a low voltage system. This regulation divides the duration of the day in three periods that depend from the electricity demand: TEU1 (high demand), TEU2 (medium demand) and TEU3 (low demand). These periods define the tariff for each hours of the day, changing accordingly with the season. As it is possible to see from the table below, the tariff is composed by two components: The first one is the toll for the installed power while the second one depends from the energy consumption and they both vary accordingly with the tariff class.

Season	Class tariff	Period of the day	Power toll [€/KW year]	Energy toll [€/KWh]
WINTER	TEU1	18-22	32,17	0,02939
	TEU2	8-18, 22-24	6,40	0,01933
	TEU3	0-8	14,27	0,01115
SUMMER	TEU1	11-15	32,17	0,02939
	TEU2	8-11, 15-24	6,40	0,01933
	TEU3	0-8	14,27	0,01115

Table 4.4-1 Tariff 3.0A

This table is applied in an excel spreadsheet to calculate the amount of energy that is respectively consumed and produced in the different period of the day, so that it is possible to know the distribution of the electricity demand and then calculate the cash flows of the facility.

4.5 Energy consumption distribution

The yearly total energy demand of the industrial facility is of around 437 MWh and it is distributed as shown in the below tables:

Month	Total energy consumption [kWh]
January	62073
February	59227
March	52532
April	35413
May	14539
June	17283
July	21071
August	16251
September	14631
October	38341
November	50781
December	55325
TOTAL	**437472**

Table 4.5-1 Yearly energy demand

Coherently with the tariff previously presented, the energy consumption is divided into its three classes and the distribution obtain is:

Month	Energy consumption **TEU1** [kWh]	Energy consumption **TEU2** [kWh]	Energy consumption **TEU3** [kWh]
January	10205	30687	21180
February	9292	29611	20323
March	8824	25818	17890
April	6589	18541	10282
May	2802	7918	3819
June	3893	9264	4125
July	5388	11425	4258
August	3663	8280	4307
September	3234	8257	3139
October	6180	19817	12343
November	8529	24957	17293
December	9083	27272	18969
Total	**77687**	**221851**	**137932**

Table 4.5-2 Energy consumption distribution

From the table it is possible to appreciate that the biggest quantity of energy consumption is during the period of class TEU2.

It is easy to understand that the tariff's classes regulate the activities run by an industrial facility. In fact, the operations that can be postponed and carried out during a period with a low prize for electricity, TEU3, let companies to save a big quantity of money and increase their incomes.

4.6 Energy production distribution

As for the energy consumption, the energy production is also divided into the three different classes, so that the energy that is injected to the grid is paid by the electric provider with a price that varies depending on the period of the day and the season considered.

Season	Energy production TEU1 [kWh]	Energy production TEU2 [kWh]	Energy production TEU3 [kWh]
Winter	1912	45259	0
Summer	36323	40971	147
Total	38236	86230	147

Table 4.6-1 Energy production distribution

The energy production is concentrated in the period of day with tariff TEU1 and TEU2 as the third class consider the night or early morning's hours where there is not light. This represents a good aspect for the affordability of the plant, as in general, the peak photovoltaic production coincides with the peak demand of electricity characterized by the highest prices. Moreover, this also improve the efficiency of the self-consumption, giving the fact that the facility's demand increases from 9 am when the photovoltaic system starts to produces energy.

4.7 Net energy production

The final stage before proceeding with the economic analysis is to calculate the energy production over the lifespan of the photovoltaic plant. This process considers the fact that there is an annual degradation of the modules and that the ideal energy output is affected by losses in the system. The main input data of the excel spreadsheet are reported in the following table:

Nominal Power (array)	60 kWn
Number of modules	228
Performance Ratio	82,4 %
Annual module degradation	0,70 %
Losses of the system	17,5 %
Lifespan of the plant	25 years

Table 4.7-1 Main input

Year		Net winter production [kWh]	Net summer production [kWh]	Net annual production [kWh]
0	2016	38.917,12	67.428,01	106.345,13
1	2017	38.333,36	66.416,59	104.749,95
2	2018	38.065,03	65.951,68	104.016,71
3	2019	37.798,57	65.490,01	103.288,59
4	2020	37.533,98	65.031,58	102.565,57
5	2021	37.271,25	64.576,36	101.847,61
6	2022	37.010,35	64.124,33	101.134,68
7	2023	36.751,28	63.675,46	100.426,73
8	2024	36.494,02	63.229,73	99.723,75
9	2025	36.238,56	62.787,12	99.025,68
10	2026	35.984,89	62.347,61	98.332,50

Year		Net winter production [kWh]	Net summer production [kWh]	Net annual production [kWh]
11	2027	35.732,99	61.911,18	97.644,17
12	2028	35.482,86	61.477,80	96.960,66
13	2029	35.234,48	61.047,46	96.281,94
14	2030	34.987,84	60.620,12	95.607,97
15	2031	34.742,93	60.195,78	94.938,71
16	2032	34.499,73	59.774,41	94.274,14
17	2033	34.258,23	59.355,99	93.614,22
18	2034	34.018,42	58.940,50	92.958,92
19	2035	33.780,29	58.527,92	92.308,21
20	2036	33.543,83	58.118,22	91.662,05
21	2037	33.309,02	57.711,39	91.020,42
22	2038	33.075,86	57.307,41	90.383,27
23	2039	32.844,33	56.906,26	89.750,59
24	2040	32.614,42	56.507,92	89.122,34
25	2041	32.386,12	56.112,36	88.498,48

Table 4.8–2 Annual net energy production

From the Net annual production, it is possible to calculate the capacity factor of the plant that is the ratio of its actual output over a period of time, to its potential output if it were possible for it to operate at full nominal power continuously over the same period of time. The formula for calculation is:

$$\boldsymbol{C_f} = \frac{\dfrac{\textbf{Annual energy production}}{\textbf{peak installed power}}}{\textbf{total year hours}}$$

Iterating the formula for each year the average value is of **0,14**; this value is very low respect other conventional ways to produce energy but it is explainable as the photovoltaics' plants rely on an energy source that depends heavily from the weather conditions and that can operate only with the presence of the sun.

Chapter 5: Economic study

This chapter describes the economic analysis that was carried out in order to obtain the values of the incomes and the payback period of the photovoltaic plant. All the financial and economic input try to be the most possible coherent with the real ones so that the obtained results give an authentic view of the affordability of a self-consumption plant.

5.1 Total cost photovoltaic plant

For evaluate the total cost of the photovoltaic plant it was necessary to compile an estimation of the cost of all the equipment, operations and installations carried out to install the plant and various. The general estimated budget is reported below:

CHAPTER 1 : PRINCIPAL EQUIPMENT

POS.	QUANTITY	Unit	CONCEPT	P.UNIT.	TOTAL
1,01	228	Unit	**Supply and montage of the photovoltaic module YL310-35b** of dimensions 1970x990x50 mm and 26.8 kg for the rooftop	144,00	32.832,00 €
			TOTAL ITEM		**32.832,00 €**
1,02	3	Unit	**Supply of inverter SunnyTripowerTL 20 kW** nominal triphasis. Included comunication unit RS485 and overvoltage protection class II	2500,00	7.500,00 €
			TOTAL ITEM		**7.500,00 €**
				TOTAL CHAPTER 1	**40.332,00 €**

CHAPTER 2 : STRUCTURE

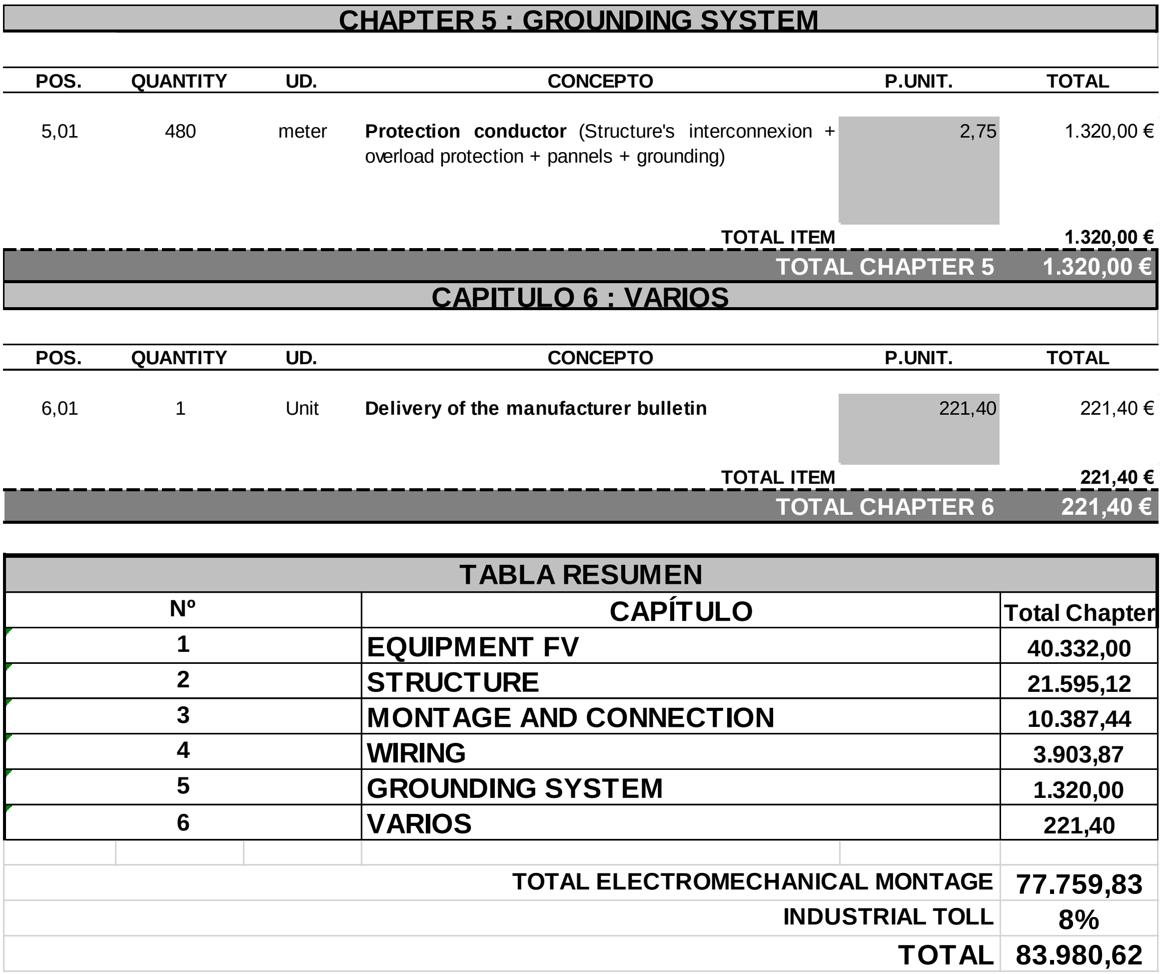
POS.	QUANTITY	UD.	CONCEPT	P.UNIT.	TOTAL
2,01	76	Unit	**Supply of auxiliar structure for rooftop Schletter PV Max.** Structure displaced with an inclination angle of 33º over the rooftop.	136,80	10.396,80 €
			TOTAL ITEM		**10.396,80 €**
2,01	76	Unit	**Montage of auxuiliar structure for rooftop.**	147,35	11.198,32 €
			TOTAL ITEM		**11.198,32 €**
				TOTAL CHAPTER 2	**21.595,12 €**

CHAPTER 3 : MONTAGE AND WIRING

POS.	QUANTITY	UD.	CONCEPT	P.UNIT.	TOTAL
3,01	228	Unit	**Montage and conexxion of the photovoltaic modules**.	30,51	6.955,19 €
			TOTAL ITEM		**6.955,19 €**
3,02	3	Unit	**Supply of control panel type A**	288,80	866,40 €
			TOTAL ITEM		**866,40 €**
3,03	3	Unit	**Montage of control panel A for DC**	52,29	156,88 €
			TOTAL ITEM		**156,88 €**
3,04	1	Unit	**Supply of control panel type B for AC group.**	1002,46	1.002,46 €
			TOTAL ITEM		**1.002,46 €**
3,05	1	Unit	**Montage of control panel type B for AC group.**	522,95	522,95 €
			TOTAL ITEM		**522,95 €**
3,05	1	Unit	**Supply and installation of the automatic interruptor in the general control and protection pannel.** According with unifilar plan.	99,14	99,14 €
			TOTAL ITEM		**99,14 €**
3,06	3	Unit	**Montage and connexion of inverters with the grid**	261,47	784,42 €
			TOTAL ITEM		**784,42 €**
				TOTAL CHAPTER 3	**10.387,44 €**

CHAPTER 4: WIRING

POS.	QUANTITY	UD.	CONCEPT	P.UNIT.	TOTAL
4,01	1483	meter	**Supply, connexion and lying in cable's plate of Topsolar PV ZZ-F / H1Z2Z2-K** Cu 0,6/1kV 1x25 mm2 according with UNE 21123-2	2,25	3.336,75 €
			TOTAL ITEM		**3.336,75 €**
4,02	408	meter	**Supply, connexion and lying in cable's plate of POWERFLEX RV-K** 0,6/1kV 1x10 mm2 according with UNE 21123-2	1,39	567,12 €
			TOTAL ITEM		**567,12 €**
				TOTAL CHAPTER 4	**3.903,87 €**



CHAPTER 5 : GROUNDING SYSTEM

POS.	QUANTITY	UD.	CONCEPTO	P.UNIT.	TOTAL
5,01	480	meter	**Protection conductor** (Structure's interconnexion + overload protection + pannels + grounding)	2,75	1.320,00 €
			TOTAL ITEM		**1.320,00 €**
				TOTAL CHAPTER 5	**1.320,00 €**

CAPITULO 6 : VARIOS

POS.	QUANTITY	UD.	CONCEPTO	P.UNIT.	TOTAL
6,01	1	Unit	**Delivery of the manufacturer bulletin**	221,40	221,40 €
			TOTAL ITEM		**221,40 €**
				TOTAL CHAPTER 6	**221,40 €**

TABLA RESUMEN

Nº	CAPÍTULO	Total Chapter
1	EQUIPMENT FV	40.332,00
2	STRUCTURE	21.595,12
3	MONTAGE AND CONNECTION	10.387,44
4	WIRING	3.903,87
5	GROUNDING SYSTEM	1.320,00
6	VARIOS	221,40
	TOTAL ELECTROMECHANICAL MONTAGE	77.759,83
	INDUSTRIAL TOLL	8%
	TOTAL	83.980,62

Figure 5.1–1 Total budge resume

Once the total cost of the plant is correctly estimated, it is possible to proceed with the economic analysis and evaluate the payback return of the plant.

It is interesting to denote that the modules and inverters constitute almost half of the total prize of the plant, followed by the structure montage with a 25% respect the total.

The final net price is of 77759 € and with a gross industrial profit of 8% the total cost is of 83980 €.

To this values it is added a 21 % of VAT (value added tax) so that the final cost for the facility is of **103.392** €.

5.2 Economic and financial parameters

The economic analysis is carried out by applying the tariff 3.0A that was introduced in the chapter 4.4 and is regulated by the Real Decreto 900/2015.

The toll applied to the facility depends by the energy consumption while there is no tax for the installed power; this is due to the fact that the installed power of the photovoltaic plant is lower than the contracted power of the facility with the electrical provider. As stated in the RD 900/2015, only in the case of a PV plant with an installed power higher than the contracted one the power toll is applied.

The input parameters to the excel spreadsheet for the economic analysis are:

Tariff 3.0A version nov/2015	
Energy price TEU1	0,159 €/kWh
Energy price TEU2	0,096 €/kWh
Energy price TEU3	0,061 €/kWh
Energy toll TEU1	0,029 €/kWh
Energy toll TEU2	0,019 €/kWh
Energy toll TEU3	0,011 €/kWh
Power toll (c€/kW)	0
Increase in the annual tariff (%)	4,5%
Increase in the annual toll (%)	0%

Table 5.2–1 Applied tariff

The tariff for the electricity varies each year depending on a lot of factors and it has been characterized in general by an increasing price, as it is shown in figure 5.2-1. Considering this trend and the future perspective an annual average increase of 3.0 % is set up for the energy tariff. This will lead to major income in future years.

Concerning the applied toll, considering that the normative 3.0A that fixed it was approved last year, it probable that the toll will not change in the next years. With this hypothesis the annual incremental for the toll is set up to 0.

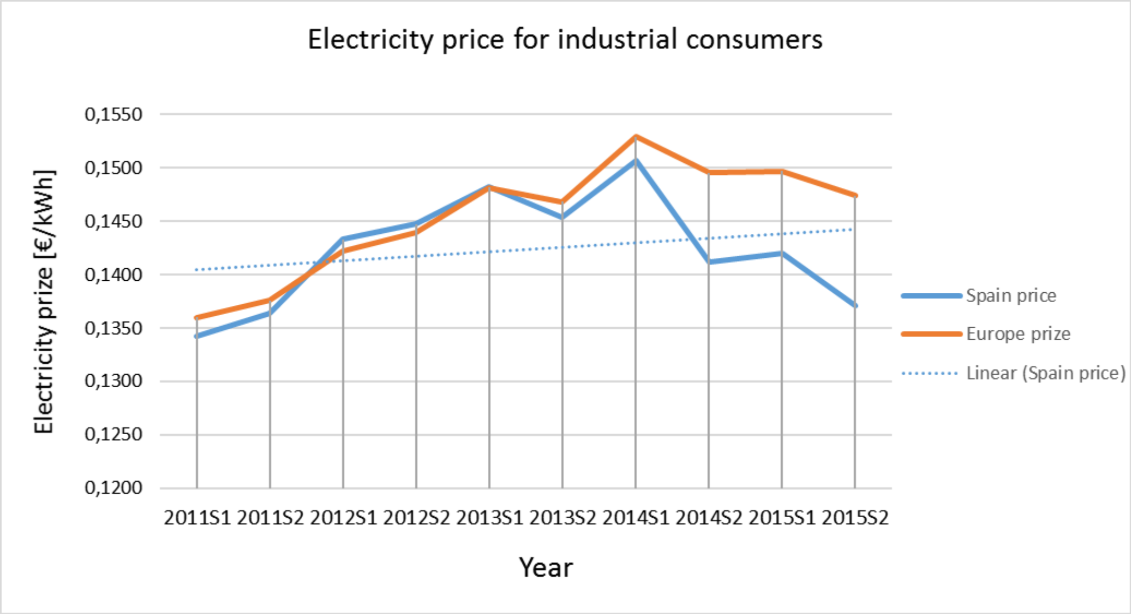


Figure 5.2-1 Electricity price for industrial consumers Spain/Europe (source: Eurostat)

For considering the financial trend of the market and the inflation rate effect on the affordability of the plant the Consumer price index (CPI) in taken into account. In fact, the annual percentage of this index is used as a measure of the inflation. The value for this parameters is set up to 2.5%.

5.3 Total annual income

The facility has two ways to pay off the photovoltaic plants:

- When the PV system is not able to meet the demand, the facility needs to take energy from the grid. The income is considered as savings from the consumed energy provided by the PV system. The electricity saved is valued with the coherent tariff depending on the period of the day;

- For the period in which the PV system is able to meet all the consumption demands and it also generates a surplus of energy, income comes from selling electricity fed to the grid. Also this energy is values with the coherent tariff for electricity varying according to the time of the day.

With these considerations, the total annual income is calculated by multiplying the total annual production by its respective tariff and then subtracting by the total toll for the produced energy. The results obtained are reported in the table.

Year		Total income [€/y]	Total energy toll [€/y]	Total annual [€/y]	Total cumulated [€]
0	2016				
1	2017	12.004,28 €	-2.333,35 €	9.670,93 €	9.670,93 €
2	2018	12.277,86 €	-2.317,02 €	9.960,84 €	19.631,76 €
3	2019	12.557,67 €	-2.300,80 €	10.256,87 €	29.888,63 €
4	2020	12.843,86 €	-2.284,69 €	10.559,16 €	40.447,80 €
5	2021	13.136,57 €	-2.268,70 €	10.867,87 €	51.315,66 €
6	2022	13.435,95 €	-2.252,82 €	11.183,13 €	62.498,79 €
7	2023	13.742,16 €	-2.237,05 €	11.505,11 €	74.003,90 €
8	2024	14.055,34 €	-2.221,39 €	11.833,95 €	85.837,85 €
9	2025	14.375,66 €	-2.205,84 €	12.169,82 €	98.007,67 €
10	2026	14.703,28 €	-2.190,40 €	12.512,88 €	110.520,55 €
11	2027	15.038,37 €	-2.175,07 €	12.863,30 €	123.383,86 €
12	2028	15.381,10 €	-2.159,84 €	13.221,25 €	136.605,11 €
13	2029	15.731,63 €	-2.144,72 €	13.586,91 €	150.192,02 €
14	2030	16.090,16 €	-2.129,71 €	13.960,44 €	164.152,46 €
15	2031	16.456,85 €	-2.114,80 €	14.342,05 €	178.494,51 €
16	2032	16.831,90 €	-2.100,00 €	14.731,90 €	193.226,41 €
17	2033	17.215,50 €	-2.085,30 €	15.130,20 €	208.356,61 €
18	2034	17.607,84 €	-2.070,70 €	15.537,14 €	223.893,75 €
19	2035	18.009,12 €	-2.056,21 €	15.952,92 €	239.846,67 €
20	2036	18.419,55 €	-2.041,81 €	16.377,74 €	256.224,41 €
21	2037	18.839,33 €	-2.027,52 €	16.811,81 €	273.036,22 €
22	2038	19.268,68 €	-2.013,33 €	17.255,35 €	290.291,57 €
23	2039	19.707,82 €	-1.999,24 €	17.708,58 €	308.000,16 €
24	2040	20.156,96 €	-1.985,24 €	18.171,72 €	326.171,87 €
25	2041	20.616,33 €	-1.971,34 €	18.644,99 €	344.816,86 €

Table 5.2–1 Total annual income

For obtaining the net annual income it is necessary to subtract to these values the annual expenses of the plant, table 5.3-2, that are composed by different components: cost derived by billing and administration, operation and maintenance expense and assurance price.

With this calculation it is possible to obtain the final cash flow of the facility and calculate the internal rate of return and the payback period.

Year		Billing/administration cost [€]	O&M cost [€]	Assurance cost [€]	General expenses [€]
0	2016				2.099,79 €
1	2017	155,54 €	777,70 €	1.166,55 €	2.152,28 €
2	2018	159,43 €	797,14 €	1.195,71 €	2.206,09 €
3	2019	163,41 €	817,07 €	1.225,61 €	2.261,24 €
4	2020	167,50 €	837,50 €	1.256,25 €	2.317,78 €
5	2021	171,69 €	858,44 €	1.287,65 €	2.375,72 €
6	2022	175,98 €	879,90 €	1.319,84 €	2.435,11 €
7	2023	180,38 €	901,89 €	1.352,84 €	2.495,99 €
8	2024	184,89 €	924,44 €	1.386,66 €	2.558,39 €
9	2025	189,51 €	947,55 €	1.421,33 €	2.622,35 €
10	2026	194,25 €	971,24 €	1.456,86 €	2.687,91 €
11	2027	199,10 €	995,52 €	1.493,28 €	2.755,11 €
12	2028	204,08 €	1.020,41 €	1.530,61 €	2.823,98 €
13	2029	209,18 €	1.045,92 €	1.568,88 €	2.894,58 €
14	2030	214,41 €	1.072,07 €	1.608,10 €	2.966,95 €
15	2031	219,77 €	1.098,87 €	1.648,30 €	3.041,12 €
16	2032	225,27 €	1.126,34 €	1.689,51 €	3.117,15 €
17	2033	230,90 €	1.154,50 €	1.731,75 €	3.195,08 €
18	2034	236,67 €	1.183,36 €	1.775,04 €	3.274,96 €
19	2035	242,59 €	1.212,95 €	1.819,42 €	3.356,83 €
20	2036	248,65 €	1.243,27 €	1.864,91 €	3.440,75 €
21	2037	254,87	1.274,35 €	1.911,53 €	3.526,77 €
22	2038	261,24 €	1.306,21 €	1.959,32 €	3.614,94 €
23	2039	267,77 €	1.338,87 €	2.008,30 €	3.705,31 €
24	2040	274,47 €	1.372,34 €	2.058,51 €	3.797,94 €
25	2041	281,33 €	1.406,65 €	2.109,97 €	2.099,79 €

Table 5.2–2 Total annual expenditure

As for the energy tariff also the general expenses are affected by the CPI, so that their values follow an increment of 2,5% each year.

5.3 Total annual cash flow and payback period

By subtracting the general expenditures to the annual income, the annual cash flow is obtained as reported in the following table:

Year		Total annual [€/y]	General expenses [€]	Annual cash flow [€]	Cumulated cash flow [€]
0	2016			-100.448,35 €	-100.448,35 €
1	2017	9.670,93 €	2.099,79 €	7.571,14 €	-92.877,22 €
2	2018	9.960,84 €	2.152,28 €	7.808,55 €	-85.068,66 €
3	2019	10.256,87 €	2.206,09 €	8.050,78 €	-77.017,89 €
4	2020	10.559,16 €	2.261,24 €	8.297,92 €	-68.719,97 €
5	2021	10.867,87 €	2.317,78 €	8.550,09 €	-60.169,87 €
6	2022	11.183,13 €	2.375,72 €	8.807,41 €	-51.362,46 €
7	2023	11.505,11 €	2.435,11 €	9.069,99 €	-42.292,47 €
8	2024	11.833,95 €	2.495,99 €	9.337,96 €	-32.954,51 €
9	2025	12.169,82 €	2.558,39 €	9.611,43 €	-23.343,08 €
10	2026	12.512,88 €	2.622,35 €	9.890,53 €	-13.452,55 €
11	2027	12.863,30 €	2.687,91 €	10.175,39 €	-3.277,15 €
12	2028	13.221,25 €	2.755,11 €	10.466,15 €	7.188,99 €
13	2029	13.586,91 €	2.823,98 €	10.762,92 €	17.951,92 €
14	2030	13.960,44 €	2.894,58 €	11.065,86 €	29.017,78 €
15	2031	14.342,05 €	2.966,95 €	11.375,10 €	40.392,88 €
16	2032	14.731,90 €	3.041,12 €	11.690,78 €	52.083,66 €
17	2033	15.130,20 €	3.117,15 €	12.013,05 €	64.096,71 €
18	2034	15.537,14 €	3.195,08 €	12.342,06 €	76.438,77 €
19	2035	15.952,92 €	3.274,96 €	12.677,96 €	89.116,73 €
20	2036	16.377,74 €	3.356,83 €	13.020,91 €	102.137,64 €
21	2037	16.811,81 €	3.440,75 €	13.371,06 €	115.508,70 €
22	2038	17.255,35 €	3.526,77 €	13.728,58 €	129.237,29 €
23	2039	17.708,58 €	3.614,94 €	14.093,64 €	143.330,93 €
24	2040	18.171,72 €	3.705,31 €	14.466,40 €	157.797,33 €
25	2041	18.644,99 €	3.797,94 €	14.847,05 €	172.644,38 €

Table 5.3–1 Cash flow

The payoff of the facility starts when the cash flow becomes positive as it possible to appreciate in figure 5.3-1. This point indicates also the payback period of the plant that results of **12 years** with a return of investment (IRR) of **8,42%**. Considering that the lifespan of the plant can be until 30 years the payback period guarantees a good pay off of the plant. Moreover, considering the savings due to the system's production and the revenue due to the selling of the exceed energy, the installed plant allows to gain the total income of **172644 €** at the end of the 25 years of activity. This grants the facility to decrease its operational costs (Opex) and to be more competitive respect to other companies.

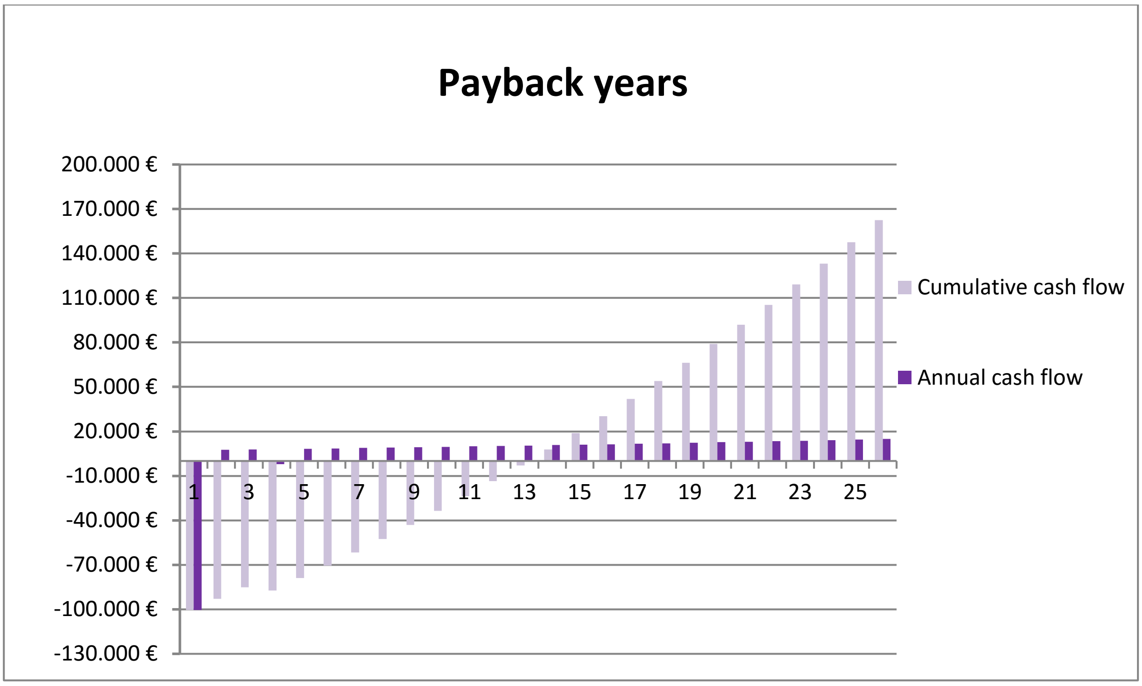


Figure 5.3–1 Payback period

5.4 Levelized cost of electricity (LCOE)

At this final stage of the economic evaluation of the plant it is interesting to make a comparison between the levelized cost of electricity of the photovoltaic system of the project respect to other technologies. The LCOE is the net present value of the unit-cost of electricity over the lifetime of a generation plant and it gives a clear assessment over its competiveness in the market.

The approach used in the analysis presented here is based on a discounting financial flows to a common basis, taking into consideration the time value of money. The formula used for calculating the LCOE of renewable energy technologies is:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Et}{(1+r)^t}}$$

I_t = investment expenditures in the year t
Mt = O&M (operation and maintenance) costs in the year t
Ft = fuel expenditures in the year t
Et = electricity generation in the year t
r = discount rate
n = lifespan of the system

The economic study case that is conducted in the report is based on a simplify analysis. For this reason, it was not possible to consider all the real factors that influence the general LCOE and were considered only the useful data required by the formulas. Specifically, the costs associated with the plant are divided into three categories:

- Cost associated with the investment (construction, materials, man power, bureaucracy, etc.…);
- Cost associated with operations and maintenance to sustain the functionality of the plant along the years;
- Cost associated with the fuel that in our case is 0 as we are using the energy from the sun;

Regarding the financial aspects, the only parameters that are considered is the rate of discount, set to a value of 3%, and the tax rates of O&M set to 2,5%.
Finally, for simply the calculation, the annual value of electricity produced is set to an average fixed value that remains constant all over the lifespan of the facility.
The input data for the evaluation are reported below in the table 5.4-1.

Installed Power [kW]	60 kW
Specific investment [€/kW]	1723,2 €/kW
Total Investment (Capex) [€]	103392 €
O&M. cost [€/kWh]	0,044 €/kWh
Life of the project [years]	25 y
Total annual energy production [kWh]	100000 kWh
WAAC Rate of discount i	3 %
rom O&M tax rate	2,5 %

Table 5.4-1. Input data [source NREL]

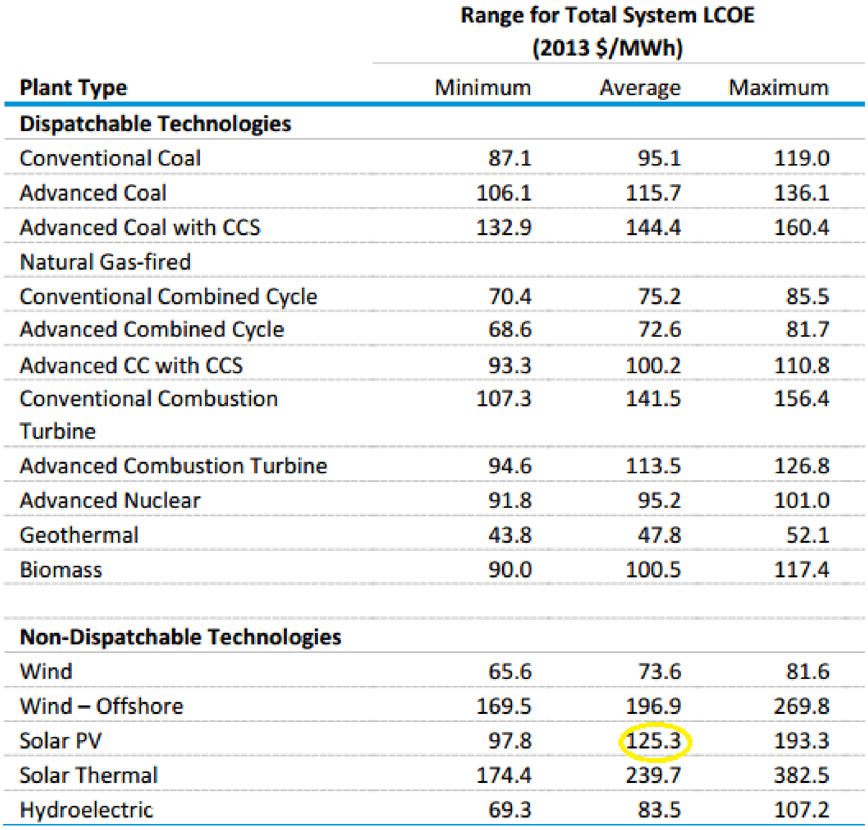
The calculation is made by running a spreadsheet in excel and the formulas that are used are:

- Depreciation factor: $fa = \frac{i*(1+i)^\wedge n}{(1+i)^{n}-1}$ (n = lifespan of the plant)
- Actualization factor: $K = \frac{1+r}{1+i}$ (r = tax rate, i = rate of discount)
- $\text{LCOE} = \frac{total\ cost\ discounted\ to\ the\ present\ value}{total\ energy\ production\ over\ lifespan}$
- Total cost = $Capex * fa + O\&M\ cost * fa * fo\&m$

The results obtained is a LCOE of 11,8 c€ for kWh or of 118 € for MWh that is similar to the average price given by the reference table 5.4-1 published by EIA[6] in 2013 for the PV technologies.

The price's variance depends from the region of the world considered and from the level of total radiation from the sun. Considering that Spain is a country with a medium-high level of solar radiance, the obtained result is coherent with the table, setting the value between the average and minimum value for LCOE.

It is possible to observe that the photovoltaic production's cost is already competitive with some of the conventional ways to produce energy, such the ones that use advanced coal, combustion turbine or biomass. Moreover, thanks to the continue research and improvement of the still young solar technologies, it is strongly probable that in the next few years the LCOE for the photovoltaics generation plants will decrease and become more competitive and even cheaper than other generation technologies.



	Range for Total System LCOE (2013 $/MWh)		
Plant Type	Minimum	Average	Maximum
Dispatchable Technologies			
Conventional Coal	87.1	95.1	119.0
Advanced Coal	106.1	115.7	136.1
Advanced Coal with CCS	132.9	144.4	160.4
Natural Gas-fired			
Conventional Combined Cycle	70.4	75.2	85.5
Advanced Combined Cycle	68.6	72.6	81.7
Advanced CC with CCS	93.3	100.2	110.8
Conventional Combustion Turbine	107.3	141.5	156.4
Advanced Combustion Turbine	94.6	113.5	126.8
Advanced Nuclear	91.8	95.2	101.0
Geothermal	43.8	47.8	52.1
Biomass	90.0	100.5	117.4
Non-Dispatchable Technologies			
Wind	65.6	73.6	81.6
Wind – Offshore	169.5	196.9	269.8
Solar PV	97.8	125.3	193.3
Solar Thermal	174.4	239.7	382.5
Hydroelectric	69.3	83.5	107.2

Figure 5.4–1 Regional variation in LCOE for new generation technologies [$/MWh] (source: EIA)

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[6] EIA: Energy Information Administration

Chapter 6: Conclusions

This finale chapter wants to comments the obtained results and proposes possible future scenarios and models for the development of a competitive and sustainable technology for the energy generation.

6.1 Methodology and results considerations

The project wanted to propose a realist and feasible model of photovoltaic plant integrated in an industrial facility that respects the technical and electromechanical regulations imposed by the industry and the government. The technical design was carried out by PVsyst, a software that is used from manufacture's companies of solar modules, for being the most possible coherent with the procedures of a real plant. This was especially important for the calculation of the performance ratio and the percentage of losses of the system, as these two data are then use for the economic evaluation and have a strong repercussion on it. The second stage was to decide the disposal of the equipment according with the available area and structure of the facility. For this purpose, AutoCAD had been really useful to making the correct sizing of the plant by disposing the modules for making the most of the available space of the rooftop. Moreover, the plan of the system was fundamental to measure the cable's length and choose their correct section. Once the technical procedure was ended with success, the following step had been to insert all the technical input data to an excel spreadsheet for obtaining the production and economic results. Although the economic evaluation had try to be the most possible accurate to a real one, some financial parameters were not considered for their complexity and difficult integration in the calculations. Nevertheless, the results obtained have shown to be comparable and coherent with the trends of the market, so that it is possible to stated that the applied model has led to satisfying and valuable results.

6.1 Project limitations and possible expansions

The project analysed a photovoltaic plant following the model of self-consumption connected to the grid. This is a viable and well integrated model for industrial facility in Spain, for the actual normative and electrical system. However, it would have been also interesting to see how a storage system affect the energy flows and the general economic affordability. In fact, a system like that would guarantee more energetic independence to the facility and also would decrease the load to the public grid, taking a series of advantages for both parties. The choice to not implementing a battery storage system to the plant was led by the actual RD 900/2015. In fact, with this normative, a storage system would be more viable and convenient only if the facility is completely isolated from the grid, because it would exonerate it from the payment of the power toll for the grid maintenance and services. Moreover, also with the most recent storage technologies, it would be difficult to design and disposed a plant that is both energetically and economically affordable. Certainly, in the next years these systems will acquire an increasing interest due to the development of innovative storing system. Still, the major problem for government and public institution, will be to regulate how to maintain the grid’s infrastructure if a major quantity of private companies or families shut them off from the grid and so not contribute to its sustainment.

Another interesting extensions of the project would have been to consider an adjustable mounting structure for the modules for optimizing their inclination during the year. This would certainly guarantee a higher energetic yield from the sun, but it would also mean a more expensive structure. Moreover, it would have been more difficult to make a model that makes a prediction of the total annual production of the plant.

6.2 Future development perspectives

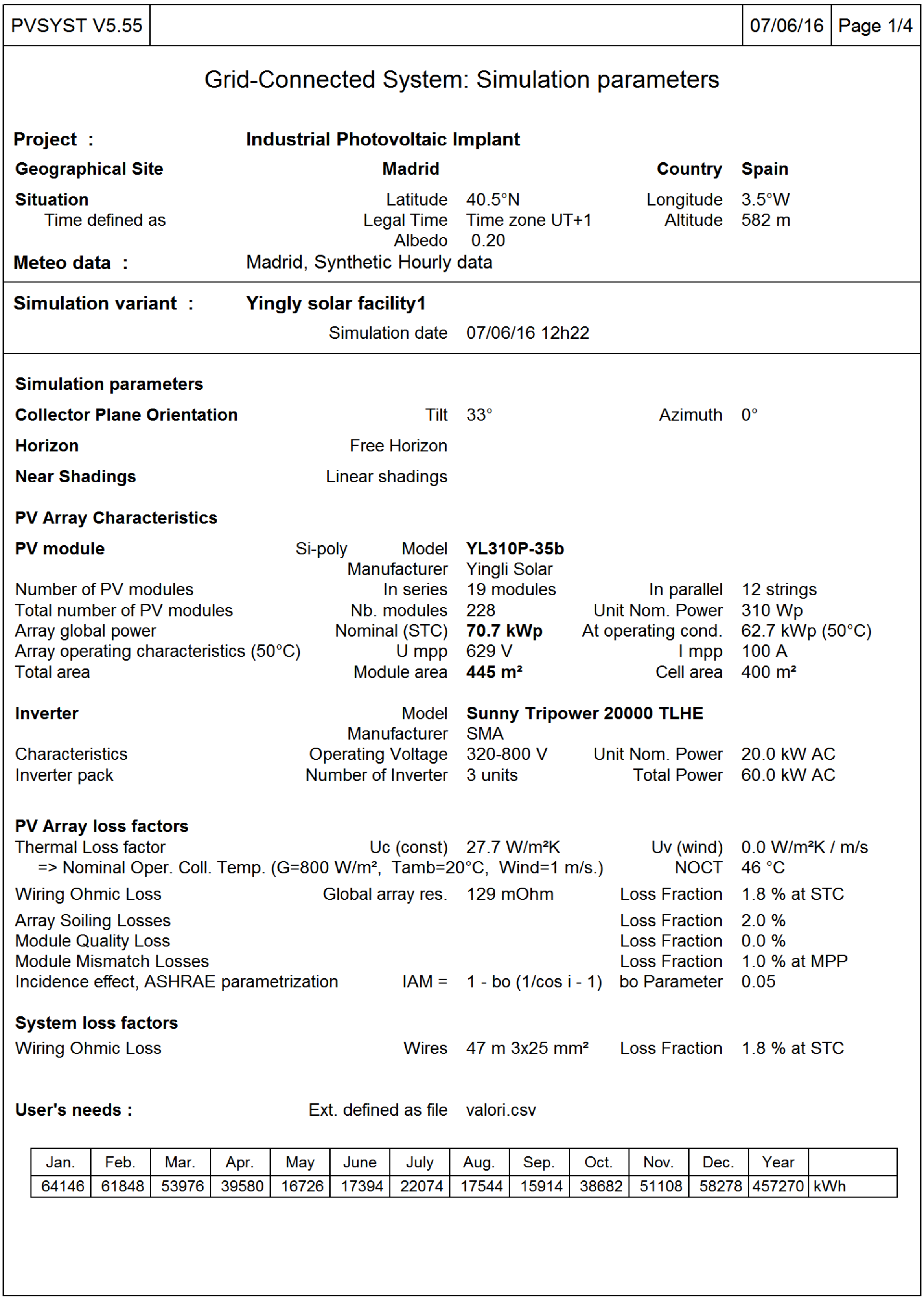
Within the technologies that will lead to a green future, photovoltaic is expected to makes a significant contribution to achieving this goal, as being the renewable energy technology with the largest possibility for cost reduction and efficiency gain. The road map for a strategic development of the solar implementation includes a series of targets with different time frames. For the next years the main objectives are: First, increase performance ratio and decrease the degradation of the modules. Second, reduce silicon consumption to 3 g/W while increasing module longevity. Third, generalise reusable and completely recyclable modules. While whiting a decade, the main target is to develop specific PV materials for building, road or gadgets integration by using innovative structure as thin fil layers or organic cells.

In general, the PV manufacturer is already becoming a mass-producing industry with big company that are imposing them self on the market. This will lead to an increasing competiveness and a global cost reduction. Nevertheless, although the electricity produced from the PV will be cheaper, the sector will remains driven by policy and normative at both national and EU levels.

6.1 Final consideration

The obtained results have attained to demonstrate the feasibility and affordability of the photovoltaic plant, even though the actual Spanish normative is not stimulating with any type of incentives the diffusion of the technology. It is a significant achievement not only for the solar industry but for all the society as it gives a concrete proof that there is the real possibility to produce energy in a clean and sustainable way. Moreover, it gives the change to private companies or citizens to produce their own energy while respecting the environment, increasing the sensibility and responsibility toward the planet. The photovoltaic technology has all the potential to represents a big player in the accomplishment of the COP21 objectives, and if combines with other renewable energy sources, the road for saving the planet from the global warming appears less difficult and challenging. Nevertheless, for enhancing the development and diffusion of these green technologies there is still a lot of work to do. Not only governments, institutions and corporations need to promote and sustain their diffusion with new normative and subsidies, but they should also transmit and popularize a common feeling through the population that the future is in the hand of each person and that each contribution has a fundamental value.

ANNEX A: PVSYST SIMULATION REPORT



PVSYST V5.55		07/06/16	Page 1/4

Grid-Connected System: Simulation parameters

Project : **Industrial Photovoltaic Implant**

Geographical Site	**Madrid**		**Country**	**Spain**
Situation	Latitude	40.5°N	Longitude	3.5°W
Time defined as	Legal Time	Time zone UT+1	Altitude	582 m
	Albedo	0.20		

Meteo data : Madrid, Synthetic Hourly data

Simulation variant : **Yingly solar facility1**

Simulation date 07/06/16 12h22

Simulation parameters

Collector Plane Orientation	Tilt	33°	Azimuth	0°
Horizon	Free Horizon			
Near Shadings	Linear shadings			

PV Array Characteristics

PV module Si-poly	Model	**YL310P-35b**		
	Manufacturer	Yingli Solar		
Number of PV modules	In series	19 modules	In parallel	12 strings
Total number of PV modules	Nb. modules	228	Unit Nom. Power	310 Wp
Array global power	Nominal (STC)	**70.7 kWp**	At operating cond.	62.7 kWp (50°C)
Array operating characteristics (50°C)	U mpp	629 V	I mpp	100 A
Total area	Module area	**445 m²**	Cell area	400 m²

Inverter	Model	**Sunny Tripower 20000 TLHE**		
	Manufacturer	SMA		
Characteristics	Operating Voltage	320-800 V	Unit Nom. Power	20.0 kW AC
Inverter pack	Number of Inverter	3 units	Total Power	60.0 kW AC

PV Array loss factors

Thermal Loss factor	Uc (const)	27.7 W/m²K	Uv (wind)	0.0 W/m²K / m/s
=> Nominal Oper. Coll. Temp. (G=800 W/m², Tamb=20°C, Wind=1 m/s.)			NOCT	46 °C
Wiring Ohmic Loss	Global array res.	129 mOhm	Loss Fraction	1.8 % at STC
Array Soiling Losses			Loss Fraction	2.0 %
Module Quality Loss			Loss Fraction	0.0 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Parameter	0.05

System loss factors

Wiring Ohmic Loss	Wires	47 m 3x25 mm²	Loss Fraction	1.8 % at STC

User's needs : Ext. defined as file valori.csv

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year	
64146	61848	53976	39580	16726	17394	22074	17544	15914	38682	51108	58278	457270	kWh

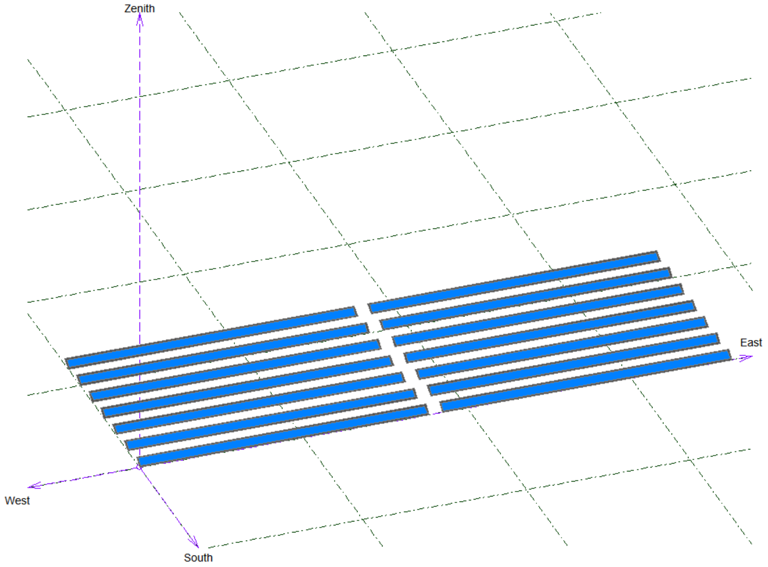
Grid-Connected System: Near shading definition

Project : **Industrial Photovoltaic Implant**

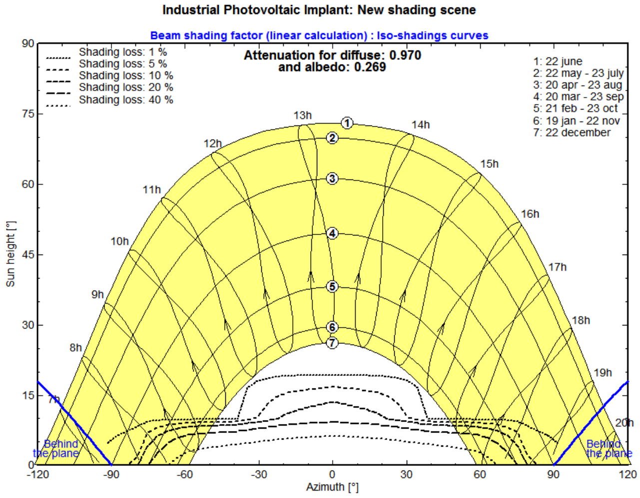
Simulation variant : **Yingly solar facility1**

Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	33°	azimuth	0°
PV modules	Model	YL310P-35b	Pnom	310 Wp
PV Array	Nb. of modules	228	Pnom total	**70.7 kWp**
Inverter	Model	Sunny Tripower 20000 TLHE	Pnom	20.00 kW ac
Inverter pack	Nb. of units	3.0	Pnom total	**60.0 kW ac**
User's needs	Ext. defined as file	valori.csv	global	457 MWh/year

Perspective of the PV-field and surrounding shading scene



Iso-shadings diagram



Grid-Connected System: Main results

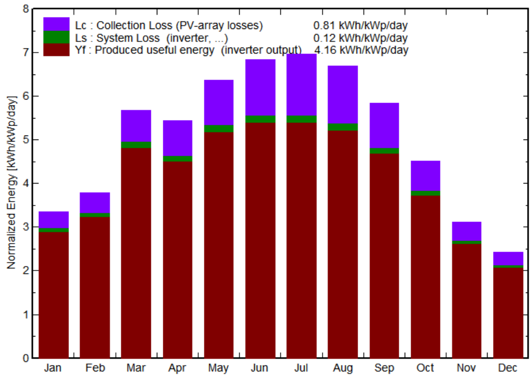
Project : **Industrial Photovoltaic Implant**

Simulation variant : **Yingly solar facility1**

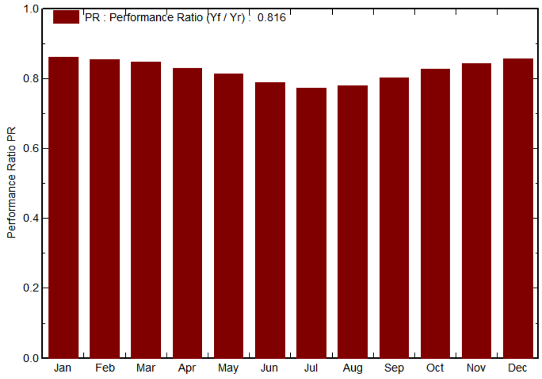
Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	33°	azimuth	0°
PV modules	Model	YL310P-35b	Pnom	310 Wp
PV Array	Nb. of modules	228	Pnom total	**70.7 kWp**
Inverter	Model	Sunny Tripower 20000 TLHE	Pnom	20.00 kW ac
Inverter pack	Nb. of units	3.0	Pnom total	**60.0 kW ac**
User's needs	Ext. defined as file	valori.csv	global	457 MWh/year

Main simulation results				
System Production	**Produced Energy**	**107.3 MWh/year**	Specific prod.	1518 kWh/kWp/year
	Performance Ratio PR	81.6 %	Solar Fraction SF	17.5 %

Normalized productions (per installed kWp): Nominal power 70.7 kWp



Performance Ratio PR



Yingly solar facility1
Balances and main results

	GlobHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E Load MWh	E User MWh	E_Grid MWh
January	66.0	5.50	104.2	98.7	6.53	64.15	6.35	0.002
February	77.0	7.00	106.2	101.1	6.61	61.85	6.42	0.000
March	141.0	9.30	176.1	168.5	10.87	53.98	10.38	0.182
April	153.0	11.60	163.0	154.9	9.85	39.58	8.90	0.665
May	204.0	15.50	197.4	187.7	11.71	16.73	5.70	5.661
June	223.0	20.40	205.3	195.0	11.81	17.39	6.26	5.196
July	230.0	24.30	216.3	205.6	12.19	22.07	6.89	4.939
August	201.0	23.80	207.8	197.7	11.79	17.54	6.66	4.789
September	150.0	20.30	175.5	167.3	10.25	15.91	4.97	4.986
October	105.0	14.50	139.9	133.5	8.44	38.68	7.37	0.831
November	64.0	8.90	93.5	88.2	5.74	51.11	5.53	0.047
December	49.0	5.90	75.0	70.7	4.68	58.28	4.55	0.000
Year	1663.0	13.96	1860.1	1768.8	110.45	457.27	79.98	27.300

Legends:				
	GlobHor	Horizontal global irradiation	EArray	Effective energy at the output of the array
	T Amb	Ambient Temperature	E Load	Energy need of the user (Load)
	GlobInc	Global incident in coll. plane	E User	Energy supplied to the user
	GlobEff	Effective Global, corr. for IAM and shadings	E_Grid	Energy injected into grid

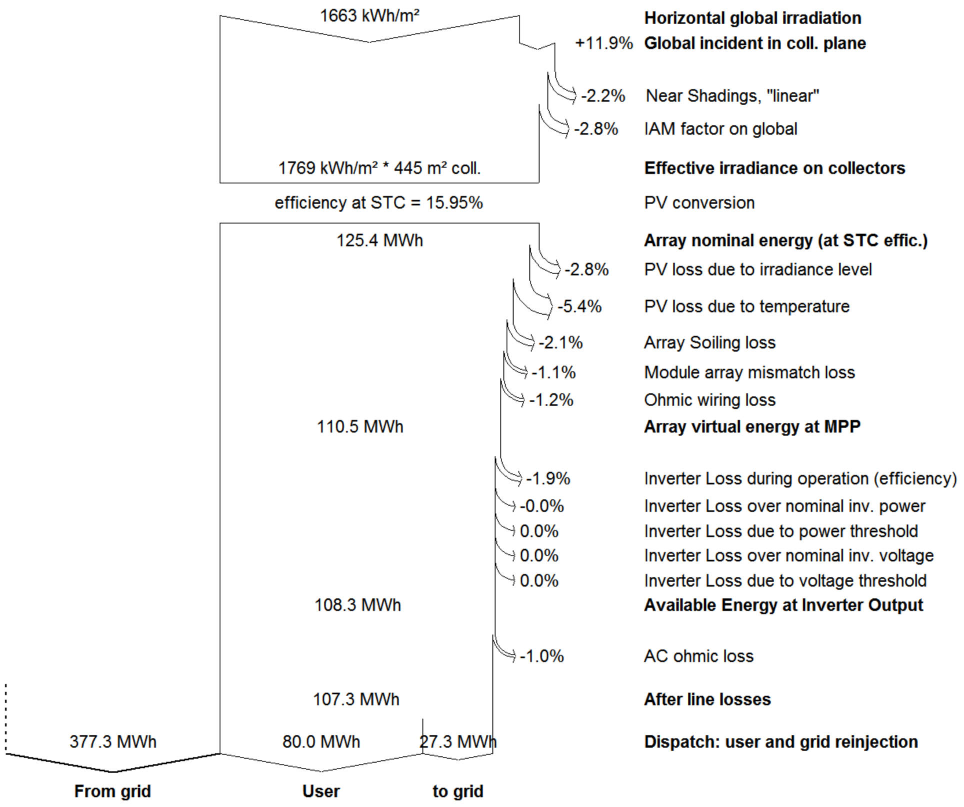
Grid-Connected System: Loss diagram

Project : **Industrial Photovoltaic Implant**

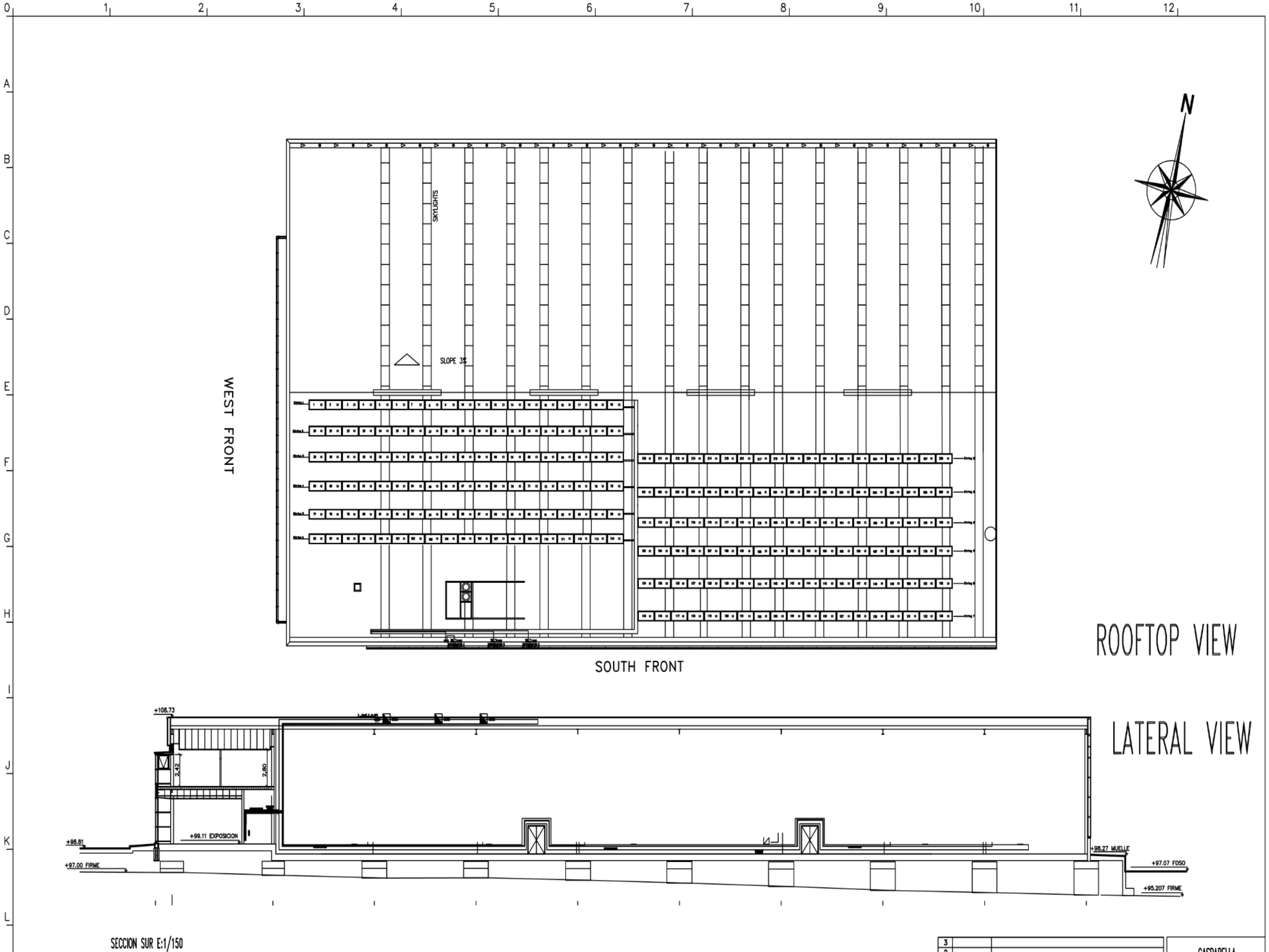
Simulation variant : **Yingly solar facility1**

Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	33°	azimuth	0°
PV modules	Model	YL310P-35b	Pnom	310 Wp
PV Array	Nb. of modules	228	Pnom total	**70.7 kWp**
Inverter	Model	Sunny Tripower 20000 TLHE	Pnom	20.00 kW ac
Inverter pack	Nb. of units	3.0	Pnom total	**60.0 kW ac**
User's needs	Ext. defined as file	valori.csv	global	457 MWh/year

Loss diagram over the whole year



ANNEX B: AUTOCAD PLANES



REV.	DATE	DESCRIPTION
3		
2		
1		
0		

ROOFTOP - PV ARRAY

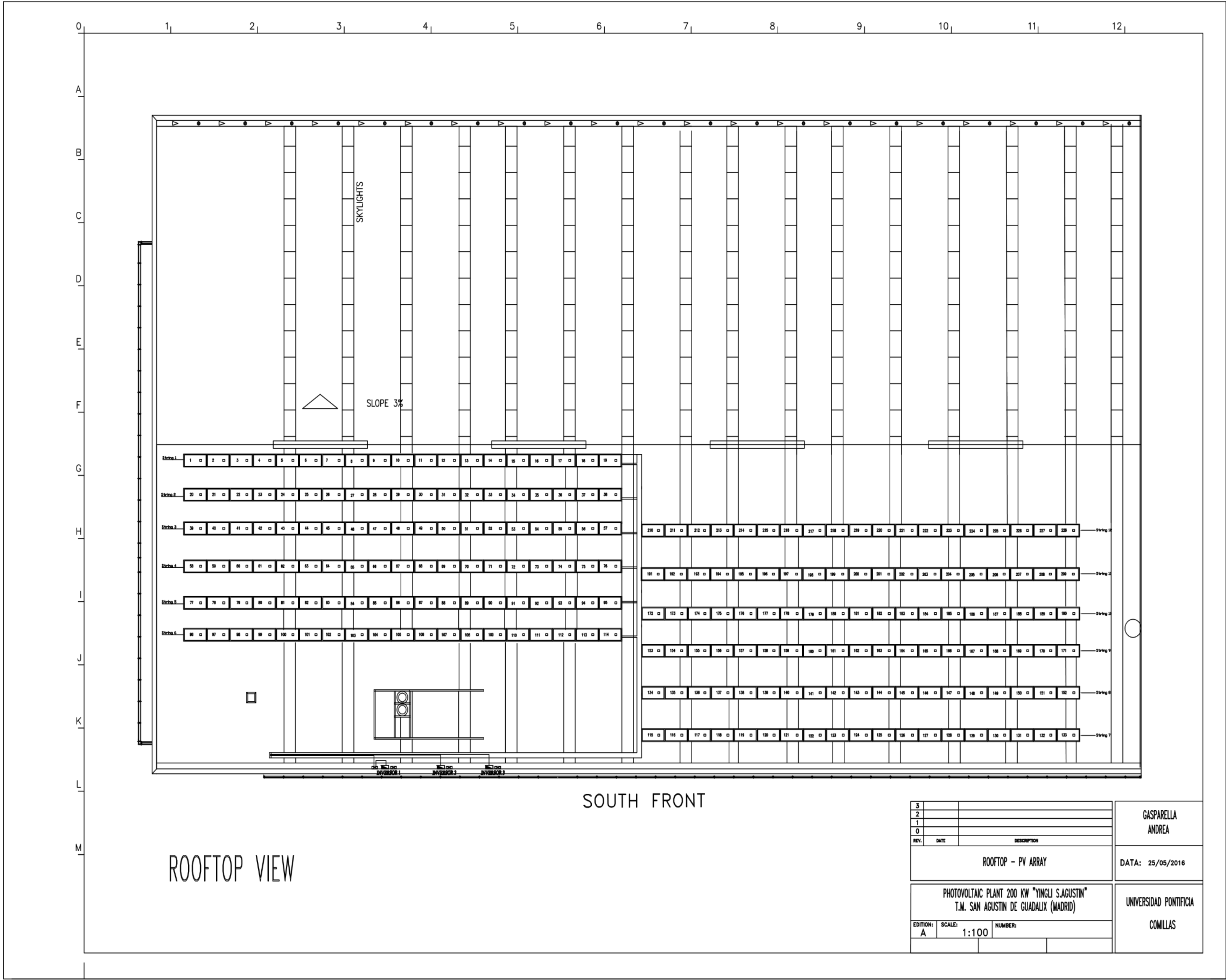
PHOTOVOLTAIC PLANT 200 KW "YINGLI S.AGUSTIN"
T.M. SAN AGUSTIN DE GUADALIX (MADRID)

EDITION: A
SCALE: 1:100
NUMBER:

GASPARELLA
ANDREA

DATA: 25/05/2016

UNIVERSIDAD PONTIFICIA
COMILLAS



REV.	DATE	DESCRIPTION
3		
2		
1		
0		

ROOFTOP - PV ARRAY

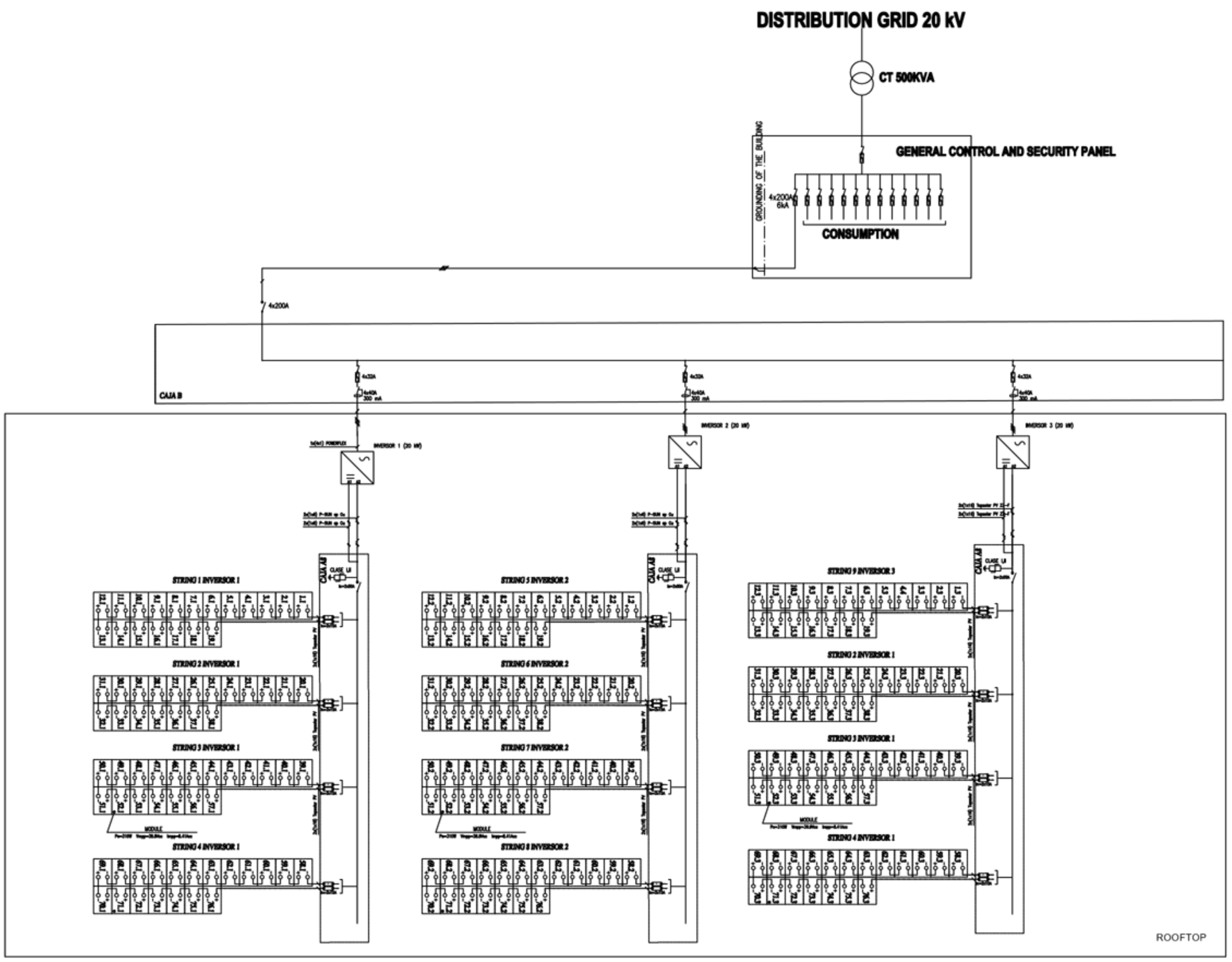
GASPARELLA
ANDREA

DATA: 25/05/2016

PHOTOVOLTAIC PLANT 200 KW "YINGLI S.AGUSTIN"
T.M. SAN AGUSTIN DE GUADALIX (MADRID)

EDITION: A
SCALE: 1:100
NUMBER:

UNIVERSIDAD PONTIFICIA
COMILLAS



DATA:

SINGLE LINE DIAGRAM ROOFTOP

GASPARELLA ANDREA

DATE: 25/05/2016

PHOTOVOLTAIC PLANT 60 KW "YINGLI S.AGUSTIN"
T.M. SAN AGUSTIN DE GUADALIX (MADRID)

UNIVERSIDAD PONTIFICIA COMILLAS

EDITION: A
SCALE: S/E

ANNEX C: EQUIPMENT TECHNICAL CATALOGUES

YGE 72 Cell NH SERIES

Powered by YINGLI

YL310P-35b
YL305P-35b
YL300P-35b
YL295P-35b
YL290P-35b
YL285P-35b
YL280P-35b

ABOUT YINGLI GREEN ENERGY

Yingli Green Energy Holding Company Limited (NYSE: YGE) is one of the world's largest fully vertically integrated PV manufacturers, which markets its products under the brand "Yingli Solar". With over 4.5GW of modules installed globally, we are a leading solar energy company built upon proven product reliability and sustainable performance. We are the first renewable energy company and the first Chinese company to sponsor the FIFA World Cup™.

PERFORMANCE

- High efficiency, multicrystalline silicon solar cells with high transmission and textured glass deliver a module efficiency of up to 16.2%, minimizing installation costs and maximizing the kWh output of your system per unit area.
- Tight positive power tolerance of 0W to +5W ensures you receive modules at or above nameplate power and contributes to minimizing module mismatch losses leading to improved system yield.
- Top ranking in the "TÜV Rheinland Energy Yield Test" and the "PHOTON Test" demonstrates high performance and annual energy production.

RELIABILITY

- Tests by independent laboratories prove that Yingli Solar modules:
  - ✓ Fully conform to certification and regulatory standards.
  - ✓ Withstand wind loads of up to 2.4kPa and snow loads of up to 5.4kPa, confirming mechanical stability.
  - ✓ Successfully endure ammonia and salt-mist exposure at the highest severity level, ensuring their performance in adverse conditions.
- Manufacturing facility certified by TÜV Rheinland to ISO 9001:2008, ISO 14001:2004 and BS OHSAS 18001:2007.

WARRANTIES

- 10-year limited product warranty[1].
- Limited power warranty[1]: 10 years at 91.2% of the minimal rated power output, 25 years at 80.7% of the minimal rated power output.

[1] In compliance with our Warranty Terms and Conditions

QUALIFICATIONS & CERTIFICATES

IEC 61215, IEC 61730, MCS, CE, ISO 9001:2008, ISO 14001:2004, BS OHSAS 18001:2007, SA 8000, PV Cycle

YINGLISOLAR.COM

YGE 72 Cell NH SERIES

ELECTRICAL PERFORMANCE

Electrical parameters at Standard Test Conditions (STC)

Module type			YLxxxP-35b (xxx=P_{max})						
Power output	P_{max}	W	310	305	300	295	290	285	280
Power output tolerances	ΔP_{max}	W	0 / 5						
Module efficiency	η_m	%	15.9	15.6	15.4	15.1	14.9	14.6	14.4
Voltage at P_{max}	V_{mpp}	V	36.9	37.0	36.7	36.3	35.8	35.5	35.5
Current at P_{max}	I_{mpp}	A	8.41	8.25	8.17	8.12	8.10	8.02	7.89
Open-circuit voltage	V_{oc}	V	46.4	46.3	46.3	45.4	45.3	45.0	45.0
Short-circuit current	I_{sc}	A	8.98	8.87	8.77	8.63	8.62	8.50	8.35

STC: 1000W/m² irradiance, 25°C module temperature, AM1.5g spectrum according to EN 60904-3.
Average relative efficiency reduction of 5% at 200W/m² according to EN 60904-1.

Electrical parameters at Nominal Operating Cell Temperature (NOCT)

Power output	P_{max}	W	224.6	220.9	217.3	214.2	210.6	207.0	203.3
Voltage at P_{max}	V_{mpp}	V	33.5	33.6	33.4	32.7	32.3	32.0	32.0
Current at P_{max}	I_{mpp}	A	6.70	6.57	6.51	6.55	6.53	6.46	6.36
Open-circuit voltage	V_{oc}	V	42.8	42.7	42.7	41.4	41.3	41.1	41.1
Short-circuit current	I_{sc}	A	7.27	7.19	7.10	6.99	6.98	6.89	6.76

NOCT: open-circuit module operation temperature at 800W/m² irradiance, 20°C ambient temperature, 1m/s wind speed.

THERMAL CHARACTERISTICS

Nominal operating cell temperature	NOCT	°C	46 +/- 2
Temperature coefficient of P_{max}	γ	%/°C	-0.45
Temperature coefficient of V_{oc}	β_{Voc}	%/°C	-0.33
Temperature coefficient of I_{sc}	α_{Isc}	%/°C	0.06
Temperature coefficient of V_{mpp}	β_{Vmpp}	%/°C	-0.45

OPERATING CONDITIONS

Max. system voltage	$1000V_{DC}$
Max. series fuse rating	15A
Limiting reverse current	15A
Operating temperature range	-40°C to 85°C
Max. static load, front (e.g., snow and wind)	5400Pa
Max. static load, back (e.g., wind)	2400Pa
Max. hailstone impact (diameter / velocity)	25mm / 23m/s

CONSTRUCTION MATERIALS

Front cover (material / thickness)	low-iron tempered glass / 4.0mm
Cell (quantity / material / dimensions / number of busbars)	72 / multicrystalline silicon / 156mm x 156mm / 2 or 3
Encapsulant (material)	ethylene vinyl acetate (EVA)
Frame (material / color / anodization color / edge sealing)	anodized aluminum alloy / silver / clear / silicone or tape
Junction box (protection degree)	≥ IP65
Cable (length / cross-sectional area)	1200 mm / 4mm²
Plug connector (type / protection degree)	MC4 / IP67 or YT08-1 / IP67 or Amphenol H4 / IP68

- Due to continuous innovation, research and product improvement, the specifications in this product information sheet are subject to change without prior notice. The specifications may deviate slightly and are not guaranteed.
- The data do not refer to a single module and they are not part of the offer, they only serve for comparison to different module types.

Yingli Green Energy Holding Co. Ltd.
service@yinglisolar.com
Tel: 0086-312-8929802

YINGLISOLAR.COM

| DS_YGE72Cell-35b_NH_EU_EN_201211_v02.20

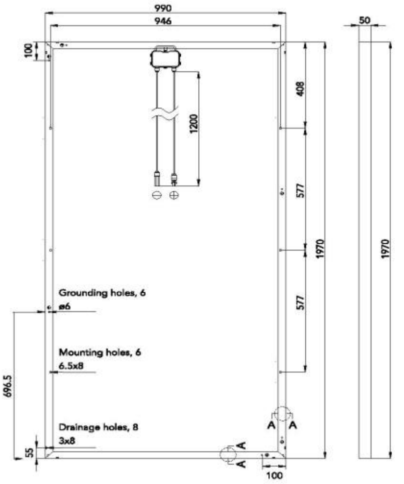
GENERAL CHARACTERISTICS

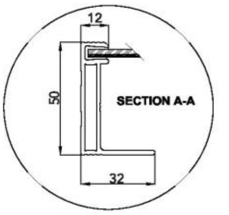
Dimensions (L / W / H)	1970mm / 990mm / 50mm
Weight	26.8kg

PACKAGING SPECIFICATIONS

Number of modules per pallet	21
Number of pallets per 40' container	24
Packaging box dimensions (L / W / H)	1990mm / 1130mm / 1170mm
Box weight	613kg

Unit: mm





Warning: Read the Installation and User Manual in its entirety before handling, installing, and operating Yingli Solar modules.

Our Partners:

SUNNY TRIPOWER 20000TL / 25000TL

Efficient

- Maximum efficiency of 98.4%

Safe

- DC surge arrester (SPD type II) can be integrated

Flexible

- DC input voltage of up to 1000 V
- Multistring capability for optimum system design
- Optional display

Innovative

- Cutting-edge grid management functions with Integrated Plant Control
- Reactive power available 24/7 (Q on Demand 24/7)

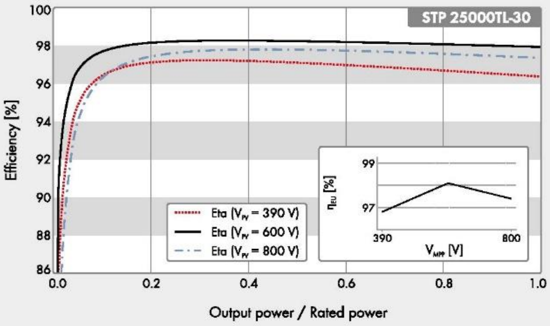
SUNNY TRIPOWER 20000TL / 25000TL

The versatile specialist for large-scale commercial plants and solar power plants

The Sunny Tripower 20000TL/25000TL is the ideal inverter for large-scale commercial and industrial plants. Not only does it deliver extraordinary high yields with an efficiency of 98.4%, but it also offers enormous design flexibility and compatibility with many PV modules thanks to its multistring capabilities and wide input voltage range.

The future is now: the Sunny Tripower 20000TL/25000TL comes with cutting-edge grid management functions such as Integrated Plant Control, which allows the inverter to regulate reactive power at the point of common coupling. Separate controllers are no longer needed, lowering system costs. Another new feature—reactive power provision on demand (Q on Demand 24/7).

Efficiency curve



Accessories

RS485 interface
DM-485CB-10

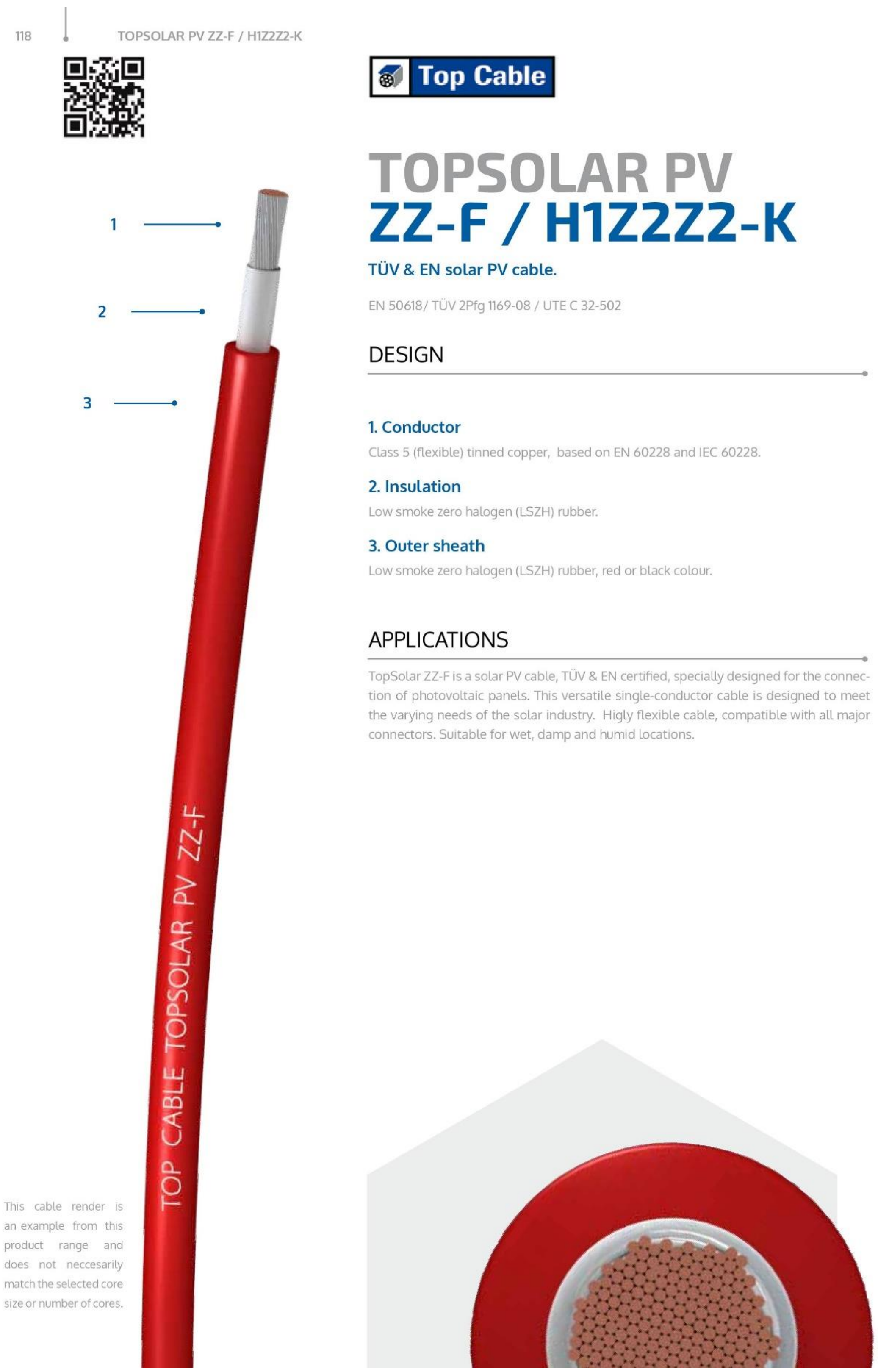
Power Controle Module
PWCMOD-10

DC surge arrester (Type II), inputs A and B DCSPD
KIT3-10

Multifunction relay
MFR01-10

● Standard features ○ Optional features – Not available
Data at nominal conditions
State: January 2016

Technical Data	Sunny Tripower 20000TL	Sunny Tripower 25000TL
Input (DC)		
Max. DC power (at cos φ = 1) / DC rated power	20440 W / 20440 W	25550 W / 25550 W
Max. input voltage	1000 V	1000 V
MPP voltage range / rated input voltage	320 V to 800 V / 600 V	390 V to 800 V / 600 V
Min. input voltage / start input voltage	150 V / 188 V	150 V / 188 V
Max. input current input A / input B	33 A / 33 A	33 A / 33 A
Number of independent MPP inputs / strings per MPP input	2 / A:3; B:3	2 / A:3; B:3
Output (AC)		
Rated power (at 230 V, 50 Hz)	20000 W	25000 W
Max. AC apparent power	20000 VA	25000 VA
AC nominal voltage	3 / N / PE; 220 V / 380 V 3 / N / PE; 230 V / 400 V 3 / N / PE; 240 V / 415 V	
AC voltage range	180 V to 280 V	
AC grid frequency / range	50 Hz / 44 Hz to 55 Hz 60 Hz / 54 Hz to 65 Hz	
Rated power frequency / rated grid voltage	50 Hz / 230 V	
Max. output current / Rated output current	29 A / 29 A	36.2 A / 36.2 A
Power factor at rated power / Adjustable displacement power factor	1 / 0 overexcited to 0 underexcited	
THD	≤ 3 %	
Feed-in phases / connection phases	3 / 3	
Efficiency		
Max. efficiency / European Efficiency	98.4% / 98.0%	98.3% / 98.1%
Protective devices		
DC-side disconnection device	●	
Ground fault monitoring / grid monitoring	● / ●	
DC surge arrester (Type II) can be integrated	○	
DC reverse polarity protection / AC short-circuit current capability / galvanically isolated	● / ● / –	
All-pole sensitive residual-current monitoring unit	●	
Protection class (according to IEC 62109-1) / overvoltage category (according to IEC 62109-1)	I / AC: III; DC: II	
General data		
Dimensions (W / H / D)	661 / 682 / 264 mm (26.0 / 26.9 / 10.4 inch)	
Weight	61 kg (134.48 lb)	
Operating temperature range	−25 °C to +60 °C (−13 °F to +140 °F)	
Noise emission (typical)	51 dB(A)	
Self-consumption (at night)	1 W	
Topology / cooling concept	Transformerless / Opticool	
Degree of protection (as per IEC 60529)	IP65	
Climatic category (according to IEC 60721-3-4)	4K4H	
Maximum permissible value for relative humidity (non-condensing)	100%	
Features / function / Accessories		
DC connection / AC connection	SUNCLIX / spring-cage terminal	
Display	○	
Interface: RS485, Speedwire/Webconnect	○ / ●	
Data interface: SMA Modbus / SunSpec Modbus	● / ●	
Multifunction relay / Power Control Module	○ / ○	
OptiTrack Global Peak / Integrated Plant Control / Q on Demand 24/7	● / ● / ●	
Off-Grid capable / SMA Fuel Save Controller compatible	● / ●	
Guarantee: 5 / 10 / 15 / 20 / 25 years	● / ○ / ○ / ○ / ○	
Certificates and permits (more available on request) * Does not apply to all national appendices of EN 50438	ANRE 30, AS 4777, BDEW 2008, C10/11:2012, CE, CEI 0-16, CEI 0-21, EN 50438*, G59/3, IEC 60068-2-x, IEC 61727, IEC 62109-1/2, IEC 62116, MEA 2013, NBR 16149, NEN EN 50438, NRS 097-2-1, PEA 2013, PPC, RD 1699/413, RD 661/2007, Res. n°7:2013, SI4777, UTE C15-712-1, VDE 0126-1-1, VDE-AR-N 4105, VFR 2014	
Type designation	STP 20000TL-30	STP 25000TL-30



Top Cable

TOPSOLAR PV ZZ-F / H1Z2Z2-K

TÜV & EN solar PV cable.

EN 50618/ TÜV 2Pfg 1169-08 / UTE C 32-502

DESIGN

1. Conductor

Class 5 (flexible) tinned copper, based on EN 60228 and IEC 60228.

2. Insulation

Low smoke zero halogen (LSZH) rubber.

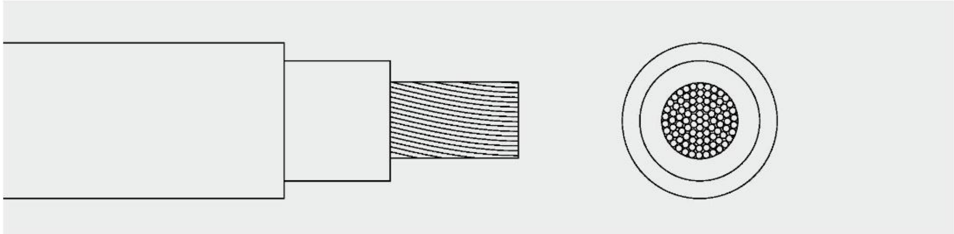
3. Outer sheath

Low smoke zero halogen (LSZH) rubber, red or black colour.

APPLICATIONS

TopSolar ZZ-F is a solar PV cable, TÜV & EN certified, specially designed for the connection of photovoltaic panels. This versatile single-conductor cable is designed to meet the varying needs of the solar industry. Higly flexible cable, compatible with all major connectors. Suitable for wet, damp and humid locations.

This cable render is an example from this product range and does not neccesarily match the selected core size or number of cores.



CHARACTERISTICS

Electrical performance

LOW VOLTAGE 1,5/1,5 1kV · (1,8) kV

Standard

EN 50618/ TÜV 2Pfg 1169-08 / UTE C 32-502

Approvals

CE
TÜV
EN
RoHS

Thermal performance

Maximum service temperature: 120°C.
Maximum short-circuit temperature: 250°C (max. 5 s).
Minimum service temperature: -40°C.

Fire performance

Flame non-propagation based on UNE-EN 60332-1 and IEC 60332-1.
LSZH (Low Smoke Zero Halogen) based on UNE-EN 60754-1 and IEC 60754-1.
Low smoke emission based on UNE-EN 61034 and IEC 61034: Light transmittance > 60%
Low corrosive gases emission based on UNE-EN 60754-2 and IEC 60754-2.

Mechanical performance

Minimum bending radius: x3 cable diameter.
Impact resistance: AG2 Medium severity.

Chemical performance

Chemical & Oil resistance: Excellent.
Grease & mineral oils resistance: Excellent.

UV Resistant

UV Resistant based on EN 50618 and TÜV 2Pfg 1169-08.

Water performance

Water presence: AD8 submerged.

Estimated Lifetime

Estimated lifetime 30 years based on UNE-EN 60216-2.

Other

Meter by meter marking.

Installation conditions

Open Air.
Buried.

Applications

Solar PV installations.

Top Cable

POWERFLEX RV-K

Cable flexible de potencia para uso industrial.

IEC 60502-1 - UNE 21123-2

Este render es un ejemplo de las diversas configuraciones de este cable. Puede ser suministrado en diversas secciones y número de conductores.

DISEÑO

1. Conductor

Cobre electrolítico, clase 5 (flexible) según UNE-EN 60228 e IEC 60228

2. Aislamiento

Polietileno reticulado (XLPE).

La identificación normalizada de los conductores aislados es la siguiente:

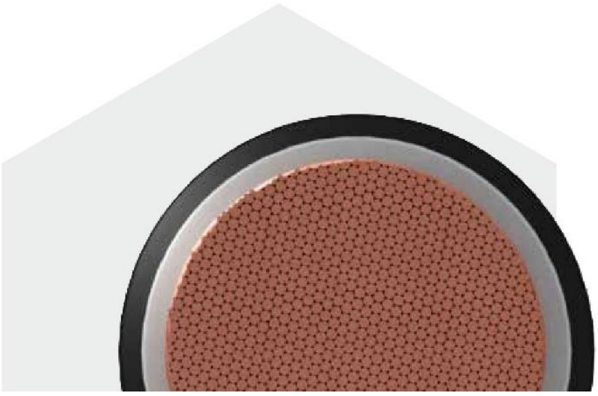
1 x	Natural
2 x	Azul + Marrón
3 G	Azul + Marrón + Amarillo/Verde
3 x	Marrón + Negro + Gris
3 x + 1 x	Marrón + Negro + Gris + Azul (sección reducida)
4 G	Marrón + Negro + Gris + Amarillo/Verde
4 x	Marrón + Negro + Gris + Azul
5 G	Marrón + Negro + Gris + Azul + Amarillo/Verde

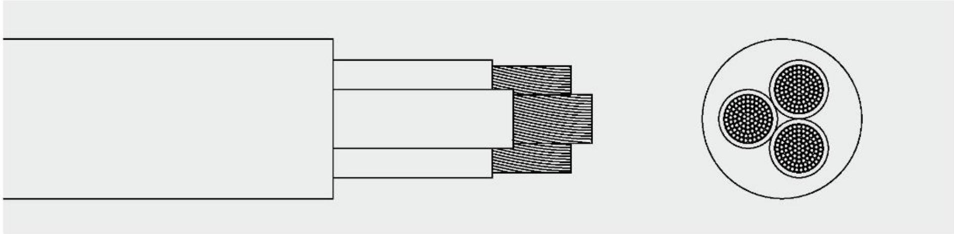
3. Cubierta

PVC flexible de color negro.

APLICACIONES

El cable Powerflex RV-K es un cable flexible de potencia diseñado para satisfacer los requisitos industriales más exigentes: conexiones industriales de baja tensión, redes urbanas, instalaciones en edificios, etc. Su flexibilidad lo hace particularmente adecuado en trazados difíciles. Gracias al diseño de sus materiales, puede ser instalado en todo tipo de condiciones ambientales: zonas húmedas y secas, instalación al aire libre, enterrado, e incluso sumergido en agua (AD7), sin que perjudique la vida útil del cable.





CARACTERÍSTICAS

Características eléctricas

BAJA TENSIÓN 0,6/1kV

Norma de referencia

IEC 60502-1 - UNE 21123-2

ITC y certificaciones

ITC: 9/20/30/31

Certificados:

- CE
- SEC
- BUREAU VERITAS
- AENOR
- RoHS

Características térmicas

Temp. máxima del conductor: 90°C.
Temp. máxima en cortocircuito: 250°C (máximo 5 s)
Temp. mínima de servicio:-40°C
(estático con protección).

Características frente al fuego

No propagación de la llama según UNE-EN 60332-1 e IEC 60332-1.
Reducida emisión de halógenos.Cloro < 15%.

Características mecánicas

Radio de curvatura: 5 x diámetro exterior
Resistencia a los impactos: AG2 Medio

Características químicas

Resistencia a los ataques químicos: Buena
Resistencia a los rayos ultravioleta: UNE 211605.

Presencia de agua

Presencia de agua: AD7 Inmersión

Otros

Marcaje: metro a metro

Condiciones de instalación

Al aire.
Enterrado.
Entubado.

Aplicaciones

Uso industrial
Alumbrado exterior.

Embalaje

Disponible en rollos de 100m -con film retractilado- y bobinas.

Top Cable

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