UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

OFFICIAL MASTER'S DEGREE IN THE
ELECTRIC POWER INDUSTRY

Master's Thesis

From a Hybrid Configuration to an Optimal PV-Only System: A Techno-Economic Analysis Under Spanish Energy Regulation

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Madrid, July 2026

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PROJECT SUMMARY

Decarbonizing the energy sector and rising trends of residential self-consumption have increased the relevance of distributed renewable energy solutions. Among the most promising options are hybrid photovoltaic and wind power systems, based on the complementariness of solar and wind energy generation. Nonetheless, the performance of such solutions highly depends on the climatic conditions, the nature of electricity consumption in the studied location and the self-consumption policy of the state concerned.

The goal of the present thesis is to conduct a techno-economic evaluation of potential energy solutions for a rural dwelling in northern Spain. Specifically, various combinations of photovoltaics, small wind generation and battery storage systems will be investigated, taking into account the current regulations of the self-consumption market in Spain. The methodology includes preliminary assessment of renewable energy generation potential using data from PVGIS and OpenWindMap databases. Subsequently, detailed modeling of the energy solution through PVsyst software followed by system configuration optimization via HOMER Pro will be conducted.

The initial task involved the design and validation of the photovoltaic system in the selected area using PVsyst. As a result, the performance of the solar panels has been deemed appropriate for the selected area, and a subsequent techno-economic evaluation via HOMER Pro can be considered valid. Several combinations of solar and wind generation were assessed and compared in terms of energy output, share of renewables, interaction with the energy grid and economic indicators. Moreover, an analysis of the potential economic benefits of battery storage was performed for each type of generation under analysis.

Scenario	**LCOE (€/kWh)**	**NPC (€)**	**PV production (kWh/yr)**	**Wind production (kWh/yr)**	**Grid import (kWh/yr)**	**Renewable fraction (%)**
PV-only	0.0727	7255	5195	0	1536	52.30
Wind-only	0.22	9866.36	0	0	2847	0
Hybrid	0.0727	7255	5195	0	1536	52.30
PV+Battery (On-grid)	0.0727	7255	5195	0	1536	52.30
PV + Battery (Off-grid)	NO FEASIBLE SOLUTION					

Table 1: Simulation results for different scenarios.

As shown by the results obtained in this thesis, despite the obvious theoretical advantages of hybrid renewable solutions, the best possible scenario for the chosen location is a photovoltaic grid-connected energy system. The local climate does not seem to be favourable for small wind generation, since installing a small wind turbine would not be economically feasible at the selected location. Similarly, a battery storage device would only bring marginal benefits when used with the selected type of generation. The most profitable energy solution achieves high levels of renewable contribution, substantially reduces imports of electricity and shows good economic performance.

Moreover, a separate economic evaluation of the photovoltaic solution was performed via calculating NPV, ROI and payback period, showing that the project brings significant economic benefit. Sensitivity analysis, performed by changing input parameters, confirms that this solution will remain profitable even under varying assumptions regarding future development of electricity price, investment cost changes and renewable energy uncertainty.

Finally, the impact of the Spanish regulatory regime on distributed renewable energy generation systems' optimization was investigated. Special attention was paid to self-consumption policies, alternative energy surcharge systems and related administrative obstacles. This thesis concludes that the regulatory regime affects the efficiency of distributed energy systems significantly, and maximizing the level of self-consumption proves to be more profitable than energy surplus production.

Therefore, the optimal design of residential energy systems should involve consideration of multiple factors, including technical, economic and regulatory ones..

KEY WORDS

Photovoltaic energy; Hybrid renewable systems; Self-consumption; HOMER Pro; PVsyst; Techno-economic analysis; Distributed generation; Spanish energy regulation.

INDEX OF THE MEMORY

INDEX OF FIGURES

INDEX OF TABLES

Chapter 1. INTRODUCTION

1.1 BACKGROUND

As regards the sector of electricity generation from renewables, the industry experiences an ongoing process of transition, triggered by scientific findings related to limiting climate change, threats to energy security, as well as the speed at which our economy is transitioning towards sustainable sources of energy. Nevertheless, the implementation of renewable energy technologies was initiated due to rising concern about the impact on climate change and energy insecurity caused by reliance on fossil fuel sources. Within this context, distributed renewable generation is among the main components of modern power systems which provide consumers with an opportunity to produce their own electricity and become involved in electricity generation through a minimum number of centralized fossil-fuel-based generating units.

There is no doubt that such renewable technologies as photovoltaic (PV) energy experience a rapid development nowadays due to constantly declining installation costs, improving module efficiency, as well as simplicity of integration into residential settings. Wind power has also become a very mature form of renewable energy technology, which is especially true in those areas where winds are favourable. Combining wind and photovoltaic systems within hybrid renewable energy systems appears to be rather appealing due to the potential complementarity of energy generation patterns provided by these sources. Thus, they can generate complementary seasonal and daily generation patterns.

Nevertheless, there exist a significant number of factors that can influence the technical and economic performance of a hybrid renewable system at a certain site. It goes without saying that in some cases, the possible advantages of the mentioned solution will not justify its implementation in the face of higher expenses and greater complexity. This fact means that it should not automatically assume superiority of hybrids over single-technology energy systems; on the contrary, a thorough examination of a specific situation is required. In the context of Spain, the adoption of RD 244/2019 [1] establishes a much more positive attitude towards residential renewable generation, including photovoltaics and wind power installations, as well as their self-consumption. At the same time, the growing price of electricity and rising concerns about energy independence make PV or wind generation installations even more attractive for residents. However, this scenario comes with certain restrictions.

1.2 MOTIVATION

This thesis is motivated by the increased necessity to analyse renewable energy systems not only theoretically, but also from the practical and engineering point of view. Even though hybrid systems are commonly seen as more technically efficient in regard to the complementarity between photovoltaic and wind sources of energy, the implementation and performance of a specific configuration can strongly depend on location-related environmental, economic and regulatory factors. Recently, there has been a significant rise in residential self-consumption in Spain caused by high cost of electricity and favourable regulations that were introduced in Royal Decree 244/2019. In spite of that, the fast deployment of photovoltaic systems did not facilitate an understanding of the actual benefit of integrating complementary technologies (such as small-scale wind generators) and storing surplus energy in batteries.

From an engineering point of view, one can say that hybrid photovoltaic-wind systems seem to be attractive since solar and wind energies can compensate each other temporally. The former will be produced in the daytime and summer months and the latter, at night and during winter months. This aspect made many authors suggest using hybrid systems as a way to increase renewables penetration and make houses less dependent on energy from the grid. However, even though there is no doubt about the possibility of complementarity between wind and photovoltaic sources, their relative efficiency will depend significantly on the actual weather conditions in particular region. Wind turbines may not generate enough electricity to be financially effective if there is not enough wind in the area.

There is another very important reason why it is necessary to consider the relationship between renewable systems design and regulations of the region. The mechanism of compensation in Spain, which is currently applied for self-consumption installations, leads to certain economic disadvantage of exporting energy compared to consuming it in the same premises. This regulation has a direct effect on the design of the optimal system. It becomes clear that in order to optimize the energy system from the economic perspective, it is necessary to take these regulations into account.

One more interesting thing about the particular case chosen for this thesis investigation is that the dwelling in question is connected to the electricity network and its location offers sufficient roof surface for integration of photovoltaic panels as well as the possibility of installing a wind generator on-site. These factors enable the analysis of several variants of a renewable system configuration and studying how they interact with each other and how the energy produced can be used both by the household itself and sold to the network company.

Moreover, this study is motivated by the necessity to develop an approach to the creation of resilient and economically efficient decentralized renewable energy systems. Even though large-scale renewable power plants are crucial in regard to the decarbonization of the country, self-consumption systems are essential from the point of view of decreasing energy losses during transportation, decentralization of energy production and active involvement of consumers in the energy transition process.

Finally, this thesis is motivated by the fact that an advanced engineering methodology should be applied in the process of analysing renewable energy generation. For this purpose, the tools and datasets PVGIS, OpenWindMap, ERA5, PVsyst and HOMER Pro were utilized in this research.

1.3 OBJECTIVES AND SCOPE

The principal objective is to determine the optimal renewable energy configuration for a grid-connected rural dwelling in northern Spain through a techno-economic analysis of the optimal system under the current Spanish self-consumption regulatory framework.

The specific objectives and corresponding tasks that will be carried out to achieve this are outlined below.

Objective O1. Evaluate and compare renewable system configurations for a grid-connected rural dwelling under real resource conditions

Task 1.1. Characterization of the solar and wind resources at the selected location using meteorological databases and hourly datasets.

Task 1.2. Estimation and characterization of the dwelling's electrical demand.

Task 1.3. Technical sizing of the photovoltaic and wind subsystems.

Task 1.4. Simulation and comparative analysis of different system configurations under grid-connected operation.

Task 1.5. Identification of the technically optimal configuration based on energy performance, renewable penetration and grid interaction.

Objective O2. Assess the techno-economic viability of distributed renewable generation systems under Spanish self-consumption conditions

Task 2.1. Development of the economic model for the analysed configurations.

Task 2.2. Calculation and comparison of key techno-economic indicators.

Task 2.3. Evaluation of the economic impact of surplus compensation mechanisms and grid interaction.

Task 2.4. Sensitivity analysis considering electricity prices, investment costs and renewable resource variability.

Objective O3. Analyse the influence of the Spanish regulatory and market framework on the feasibility of residential renewable systems

Task 3.1. Review of the Spanish regulatory framework applicable to residential self-consumption systems.

Task 3.2. Analysis of grid access conditions, simplified compensation mechanisms and surplus energy management.

Task 3.3. Evaluation of subsidies, incentives and support programs applicable to distributed generation.

Task 3.4. Assessment of administrative, technical and market barriers affecting implementation feasibility.

1.4 STRUCTURE OF THE REPORT

The structure of the thesis consists of eleven chapters which develop all the aspects related to the technical, economic and legal analysis in order to identify the best combination of renewable energy sources for the selected case study.

Chapter 1 contains information about the energy transition and the reasons why such a transition needs to be analysed. It also explains the aim of the thesis and its scope.

Chapter 2 includes a description of the literature review and state of the art related to photovoltaic energy, small-scale wind energy technologies and hybrid renewable energy systems applied mainly for residential self-consumption purposes.

Chapter 3 describes the regulation in the field of distributed generation and grid-connected self-consumption in Spain. Information related to grid access, the costs associated with grid connection and surplus compensation are presented here.

Chapter 4 describes the case study chosen for the analysis and the methodology followed for characterizing the place where it takes place, estimating the available solar and wind energy resources, determining the amount of electric power consumed and establishing economic assumptions.

Chapter 5 is focused on the technological and engineering design of the systems. First of all, the photovoltaic installation and the small wind turbine are sized and then the configuration of the photovoltaic system is validated using simulations made by PVsyst software.

Chapter 6 describes the process of modelling and optimization developed with the help of HOMER Pro. Several renewable energy configurations are modelled and optimized following some technical and economic criteria.

Chapter 7 analyses the results obtained after running the optimization process described in Chapter 6, studying the behaviour of the optimal system configuration from an energetic point of view, its behaviour regarding electricity grid use and the whole system feasibility.

Chapter 8 analyses the economic performance of the chosen solution calculating its investment cost, operation cost, NPV, ROI, payback period and other indicators.

Chapter 9 studies the sensitivity of the chosen configuration and the main economic indicators to changes in electricity price, investment cost and solar resource availability.

Chapter 10 studies the barriers and the incentives that exist in Spain for residential renewable energy systems. The future scenarios and development potentialities of RES systems are analysed.

Finally, Chapter 11 describes the conclusions of the work, its most important findings and future lines of action.

Chapter 2. LITERATURE REVIEW AND STATE OF THE ART

2.1 PHOTOVOLTAIC ENERGY

Photovoltaic energy (Figure 1) is now a days one of the most established and fastest-growing renewable technologies on a global scale.

Figure 1: Example of a residential photovoltaic solar system.

It is founded on the principle of photovoltaic effect where certain semiconductors convert solar energy into electrical energy through a process known as excitation of electrons from the valence to the conduction band [2]. If a photon has enough energy to interact with a photovoltaic cell, it gives off its energy to the electron, which moves up from the valence to the conduction band. The creation of a p-n junction allows the buildup of a voltage difference due to the separation of the generated positive holes and electrons by the presence of an electric field. Compared to other technologies, photovoltaics provides a unique ability to convert radiant energy directly to electrical energy without moving parts.

Technologically, there has been constant evolution in terms of the improvement of efficiency of conversion and substantial reduction in costs per Watt installed. From having been used only in the space sector initially, photovoltaics has gone a long way to be able to be utilized both on a small scale in distributed generation and large scale in utility-scale plants and isolated systems. At present, the leading technology is crystalline silicon which dominates the worldwide module manufacture. In the category of crystalline silicon modules, monocrystalline silicon has almost taken over from polycrystalline silicon because of superior performance characteristics. Figure 2 below shows the difference in appearance between the two types.

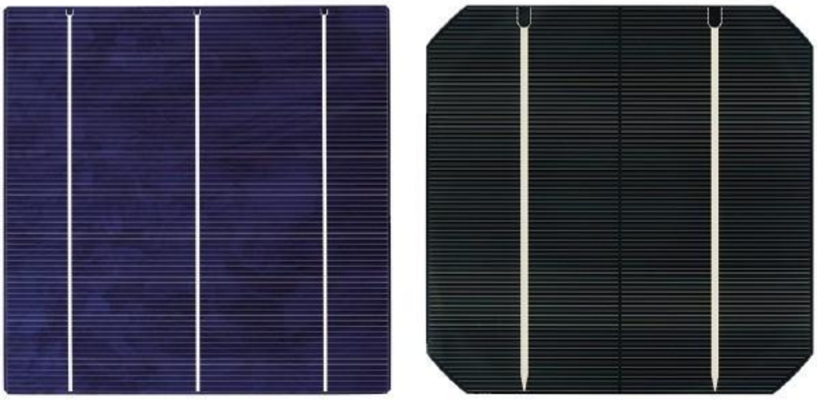

Figure 2: Difference in appearance between polycrystalline and monocrystalline silicon cells.

According to [3], innovations in crystalline silicon cells have been mainly aimed at improving the use of light through increased efficiency and reduced recombination. With the use of rear-passivated structures such as PERC architecture, internal reflections were maximized, as well as the reduction of recombination losses. After these, further efficiency increases through improved contacts (TOPCon and HJT technologies) have been made possible due to the improvement of contact passivation and resistivity. At present, such cell configurations represent the best technology on the market in terms of high-performance capabilities and reliability. The trends towards large-size cells, half-cells, multi-busbar design also reflect attempts to minimize electrical losses and improve current distribution.

In parallel, thin film technologies [4] remain relevant in some segments. Among the advantages of cadmium telluride solar panels are excellent thermodynamic characteristics and higher levels of performance in diffuse light, while CIGS technology was successfully applied in particular applications that require the flexible installation of the module. Despite lower market share compared with traditional crystalline silicon modules, these technologies, shown in Figure 3 below, still have the potential for further development and application. One of the most promising fields in advanced studies is tandem technologies. For instance, the creation of perovskite/silicon tandems aims to overcome the efficiency limit of single-junction cells using several materials with different band gaps. These allow the absorption of light in different ranges of wavelengths. Even though the achieved results in laboratory conditions are quite positive, many technological issues, including the problem of stabilization and encapsulation of such cells, prevent their industrial implementation.

Figure 3: Example of thin-film cells.

External to the cell, the photovoltaic module has seen a lot of advancement in design and materials. The glass-to-glass structure helps increase the robustness of these devices in harsh environmental conditions. Modules known as bifacial modules can collect sunlight both at the front and back sides and can significantly increase electricity output due to their ability to utilize reflected radiation from highly reflective surfaces. Solar tracking using single-axis or dual-axis tracking is increasingly being adopted in large scale power generation facilities due to the ability to maximize electricity generation throughout the day.

Power electronic components form the other crucial component of state-of-the-art photovoltaic modules. In addition to converting the DC to AC electrical output from solar cells, most inverters are equipped with MPPT algorithms which ensure maximum utilization of power under specific irradiance and temperatures. Residential and commercial installations generally rely on string inverters whereas central type inverters are mostly deployed in large scale installations. Inverters are increasingly designed with capabilities to participate in grid stabilization activities including provision of reactive power and voltage regulation capabilities.

Indeed, there is a range of different losses in the real operation of solar panels. As regards thermal losses, it should be pointed out that an increase in the temperature of the cells causes a decrease in their voltage, resulting in lower output energy. There are other types of losses such as those caused by dirt on cells, partial shading, mismatch losses between modules, losses of wiring resistance and conversion losses. It is worth noting that long-term degradation also plays a significant role since it determines the amount of energy produced over the lifetime of the solar panel. This phenomenon involves different mechanisms, among which are those caused by light, temperature, or voltage, as well as aging of encapsulant and structure materials. With the continuous development in materials and production techniques, it became possible to decrease the level of degradation.

It should be noted that recent years have been characterized by the rise of hybrid systems consisting of batteries and photovoltaic panels, which has led to significant changes in operations [5]. Such an approach contributes to an increase in renewable energy usage, as well as to better surplus management and stability in electricity generation. DC or AC coupling architectures can be applied in order to combine batteries and solar panels and the selection of these types of coupling depends on the kind of installation and operational goals.

See more fully in [6].

2.2 WIND ENERGY

Small wind turbines [7], also called mini wind or small wind systems, involve turbines whose capacity is usually below 100 kW and that serve mainly residential consumption purposes, remote rural electrification and hybrid renewable systems. Contrary to big wind systems, mini wind turbines usually work under low hub height, more turbulent environments and uneven wind conditions; factors that affect aerodynamical, structural and electrical designs of mini wind systems.

The technological evolution of small wind turbines includes the maximization of efficiency in low Reynolds numbers, minimization of maintenance costs, improvements in power electronics, as well as integration with photovoltaic cells and batteries.

From a technological viewpoint, the basic classification of mini wind turbines lies on the angle between the shaft and the incident wind flow. The following types can be found, according to [8]:

- <u>Horizontal axis wind turbines</u>

The most popular form of wind turbine is horizontal axis wind turbines (HAWT). Here the shaft of the rotor is parallel to the wind direction; thus, they need a yaw mechanism to ensure that the rotor surface is normal to the flow direction.

They depend mainly on aerodynamic lift force, thereby obtaining higher values of power coefficient compared to other types of turbines. Hence, they have better efficiencies especially for areas with steady winds and average speeds higher than 4-5m/s.

There are two main forms of HAWTs, classified by:

- Position of the rotor either upwind or downwind of the tower.
- Control mechanism used, either stall control or variable pitch.
- Use of permanent magnet synchronous generator, especially for small power stations due to their high efficiencies and lower maintenance costs.

Moreover, it can be seen in Figure 4 an example of a HAWT.

Figure 4: Example of a HAWT.

The operation of the horizontal axis wind turbine illustrated in Figure 4 and Figure 5 involves the use of an energy conversion process, which translates the kinetic energy of the wind to electrical energy. As explained before, the first step in this process involves the reception of the kinetic energy contained in the moving air flow and its transformation into rotational energy using the rotor as the device in charge of capturing the energy of the medium. The rotor is made up of the blades and the hub and the amount of energy captured by them is determined mainly by the swept area and the wind speed, with the last one being the most significant factor due to its relationship with the available power, which is directly proportional to the cube of the speed.

The blades are profiles that are able to produce lift in the presence of wind due to their shape and angle of attack. In this way, a difference in pressure is generated between both sides of the blade, causing the generation of a force with a tangential component that will cause the rotation of the rotor. Some models have the possibility of changing the blade's inclination through pitch control systems, which will optimize the energy capture at different wind speeds.

The hub is the device that physically couples the blades with the drive shaft. It transfers the torque developed by the aerodynamics of the rotor to the drive train. Moreover, in case of the use of active regulation, the hub contains all necessary mechanisms for adjusting the pitch angles of the blades.

The rotational motion produced by the rotor is transferred further to the drive train, which is the mechanical unit intended to drive energy from the low-speed shaft to the generator. Normally, a gear box, increasing the rotational speed of motion, is a part of the drive train in traditional designs of the drive trains. The rotor in the mini generator is driven with a relatively low rotational speed and high torque while the electric generator demands relatively high rotational speed in order to function effectively. This problem is solved by the gear box through gearing. However, most modern generators have eliminated gear boxes due to more efficient performance of direct drive generators.

The generator is the device that converts mechanical energy into electric energy on the basis of electromagnetic induction. As the result of rotation, a change in magnetic flux in the stator causes electric current induction. Small wind generators use permanent magnet synchronous generators that are known to be quite efficient and simple as electric machines.

All these mechanical and electrical components are enclosed inside the nacelle, which serves as a casing against harsh environmental elements. There are also other systems like mechanical brakes, speed sensors and controllers included in the nacelle to assure that these systems work in a safe way.

Lastly, the tower holds the rotor-nacelle system at some level from the ground. Its primary purpose is to position the wind turbine in such a way that there is faster airflow, which would increase the power generation process significantly. Thus, the height of the tower should be taken into account when designing a wind turbine because wind flow intensity grows with increasing altitude according to known data on atmospheric processes.

In general, the functioning of the wind turbine is organized by one consecutive cycle in which the rotor moves because of wind power, transmits the torque through the power train and generates energy which can be further used, stored, or injected into the grid.

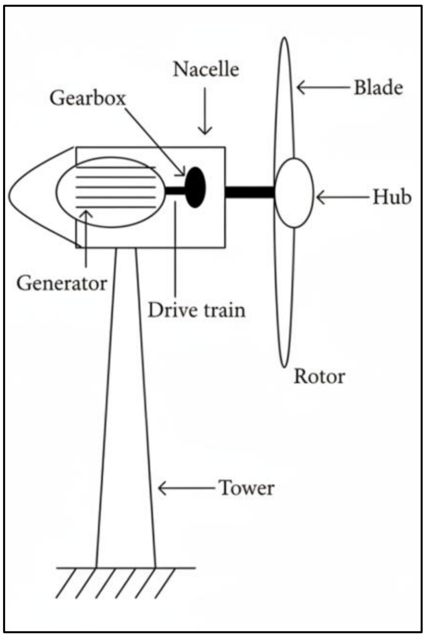

Figure 5: Components of a HAWT.

In terms of certification and structural design, the international regulatory reference is IEC 61400-2 [9], specific to small wind turbines.

See more fully in [10].

- <u>Vertical axis wind turbines</u>

The vertical axis wind turbine (VAWT) has an axis of rotation perpendicular to the direction of the air flow, which allows it to do without an orientation system. There are two basic types:

- Savonius type (drag-based): It uses the difference in drag force on convex and concave surfaces; it is relatively easy from a mechanical perspective (Figure 6), sturdy, works best at small wind velocities, but has a limited aerodynamic performance and relatively low values of the coefficient of power compared to HAWT turbines.

Figure 6: Example of a Savonius type (VAWT).

- Darrieus type (lift-based): It works by using the lifting forces generated by rotating aerodynamic profiles; the most common types are "eggbeater" and H-rotors (Figure 7).

Figure 7: Example of a Darrieus type (VAWT).

2.3 HYBRID RENEWABLE SYSTEMS

Combining the two power sources in a hybrid photovoltaic-wind system [11] is becoming increasingly popular recently as a means to increase the efficiency and stability of distributed energy generation. Although both power sources can generate electricity using renewable energy, production for both of them is greatly affected by environmental conditions and hence is variable in nature. Using both energy sources together can help address this problem.

The advantage that hybrid photovoltaic-wind systems have is that of the complementary nature of solar and wind energy sources. While photovoltaic power generation depends completely on the availability of solar irradiation and produces maximum electricity only in daylight hours, wind generation is dependent on the circulation of air in the atmosphere and hence generation is possible even outside daylight hours. Wind speeds, especially in the north of Spain, are higher in autumn and winter seasons compared to summer.

The seasonality and daily variability in production make it possible to use the hybrid system to eliminate the fluctuations in renewable power. When there is insufficient power from the photovoltaic system due to either night-time or wintertime conditions, the wind can be used to supply some power. Similarly, when the wind is calm, the photovoltaic system will still be able to generate power. The combined power from the two different sources will, therefore, show more stability compared to power generation using one of the sources alone.

The other key benefit associated with hybrid renewable power systems is reduced need for energy storage facilities. Renewable power systems normally require energy storage facilities since power generation is variable. However, through integration of different power sources within the system, the variability of energy production becomes less frequent hence reducing the need for storing energy.

As far as the design of the system is concerned, it should be noted that hybrid systems could further increase the efficiency of using existing infrastructure. The usage of power electronics, interconnection equipment and energy management systems could be made joint for both types of generation, thus making such an approach cheaper from the perspective of costs per one unit of installed capacity. In addition, hybrid systems would help increase renewable energy penetration without causing any significant problems for grid stability and curtailment.

When it comes to the issue of rural electrification and electricity consumption by households, it should be emphasized that photovoltaic-wind hybrid systems constitute a very promising option indeed. In rural areas, there tend to be both solar and wind energy resources that could be used jointly, thus allowing one to achieve greater levels of energy independence without having to depend heavily on the supply of electricity from other regions.

In conclusion, hybrid renewable systems are becoming increasingly popular in recent years as a decentralized generation alternative.

Chapter 3. GRID CONNECTION AND REGULATORY FRAMEWORK

3.1 GRID ACCESS CONDITIONS

Access to the electrical grid for installations of distributed generation in Spain is governed by a certain legal framework, which makes a distinction between big power plants and self-consumption installations that connect to the electricity network via an already existing supply point. If a small installation is used for self-consumption purposes for a residential building as in the proposed system, the relevant legal framework is specified by the Royal Decree 244/2019 [1] and Royal Decree 1183/2020 [12].

Under Royal Decree 244/2019, the administrative, technical and economic aspects of self-consumption of electricity are outlined. The types of self-consumption simplified surplus calculation procedure and the technical and administrative conditions that apply to small installations are set out by this decree.

On the other hand, Royal Decree 1183/2020 regulates the procedure of access and connection to the networks for those installations that generate power and are connected to the transmission and distribution networks in Spain. While this decree lays down the legal basis for accessing and connecting to the power networks, there are exceptions to some specific self-consumption installations with low installed capacity, for example, installation up to 15 kW.

Thus, Royal Decree 244/2019 outlines the legislation for self-consumption, while Royal Decree 1183/2020 regulates the legal framework for access and connection within which the exceptions are applied.

As a result, for an urban dwelling, grid connection takes place at an existing connection point, under the condition that the technical conditions set forth in the regulation of the distribution company and Low Voltage Electrical Regulation (Royal Decree 842/2002 [13]) are met.

3.2 CONNECTION COSTS

Even though residential self-consumption installations do not need to go through the process of access and connection due to their special characteristic, this does not imply that there are no expenses involved in connecting to the electricity network.

In this sense, connection costs involve technical adaptation of the access point, evaluation of the local grid capacity, metering system installation/update and incorporation of necessary electrical protection equipment in accordance with technical standards. In addition, the use of an additional meter that monitors both consumption and surplus of electricity produced by the installation, if any, represents a usual expense in such systems.

Regarding the remuneration model adopted for distribution networks, it is defined according to the provisions of Royal Decree 1048/2013 [14] establishing the economic regime for distribution activities. Even though such decree provides provisions about expansion and access rights for new demands, for small self-consumption installations that connect at the same point of consumption, expenses are restricted to technical issues defined by the distribution operator.

Moreover, Circular No. 1/2021 [15] issued by the National Markets and Competition Commission (CNMC) discusses various issues related to access and connection, which include technical and economic considerations in respect of the distribution networks.

In actuality, the connection costs for households generally depend on several considerations such as installed power capacity, distance from the point of connection, requirements of network strengthening and protection considerations. However, the connection cost is not defined in terms of a flat rate per kW but varies according to specific technical circumstances.

3.3 SELF-CONSUMPTION REGULATION

The regulatory framework for self-consumption in Spain was firmly established with the introduction of Royal Decree 244/2019 [1], which eliminated earlier administrative obstacles and created a more favourable environment for distributed generation systems.

This decree establishes two principal categories of self-consumption: systems without surplus injection and systems with surplus injection. In the second category, installations with an installed capacity equal to or below 100 kW that satisfy the corresponding requirements may access the simplified surplus compensation mechanism. Through this arrangement, the electricity exported to the grid is not traded directly in the electricity market; instead, it is economically compensated through deductions applied to the consumer's electricity bill, lowering the cost associated with electricity imported from the grid.

Also, the installations have to meet the criteria of the regulations for low-voltage electrotechnics (Royal Decree 842/2002 [13]), as well as the particular criteria of the distribution network. This involves the provision of an anti-island protection mechanism and a device which is able to automatically disconnect from the grid. Furthermore, it is important that all these conditions are in accordance with supply quality and safety limits.

The existing legal framework directly influences the economic viability of the system examined due to the fact that it determines surplus injection possibilities, pricing of exports and necessary legalization procedures.

Chapter 4. CASE STUDY DEFINITION

4.1 LOCATION AND CLIMATIC CONDITIONS

The case study analysed in this thesis corresponds to a rural dwelling located at Carretera Artxanda-Santo Domingo Errepidea, 24, 48015 Bilbao, Bizkaia, Spain, presented in Figure 8.

Figure 8: Rural dwelling.

The geographical coordinates of the site are 43.274° N latitude and −2.912° W longitude, with an approximate elevation of 195 meters above sea level, shown in Figure 9.

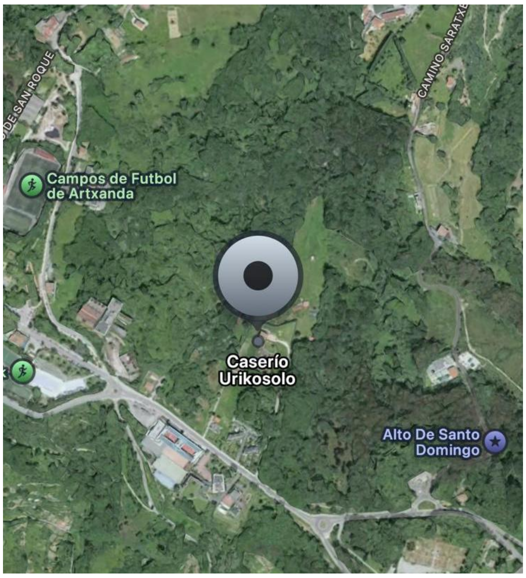

Figure 9: Ubication rural dwelling.

The dwelling is located in the northern part of Spain, specifically in the province of Bizkaia in the autonomous community of the Basque Country. The area is defined as semi-rural with slight terrain undulations that are common for Artxanda-Santo Domingo. As far as the geographical location is concerned, it should be mentioned that there is a direct correlation between the number of available resources and the geographic location of the place under consideration since solar irradiation as well as wind resources depend on such factors as elevation, distance from sea and other geographical characteristics. It is noteworthy that the presence of a coastline leads to the availability of moderate solar irradiation and favourable wind conditions.

Regarding the climatic features of the selected area, it should be noted that oceanic climate is prevalent there. Thus, the temperature varies slightly during different seasons while humidity is relatively high. The value of solar irradiation on inclined plane equals 1450 kWh/m^2·year (*4.2.Solar resource*), meaning that there is moderate potential for photovoltaics in northern Spain. The speed of the wind is also moderate and equals 15 km/h at low height (*4.3.Wind resource assessment*). However, with regard to the wind vertical profile, it might be higher.

The building is a standalone house built in a two-story structure with an estimated façade width of about 10-12 meters and a building height of almost 8 meters measured from the ground floor up to the roof apex. The house is also hooked up to the electricity distribution network and uses a traditional supply system. The calculated maximum power consumption of the house is roughly 3.70 kW, while the average daily consumption amounts to approximately 7.81 kWh/day as discussed in Section 4.4.1.

Given its semi-rural setting, availability of the roof area for solar cell installation and availability of ample space to install a small wind turbine generator, the building qualifies as a good case study for the evaluation and design of a grid-tied hybrid renewable energy system. The electrical grid will serve as a back-up source in times when renewable sources cannot fulfil all the requirements and also act as a sink for excess energy.

4.2 SOLAR RESOURCE ASSESSMENT

The evaluation of the solar potential at the chosen site (latitude 43.274° N, longitude -2.912°) has been carried out through the use of the PVGIS-SARAH3 database. The most appropriate configuration of a fixed photovoltaic installation, shown in Figure 10, implies 35° tilt and southward orientation (0° azimuth). The annual irradiation of the tilted plane will thus be equal to 1452.51 kWh/m². The calculated photovoltaic yield of the system under these parameters would amount to 1150.16 kWh/kWp/year, with losses being accounted for up to 20.82% (angle-of-incidence, spectral, temperature and low-irradiance losses). The obtained data (Figure 10) show that the site represents good photovoltaic generation potential in northern Spain.

Resultados de la simulación	
Ángulo de inclinación:	35 (opt) °
Ángulo de azimut:	0 °
Producción anual FV:	1150.16 kWh
Irradiación anual:	1452.51 kWh/m²
Variación interanual:	37.27 kWh
Cambios en la producción debido a:	
Ángulo de incidencia:	-2.83 %
Efectos espectrales:	1.56 %
Temperatura y baja irradiancia:	-6.69 %
Pérdidas totales:	-20.82 %

Figure 10: Simulation with PVGIS.

From the graph shown in Figure 11, one can conclude that there is significant seasonal dependency in the system's energy generation. Peak generation is achieved in summer when the maximum amounts of generated energy reach above 120 kWh in May, July and August, while in winter the produced energy drops down to 57 kWh in December and January. It means that summertime energy generation exceeds wintertime by more than two times.

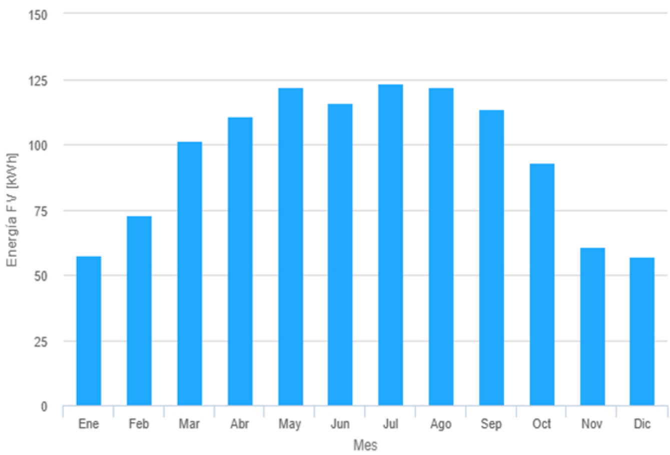

Figure 11: Monthly photovoltaic energy production bar chart.

The irradiation values on the tilted surface are also characterized by the same tendency, with maximal irradiation in late spring and summer and minimal irradiation values in winter (Figure 12). This proves that the variability of electricity generation is mostly influenced by seasonal variations in solar radiation. The strong dependence of the electricity generation on irradiation makes one assume that PV generation may not guarantee constant renewable energy generation all year round, especially in winters with increased domestic demand.

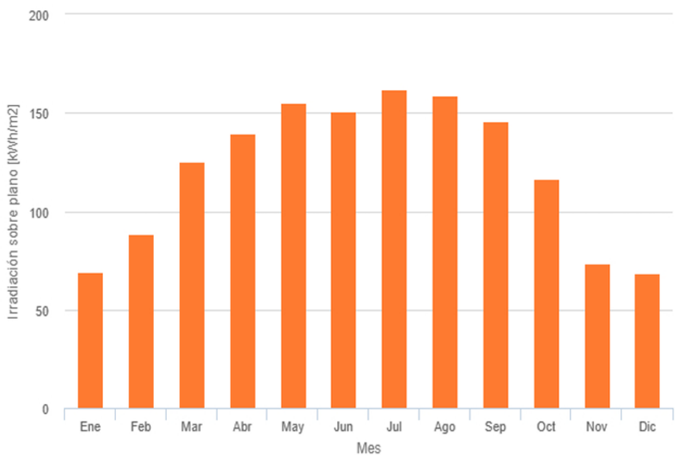

Figure 12: Monthly irradiation on inclined plane bar chart.

The yearly interannual variability (Figure 13) of the process expressed in the monthly standard deviation values is quite low. It shows that the solar energy resource is rather stable, which increases confidence in calculations of future energy yield.

Mes	E_m	H(i)_m	SD_n
Enero	57.3	69.0	10.7
Febrero	73.1	88.3	14.8
Marzo	101.5	125.5	16.3
Abril	110.9	139.5	14.3
Mayo	121.9	154.9	12.9
Junio	115.8	150.5	8.8
Julio	123.5	161.9	9.4
Agosto	122.1	158.9	7.3
Septiembre	113.6	145.7	7.1
Octubre	92.8	116.4	9.9
Noviembre	60.6	73.3	12.7
Diciembre	57.1	68.6	10.4

Figure 13: Monthly values of energy production, irradiation and standard deviation.

In conclusion, the analysis of results proves that the chosen rural location is capable of providing enough solar power for setting up the photovoltaic system. The presence of strong seasonality in the production characteristics, however, requires assessing the suitability of other sources of renewable energy, such as wind energy.

4.2.1 SOLAR RESOURCE DATA AND METHODOLOGY

The estimation of the photovoltaic resource in the chosen location was performed through the use of the database PVGIS-SARAH3. The database is widely regarded as the main solar radiation data set for photovoltaic energy analyses in Europe. PVGIS stands for Photovoltaic Geographical Information System and refers to a geographical database created by the Joint Research Centre (JRC) of the European Commission for long-term estimation of solar radiation and photovoltaic production based on satellite and meteorological observations.

SARAH3 (Surface Solar Radiation Data Set - Heliosat) is a set of satellite measurements of solar radiation that provide accurate information about the solar resource in Europe, Africa and part of Asia with a resolution of 5 km and hourly time steps.

From a practical perspective, PVGIS software application can be applied to photovoltaic projects in the early stages to determine the suitability of the particular location for generating electricity from solar sources and to make estimates of the anticipated energy generation capacity of the installation. In this research work, it has been used to identify the solar potential of the site chosen for the case study and to obtain the first approximation of the energy generation potential of the installation in the given climate zone.

Solar resource information in PVGIS software application is usually supplied using a Typical Meteorological Year (TMY). TMY refers to a hypothetical year built up based on long-term meteorological data that represents typical climatic conditions in a particular geographic location. Using TMY in the simulation process enables accounting for the seasonal fluctuations in solar irradiation while avoiding distortion by any extraordinary meteorological phenomenon occurring in certain years.

For the analysis of photovoltaic systems, the solar resource is generally described through parameters such as Global Horizontal Irradiation (GHI), irradiation on the plane of the array (POA or GTI) and specific photovoltaic yield. Among these indicators, the specific yield is especially important during the preliminary sizing stage because it establishes a direct relationship between the installed photovoltaic capacity and the expected annual electricity generation.

The specific yield refers to the amount of electrical energy generated annually for each unit of installed photovoltaic capacity and is usually expressed in kWh/kWp·year. This parameter is determined as the ratio between the yearly electrical production of the photovoltaic installation and its nominal installed power under standard test conditions (STC):

$$Y_{specific} = \frac{E_{annual}}{P_{installed}}$$

Where E_{annual} is the annual electrical energy generated by the system (kWh/year) and $P_{installed}$ is the installed photovoltaic capacity (kWp).

This indicator takes into account the effect of solar radiation, system inclination and orientation, temperatures and various other losses in the system, like inverter losses, mismatch losses and wiring losses. Due to this very reason, the specific yield becomes a useful variable when evaluating the photovoltaic capability of two locations and predicting the necessary installed capacity to satisfy the energy demand.

In the current study, the PVGIS model would be applied to determine the irradiance values and the specific yield of the site where the rural house is located. These values would then be used in the energy sizing process during the photovoltaic generator design.

4.3 WIND RESOURCE ASSESSMENT

Wind energy potential in the chosen area has been estimated on the basis of regional Wind Atlas data and reanalysis databases such as OpenWindMap. The chosen site offers advantageous wind resources because of its vicinity to the coast of Cantabria and exposure to weather phenomena coming from the Atlantic Ocean. OpenWindMap reports an annual average wind speed of 15 km/h at a station in Portugalete, Bilbao (see Figure 14).

Figure 14: Wind information obtained from OpenWIndMap.

Wind speed shows its maximum values in the autumn-winter period due to high-pressure gradients and storms coming from the Atlantic Ocean. Such seasonality of wind speed is in direct contrast to the photovoltaics, the productivity of which is much higher in the summer season. Therefore, the highest values of wind energy productivity may be expected precisely in those periods when photovoltaic productivity is low (November-March).

The amount of power generated from a small wind turbine varies directly with wind speed, which is a cubic function within the range of operation of the wind turbine [16]. Thus, even slight fluctuations in wind speed can cause considerable impacts on the amount of electricity produced. But this also means that places having relatively lower wind speeds could be facing low power generation, especially when wind speeds are consistently close to or below the cut-in speed of the turbine.

Moreover, there are several ways through which wind energy varies in contrast to solar energy on a daily basis. In the case of solar power, its generation occurs only during daytime while wind energy generation may happen during both day and night [17].

In terms of resource variability, wind will be more variable than solar radiation on a short-term basis. The effect of adding wind as an energy source in a PV-wind hybrid configuration might contribute to lower variability in the total generated power. Nonetheless, such an impact will depend heavily on the wind resources available at the particular location where the hybrid system is installed. In cases where there is limited wind activity, the use of a hybrid configuration would have limited benefits.

Based on the mismatch that was noticed between the photovoltaic generation pattern and the electricity demand during winter season, it makes sense to consider adding a mini wind turbine to increase the number of renewables utilized. This would be possible, of course, under the assumption of obtaining high enough wind speed levels and avoiding adverse impacts due to turbulence and obstacles present nearby.

To conclude, the wind energy potential at the selected location shows traits that make it a candidate for analysis in a hybrid power system. However, due to the weak wind regime at the site in question and the susceptibility of small wind turbine installations to wind regimes, a more thorough analysis should be made in order to determine whether wind energy can contribute significantly to the system's total efficiency.

4.3.1 EOLIC RESOURCE

Wind energy results from the temperature disparities on Earth caused by solar radiation. The temperature differences create pressure gradients, resulting in the flow of air from areas with higher pressures to areas of lower pressure. This process, along with the Coriolis force (due to Earth rotation) and surface interaction, results in the formation of atmospheric circulation patterns on different time scales and levels of persistence [18].

The different scales of atmospheric movements are distinguished according to a spatial viewpoint as follows:

- Macroscale (> 1000 km) and connected with the synoptic systems like anticyclones, depressions or storms.
- Mesoscale (10 - 500 km) and characterized by the presence of sea breezes, orographic winds, etc.
- Microscale (0 - 10 km) influenced directly by the presence of reliefs and/or unevenness of the land.

Within wind resources studies necessary for the installation of a wind turbine, the latter scale assumes special importance because the behaviour of the wind at the place of installation of the turbine depends on it. The presence of hills, buildings, or changes of relief produces a modification of the vertical wind profile, generates turbulence and wakes in the air flow.

Among the parameters influencing the energy production of a wind turbine there is the wind speed besides turbulence intensity, a parameter that expresses itself in the ratio between the standard deviation of wind speed and its mean value. Turbulence causes fluctuations and adds further dynamic loads on the blades, hub and tower of the wind turbine. High turbulence accelerates aging of the mechanical structures of the wind turbine and often causes its stoppage.

It is for this reason that the choice of an adequate wind farm location cannot be based only on high average wind speed. Indeed, it requires considering several specific parameters related to the wind turbine design, as well as the physical characteristics of the terrain on which the wind farms will be established. These include, among other factors, a sufficient average wind speed, low turbulence to mitigate fatigue loads, clear vertical wind speed profile according to the power or logarithmic law, as well as a simple orography to ensure smooth air flow without wake effects and high stresses on the wind turbine.

From the standpoint of territorial distribution, wind sources are not distributed evenly. They are found in those places where there are favourable orographic conditions and constant wind regime. Concerning the Iberian Peninsula, the territories richest in wind energy sources are mostly concentrated in the following areas:

- To the north-western part of the peninsula (Galicia, Asturias, Cantabria and Basque Country).
- To the Ebro Valley.
- To highlands of Castile and León, Castile-La Mancha and Andalusia.
- To the south-eastern part of the peninsula.

The distribution of the wind speed at 150 m high altitude directly depends on the available wind power, as stated in [16]. The wind energy content is directly proportional to the third power of the wind speed:

$$P = \frac{1}{2}\rho A v^3$$

Where ρ is the air density, A is the area swept by the rotor and v is the wind speed.

As can be seen from the equation, even slight changes in the average speed can increase considerably the generated energy, hence the importance of a detailed analysis performed during a campaign of long-term measurements (normally 1-3 years).

Over the last few decades, there has been remarkable development of the Spanish wind power industry, which made the country one of the European leaders in terms of installed wind capacity. Such progress was due to the favourable wind resources, constant legislative support and steady progress in technology. It should be noted, however, that almost all sites with excellent wind characteristics, characterized by relatively high average wind speed and small values of the turbulence intensity, have already been explored, so the main attention is currently paid to development in technological aspects.

The current phase of wind energy can be realized through various means [19]. The major approach has been the repowering of old wind farms where the initial turbines have been replaced by advanced machines having greater efficiency, larger rotor diameter and taller hub height, which will help achieve better energy output in the same area and will also reduce the number of wind turbines used. At the same time, it has become a clear tendency to install wind turbines with bigger capacity, mostly surpassing 5-6 MW in onshore cases.

Another important development in recent years has become the implementation of offshore wind technology that will help to gain access to more powerful winds in order to overcome the limitation of space. Finally, the inclusion of wind energy into hybrid energy systems together with photovoltaics and energy storage technologies has gained much significance. Hybrid energy systems provide greater flexibility and smoothness of the process as well as easier integration into renewable energy networks.

In addition, according to [20], thanks to technological improvements, it has become possible to raise hub heights (up to 120-170 m for onshore applications) and rotor diameters, thus improving the capacity factor thanks to better wind quality at higher levels.

4.4 ELECTRICAL DEMAND ESTIMATION

If there is no access to fine-grained data regarding electricity consumption, household demand can be determined through a bottom-up approach involving the identification and analysis of electrical loads in individual households. This approach is commonly employed in residential energy analyses and distributed generation systems design since it permits modelling consumption patterns based on appliance-related information.

This load estimation process requires first the identification of the electrical appliances installed in a household, the determination of their power ratings and an estimate of their daily operation duration, which can be determined by:

$$E_i = P_i \cdot t_i$$

where:

- E_i is the daily energy consumption of appliance i(Wh/day),
- P_i is the rated electrical power of the appliance (W),
- t_i is the average daily operating time (hours/day).

The total daily energy demand of the household is obtained by summing the individual consumption of all considered appliances:

$$E_{total} = \sum_i E_i$$

This approach permits evaluating the contribution made by different classes of electrical loads, namely lighting, household appliances and auxiliary devices. Moreover, it enables the detection of the most power-demanding loads among all those installed in the household.

A series of assumptions is necessary to arrive at an estimate of real residential electricity consumption levels. First, the number of residents occupying the building and their occupancy pattern are taken into account as they are directly related to the use of household appliances. As regards rural residential houses, the use of electricity there refers to lighting, cooling, cooking devices, home entertainment appliances and occasional usage of high-powered appliances like washing machines or irons.

Secondly, the duration of work for each appliance is calculated based on average consumption rates. Those figures indicate daily average operation periods but do not imply continuous operation. For instance, light consumption is mostly observed in the evening and at night; whereas the use of some other devices, including washing machines and irons, can vary from day to day.

In addition, one should understand that all the appliances do not work at their maximum capacity at the same time. Therefore, it is necessary to apply the simultaneous factor in assessing the maximum demand of the house. It will account for the random character of appliance usage and prevent the excess size of the electrical system. In this case, a simultaneity factor of 0.8 is used in the calculations, which is typical in such assessments according to engineering experience.

With this approach, it is possible to calculate the electricity demand of the analysed rural house through considering the principal lighting loads and electrical appliances in the house.

More information available in [21] and [22].

4.4.1 DAILY DEMAND

The selected case study corresponds to a grid-connected rural dwelling situated in Bilbao. As detailed electricity consumption measurements are not available, the household electrical demand is estimated through a bottom-up methodology based on the nominal power and average daily operating time of the main household appliances and lighting systems installed in the dwelling.

The different categories of electrical consumption considered in the demand assessment are detailed in Table 2 and Table 3.

- Lighting

Location	**nº**	**Power (W)**	**Hours (h)**	**Energy (Wh)**
Living Room	4	18	5	360
Kitchen	3	18	3	162
Bathroom	2	18	1	36
Bedroom	2	18	2	72
Room	1	18	1	18
Attic	1	18	0.1	1.8
Outdoor	2	18	8	288
Total		**270**		**937.80**

Table 2: Lightning consumption.

- Electrical appliances

Appliance	**No.**	**Power (W)**	**Hours (h)**	**Energy (Wh)**
Antenna	1	4	4	16
Washing Machine	1	2300	0.5	1150
Refrigerator	1	160	24	3840
Television	1	35	5	175
Laptop	1	300	2	600
Small Appliance	1	200	0.5	100
Water Pump	1	370	1	370
Iron	1	1000	0.5	500
Fan	1	60	0.3	120
Total		**4429**		**6871**

Table 3: Electrical appliances.

Taking into consideration Table 2 and Table 3, the total power is calculated as follows:

$$P_{AC,peak} = \sum_i P_i = P_{lightning} + P_{others} = 270\ W + 4429W = 4699\ W$$

To prevent oversizing of the installation, a simultaneity factor of 80 % is considered for the maximum theoretical electrical demand. This assumption reflects that all appliances do not operate simultaneously at full rated power and represents a common practice in residential electrical load calculations. After applying the simultaneity factor, the following result is obtained:

$$P_{AC,design} = 0.8 \cdot 4699\ W = 3759\ W$$

Finally, based on the daily energy consumption values for each class of equipment, the total daily energy demand is obtained:

$$E_{total}\left(\frac{Wh}{day}\right) = 937.8 + 6871 = 7808.8\left(\frac{Wh}{day}\right) = 7.81\left(\frac{kWh}{day}\right)$$

This corresponds to an approximate annual electricity demand of:

$$E_{annual} = 7808.8\left(\frac{Wh}{day}\right) \cdot 365\ days = 2850.20\left(\frac{kWh}{year}\right)$$

which represents the estimated yearly energy consumption of the dwelling.

4.4.2 LOAD PROFILE CHARACTERIZATION

Alongside the estimation of total energy demand of the house per day, it is vital to evaluate the load profile of the house because of the temporal nature of the electricity demand, which plays a fundamental role in the conception of the hybrid renewable system. In fact, both photovoltaic and wind power plants show variable production levels, depending on sunlight and wind respectively and thus there is the need to assess the compatibility between electricity production and consumption on a temporal basis rather than a pure annual basis.

A typical house located in a rural area shows peak electricity demand in morning and evening times because the occupants are more active at those moments and lower demands during noon and night times. The evening period experiences higher energy demand due to the use of lights, cooking, electronics and heating systems, but the photovoltaic system stops working, which is an important reason for implementing hybrid solutions or grid connectivity.

On the other hand, during the daytime period, the electricity demand could partially be provided by the photovoltaic system, thereby raising the level of self-consumption. However, during the nighttime period, the demand could be covered using wind power generation, if available, or grid electricity. Therefore, the wind power plant may help cover the nighttime period demand.

In regard to seasonality, residential electricity usage may increase during winter seasons because of more hours of illumination, auxiliary electric heaters and more indoor activities. On the other hand, in accordance with section *4.2 Solar* , PV energy generation is less during winter seasons because of less sunlight available. On the contrary, as discussed in *4.3 Wind* section, wind energy generation increases during winter seasons, making an opposite pair of both energies.

This indicates that the definition of the load curve is crucial for the proper design of a hybrid system since it defines the level of matching between renewable energy generation and electricity demand, the quantity of imported power from the network and the possibility of exporting surplus power to the grid.

4.5 GRID CONNECTION CONDITIONS

The rural house selected for this project is part of the low-voltage electrical distribution network managed by the public utility company. For this reason, the proposed hybrid PV-WIND system will be connected to the electrical grid and operate in a grid-tied manner. In such configurations, there is installation of renewable power generation devices which feed part of the household load and the electricity grid serves as the backup source and energy sink depending on whether the power generated by renewables is enough or not.

As mentioned above, the hybrid photovoltaic-wind system will operate in a self-consumption with excess energy compensation mode. As noted in *Chapter 3. Grid* *connection and regulatory framework*, this refers to those cases when the generated electricity covers the consumption needs of the user's facility and the excess of electricity is sold back into the grid through a simplified compensation mechanism. The opposite case when the consumption needs of the household exceed the renewable power generation is also provided for by this arrangement.

Electrical-wise, the photovoltaic generator provides direct current (DC). This current is inverted to alternating current (AC) by a grid-tied inverter. The wind generator supplies electricity in the form of variable-frequency alternating current, which needs to be rectified and then converted back to grid-synchronized AC. These two systems are connected to the distribution board of the house's AC network, providing the electricity load in its most common form and connecting the system to the grid via a bidirectional meter.

As can be observed from the above configuration, there is no need for any type of battery storage system here. Instead of batteries, the electrical grid acts as an energy buffer, storing the excess amount of energy supplied to the grid and delivering the energy when renewable generation is not enough. This solution greatly decreases the initial expenses involved in installing an independent system with battery storage and also increases dependence on the grid.

The inverter should have the capability to supply electricity at the maximum level of demand in the dwelling, as estimated in *4.4.1 Daily demand* and also generate the maximum possible power from the renewable source. Finally, compliance with all technical standards required in the Low Voltage Electrical Regulation should be ensured.

The grid-connected option makes it possible to analyse indicators like self-consumption, level of renewable sources participation, energy imported from the grid and surplus energy sent to the grid. They are crucial in the technical and economic estimation of hybrid systems and are going to be analysed during the simulation process.

4.6 ECONOMIC PARAMETERS

To carry out the economic assessment of the considered hybrid solar-wind system, it is necessary to identify some economic parameters affecting the cost of the entire system and its profitability as an investment. In *Chapter 6. Simulation and optimization (HOMER Pro)*, such parameters will be used for system optimization and calculation of some economic factors, like Net Present Cost (NPC) and Levelized Cost of Energy (LCOE).

The main economic factors include electricity buying rate from the grid, compensation for surplus electricity supplied to the grid, project lifespan, discount rate, inflation rate and investment expenses.

Project lifetime refers to the timeframe of the economic analysis, usually 20-25 years for renewable energy systems. Discount rate is used to consider the time value of money, used to calculate the present values of costs and revenues in the future. Inflation rate is used to account for the expected growth in electricity prices and O&M costs.

Investment cost consists of the cost of purchasing photovoltaics, a wind turbine, inverter and installing equipment. Besides the cost of investment, O&M costs will have to be included in the calculations, specifically referring to a wind turbine, whose mechanical components need regular maintenance and repairs.

Electricity purchase price is the price of importing electricity, while the surplus compensation price is the revenue gained from exporting excess electricity generated by the system within the framework of the self-consumption with surplus compensation concept.

Economic parameters [23] mentioned above are necessary for finding the optimum configuration of the system because the sizing of photovoltaic/wind systems will depend on not just technical requirements but also on economic considerations. Economic analysis should be carried out in order to find the optimal size of the system that will allow us to generate electricity at minimal cost.

Chapter 5. SYSTEM DESIGN AND SIZING

5.1 SIZING CRITERIA

The sizing of the hybrid PV-WIND system is performed considering both technical and economic considerations. Unlike the isolated systems, which require generation and storage capabilities that can meet the whole demand at any moment, the grid connected system provides more freedom in terms of sizing, because the grid can supply energy whenever there is a lack of renewable production.

Thus, the goal of the sizing process is not to achieve full energy independence from the grid, but to optimize the installed capacity of the hybrid systems in terms of the cost-effectiveness while maximizing the use of renewables.

The following are the most important sizing parameters:

- Minimize the Net Present Cost (NPC) of the system.
- Minimize the Levelized Cost of Energy (LCOE).
- Maximize renewable energy penetration.
- Maximize self-consumption of renewable energy.
- Reduce the amount of electricity imported from the grid.
- Avoid oversizing of the generation systems.

The existence of the electrical grid implies that the size of the renewable energy systems can be designed primarily using annual energy considerations rather than peak power considerations. This means that the size of the PV and wind energy systems is designed in such a way that they can cover some portion of the annual energy requirement while the electricity required during the periods when the generation of renewable energy is not enough can come from the grid.

The size of the PV energy system is determined based on the annual energy requirements and the energy generation potential of the site while the size of the wind energy system is determined considering the wind energy available and the power curve of the wind turbine generator. The best configuration for the hybrid system can be determined by running simulations through the HOMER program.

The sizing process helps to find an efficient and cost-effective hybrid energy system design.

5.2 WIND SYSTEM DESIGN

To size the proposed wind energy system, the wind resource at the chosen location (refer to Figure 15) was evaluated based on hourly meteorological information derived from the ERA5 reanalysis database generated by the ECMWF.

Figure 15: Location where the measure is done.

The ERA5 reanalysis database offers representative information of the wind resource at the considered location based on long-term records. Furthermore, ERA5 is a worldwide atmospheric reanalysis database which integrates numerical weather prediction models and historical observational data from various sources including satellites and ground-based stations to reconstruct the past atmospheric conditions in a physically consistent way. ERA5 contains hourly meteorological parameters with good temporal resolution and is widely used in studies on renewable energy and wind resource assessment.

Hourly wind information at a height of 10 meters above the ground was acquired from ERA5 for the coordinates of the chosen rural house (43.274° N, −2.912° W). Zonal and meridional wind components, referred to as u_{10} and v_{10}, respectively, were retrieved. While u_{10} is the east-west wind component, v_{10} is the north-south component.

Given that wind speed is a vector quantity, the wind speed magnitude at 10 meters needs to be estimated based on the two components perpendicular to each other. Accordingly, the hourly wind speed was estimated as follows:

$$v = \sqrt{u_{10}^2 + v_{10}^2}$$

Where v is the wind speed magnitude at 10 m (m/s), u_{10} is the zonal wind component (m/s) and v_{10} is the meridional wind component (m/s).

The method makes it possible to convert the two horizontal wind components into one wind speed value at each hourly point. As a result, the hourly time series serves as a starting point for calculating the wind energy production potential of the wind turbine under consideration.

Nevertheless, most modern wind turbines have hub heights that differ from 10 meters used by ERA5. This implies that the wind speed needs to be extrapolated from 10 meters to a certain hub height. The power law wind profile was used to extrapolate the wind speed from 10 meters.

$$v(z) = v(z_{ref}) \left(\frac{z}{z_{ref}} \right)^{\alpha}$$

Where $v(z)$ is the wind speed at the desired height z, $v(z_{ref})$ is the wind speed at the reference height, z is the turbine hub height, z_{ref} is the reference height (10 m in ERA5) and α is the wind shear exponent.

Wind shear exponent takes into consideration the effect of roughness of the terrain as well as the atmospheric stability on the wind profile. The usual values for the parameter range between approximately 0.10 for open water and 0.40 for densely populated urban area. As such, considering that the site under study is semi-rural in nature with some terrain differences but without any obstruction from the urban surroundings, it was decided to use a typical engineering value of $\alpha = 0.14$ corresponding to open rural areas [16].

The wind speed series produced using the technique mentioned above was further used for determining the annual energy output of the wind turbine to dimension its part of the renewable hybrid energy system.

The house is approximately 8 meters high, hence placing the turbine on the roof will give a hub height of approximately 9 meters. With respect to the vertical extrapolation, the mean wind speed of 9 meters will be 2.47 m/s.

After deriving hourly wind speed time series for this particular hub height, the electrical output was computed using the power curve of the selected turbine model (Figure 16). A small wind turbine model of 2 kW produced by Aerolic was used as the reference and its specifications are listed in the Appendix. The power output was determined according to the operation zones defined for the wind turbine: no power generated in case of below cut-in speed winds; gradual increase in the partial load zone; constant rated power at rated and cut-out wind speeds and zero electrical generation above cut-out wind speeds.

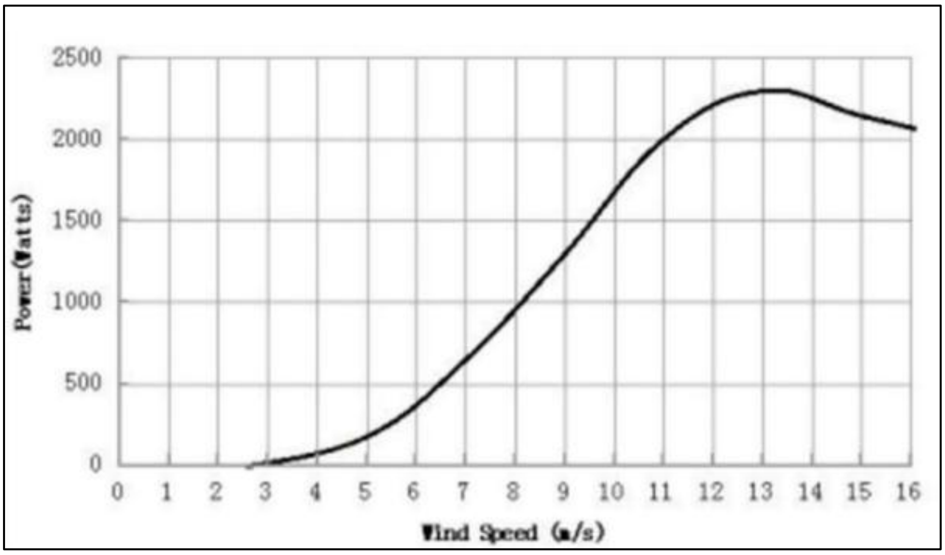

Figure 16: Power curve of the 2kW small wind turbine manufactured by Aerolic

Annual energy production was calculated by summing up the daily energy generation for 8760 hours of a year. For 9 m hub height, the AEP is found to be 235. 05 kWh/year, with about 68% annual hours of wind speeds below the cut-in speed. Compared with the annual electricity consumption of the house which is 2850.20 kWh/year, the wind turbine can generate electricity equivalent to only 8% of the total electricity consumed per year.

A sensitivity analysis was then conducted to determine the effect of elevation on energy production. An increase in the hub height from 9 m to 15 m led to an increase in the annual energy production to 340.40 kWh/year (Figure 17) at the cost of the 44.8% enhancement. In addition, 64% of annual hours are still below the cut-in speed, hence the wind resources are moderate.

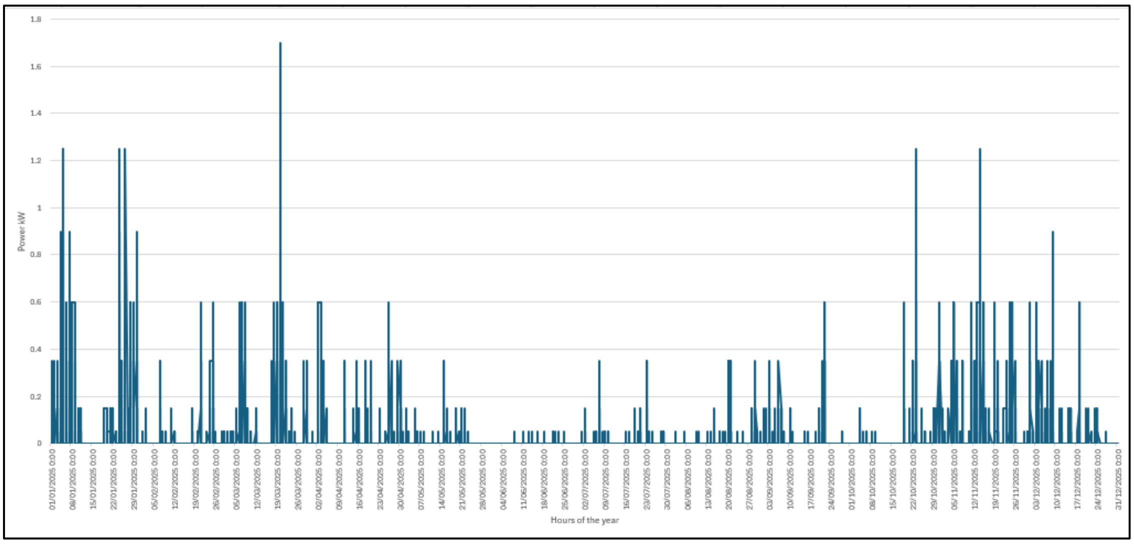

Figure 17: Hourly wind power generation throughout the year.

Based on these results (see Figure 17), the wind potential of the selected site is low for the purposes of small-scale energy generation. Although increasing the hub height up to 15 m allows increasing annual energy generation, the turbine still does not achieve the cut-in speed during most of the period, thus reducing its overall contribution. Thus, installing a more powerful turbine will not make much sense in terms of efficiency since the main problem concerns the wind regime and not the turbine itself.

Therefore, installation of the selected turbine (2 kW turbine at 15 m) represents a feasible trade-off between generation and energy production. However, the total amount of annual wind energy generation will remain low, i.e., it is expected to produce approximately 340.40 kWh/year, which accounts for about 8% of the consumption needs of the household. As a result, despite the possibility of complementing photovoltaic generation with wind energy production due to seasonality of the energy regime, the influence of wind energy on the overall efficiency of the hybrid system will remain negligible.

5.2.1 TURBINE SELECTION

Selection of a particular wind turbine represents a crucial aspect of the subsystem design. In cases of small-scale application of wind turbines, their poor compatibility with local conditions can substantially reduce electricity production even if the nominal power of the installed turbine is quite high. As a result, the selection of the appropriate turbine should be based not only on the turbine's nominal power but also on other important parameters as well.

Thus, the chosen wind energy source for the small-scale application has been identified. In particular, the 2 kW small wind turbine produced by Aerolic has been selected. Based on the manufacturer's information, it is capable of generating 2000 W of energy at wind speeds of 11 m/s, with the maximum generation of 2300 W. The cut-in wind speed amounts to 2.5 m/s.

The relatively low cut-in speed of 2.5 m/s enables using the turbine in regions characterized by moderate or low wind resources, as it increases the operating hours during the year. Nevertheless, it should be stated that despite the low wind speed necessary for starting the operation of the wind turbine, the amount of energy produced is low and only the wind speeds higher than average provide a considerable energy output.

It is possible to determine the rotor diameter of the turbine, which equals to 2.88 m. As a result, the swept area and the kinetic energy captured by the rotor can be calculated using the following formula:

$$A = \pi \left(\frac{D}{2}\right)^2 = 6.51\, m^2$$

In this way, the rotor diameter becomes one of the important parameters determining the performance of the wind turbine, especially in low-wind-speed areas.

The turbine uses a three-blade rotor built from fiberglass. This rotor type is popular in wind turbines due to its good efficiency, relatively high strength and low cost. The generator used is the permanent magnet synchronous generator, whose high efficiency and low maintenance costs make it advantageous in comparison with the other generator types. Moreover, the wind turbine features an electromagnetic brake and manual lock-up mechanism, which ensures safety of its operation under high wind speeds (up to 35 m/s).

Finally, the technical coherence of the chosen turbine should be verified in light of the local wind resource available. It was seen previously that the mean wind velocity at the site is low and hence the majority of the time is spent operating within or near the cut-in region of the turbine. Choosing a wind turbine with a low cut-in and reasonable rated power can be seen as the most technically coherent option.

5.3 PHOTOVOLTAIC SYSTEM DESIGN

As a first step to analyse the dimensions of the photovoltaic generator, the following steps and parameters will be considered:

According to [24], the sizing of a photovoltaic generator will include two steps as follows:

- The energy sizing, where the necessary amount of power for the photovoltaic panels will be defined based on annual consumption and site characteristics.
- The electrical sizing, which consists of defining an optimum connection in series of modules (strings), ensuring voltage and current limits, together with inverter compatibility.

In order to ensure system safety, a design temperature of −10 °C will be adopted to guarantee that the open-circuit voltage of the strings does not exceed the maximum value allowed by the inverter.

5.3.1 INITIAL DATA AND COMPONENTS

To continue sizing the photovoltaic system it is first required to consider the energy analysis of the rural house done until now.

As shown in the previous section (*4.4.1. Daily demand*), the daily average consumption can be assumed to be 7808.80 Wh/day, equivalent to 7.81 kWh/day. Extending this amount of energy into a whole year, the annual energy demand would be about 2850.20 kWh/year. The latter value is the key to sizing the renewable generation system and its eventual storage system.

In addition, the house counts with a small generation system of wind power whose annual production was determined in a previous calculation (*5.2.Wind system design*): it is 340.40 kWh/year. Such an amount of energy corresponds to only 8% of the annual demand of the house, thus reducing the energy which needs to be generated by the photovoltaic system.

For the characterization of the solar resource, an annual yield factor has been calculated equal to 1150.16 kWh/kWp/year (*4.2.Solar resource*). This figure means that, taking into account total losses of 20.82%, 1 kWp photovoltaic system installed at that location could produce such an amount of energy per year.

Finally, both module and inverter have been chosen.

➢ <u>Photovoltaic Module</u>

The Tensite N-Type TOPCon 500 W panel is chosen for the photovoltaic generation, which uses N-type monocrystalline solar panels that include TOPCon cells, featuring higher efficiency and superior thermal performance compared to the traditional technologies of P-type silicon.

The module has a nominal power under standard conditions (STC: 1000 W/m², 25 °C, AM 1.5) of $P_{STC} = 500\ W$.

Its main electrical parameters under STC are:

- Open circuit voltage:

$$V_{OC,STC} = 44.40\ V$$

- Voltage at maximum power point:

$$V_{MP,STC} = 37.05\ V$$

- Current at maximum power point:

$$I_{MP} = 13.50\ A$$

- Short-circuit current:

$$I_{SC} = 14.25\ A$$

Likewise, the temperature coefficient of the voltage at maximum power:

$$\beta_{Vmp} = -0.30\ \%/°C$$

It measures the relative deviation of the voltage of the PV module, depending on the temperature of its operation. This characteristic is crucial to evaluate the compatibility of MPPT with inverter under operating conditions with high temperature.

Moreover, the temperature coefficient of the open-circuit voltage is:

$$\beta_{Voc} = -0.24\ \%/°C$$

It is important for the sizing process of electrical parameters, considering that under low temperatures, open-circuit voltage increases, reaching the maximum limit of the inverter. In other words, this is an important consideration, as explained earlier, the design temperature should be not less than −10°C to meet the electrical limitations.

Module selection is based on the following technical considerations:

- Higher power per module (500 W).
- N-Type TOPCon technology with better thermal properties.
- Voltage and current characteristics suitable for residential hybrid inverters 600 V DC.

➢ Inverter

For the purposes of energy conversion and overall system management, a Sungrow SH3-6RS hybrid inverter has been chosen as an appropriate component. It is a single-phase inverter that is meant for domestic use cases.

The Sungrow SH3-6RS inverter includes a DC/AC inverter, an MPPT controller, a bidirectional battery charger and an EMS that takes care of self-consumption of produced energy.

Among the basic electrical parameters associated with the size of the photovoltaic generator:

- Maximum DC input voltage:

$$V_{DC,máx} = 600\ V$$

- MPPT tracking operating range:

$$40\ V \leq V_{MPPT} \leq 560\ V$$

- Maximum input current per MPPT:

$$I_{máx} = 16\ A$$

- Maximum short-circuit current per MPPT:

$$I_{SC,máx} = 20\ A$$

- Maximum AC output power

$$P_{máx\ AC} = 3680\ W$$

- Number of independent MPPT trackers:

$$2 \quad trackers$$

The use of this particular inverter is justified due to:

- The ability to be used with up to 600 V DC configurations, thus giving more flexibility with regard to series configuration of modules.
- The existence of two independent MPPTs, which provides the ability to expand the system in the future or configure it differently.
- The hybrid nature, giving the opportunity to install batteries for additional energy storage, which is a very important point considering the location.

- The rating power of the inverter being sufficient for covering the electricity consumption of the house.

The compatibility between the chosen module and inverter will be evaluated below, based on open-circuit voltage calculations and currents' limitations per MPPT at min temperature.

5.3.2 ENERGY SIZING

Regarding energy sizing of the photovoltaic system, it must be considered the yearly electricity consumption of the residence, taking into account the share given by the wind sub-system. Since the proposed wind turbine provides an estimated annual production of 340.40 kWh/year, then it is obtained the minimum energy necessary to be supplied by the PV generator:

$$E_{PV,needed} = 2850.20 - 340.40 = 2509.80 \text{ kWh/year}$$

In order to transform this yearly energy need into photovoltaic generation capacity, it is used the specific energy yield of the chosen installation site. Thus, the minimal installed photovoltaic power is calculated according to:

$$P_{PV,min} = \frac{E_{PV,needed}}{Y} = \frac{2509.80}{1150.16} = 2.18 \text{ kWp}$$

But when designing a photovoltaic system for residential purposes, especially in rural areas, the sizing process should take into consideration more factors than only the yearly energy balance. The generation provided by solar panels presents high variations throughout the year, especially at seasonal times, while it does not exist during the night.

Therefore, the design of such systems based on annual average values can lead to insufficient generation during critical moments. Consequently, in order to enhance the performance of the system, an oversized photovoltaic generation capacity is applied. For this analysis, it will be considered a power generation capacity of approximately 4.0 kWp.

Thus, through this decision, the system robustness will be increased, providing higher energy availability under low irradiance situations. In addition, an oversized system will be able to cover higher self-consumption levels, decreasing the reliance on grid power in cold months.

As a measure of inverter capacity sufficiency, the ratio of DC-to-AC power will be used, which amounts to:

$$\frac{P_{DC}}{P_{AC}} = \frac{4.0}{3.68} = 1.09$$

where the denominator represents the maximum possible power of the inverter. According to [25], its value falls into the recommended range of 1.05-1.3 for photovoltaic installations at homes. Operation of such systems in the specified interval allows achieving better inverter utilization and higher energy output during periods of poor irradiation conditions, while maintaining the losses at acceptable levels.

Thus, optimal oversizing ensures high performance of the photovoltaic installation without compromising safety, being an effective trade-off between productivity and efficiency of the system.

Finally, taking into account the rated power of 500 Wp for the chosen PV modules, the necessary installed power will be achieved by:

$$N_{mod} = \frac{4000}{500} = 8 \text{ modules}$$

In this manner, the initial sizing of the photovoltaic installation will be performed from the energy point of view, giving grounds for proceeding with the further electrical design of the installation.

5.3.3 ELECTRIC SIZING

With the choice of the power level of PV, the next stage of calculation involves determining the parameters of the strings and checking whether the DC voltage of the inverter does not exceed the allowable limits under the nominal (STC) and cold ambient temperatures. It is important to remember that the open circuit voltage of the PV modules grows with decreasing temperature and it might lead to tripping or even breakdown of some parts.

- Low temperature verification

To evaluate the worst-case low temperature voltage condition, as it has been said before, a conservative minimum ambient/module temperature of $T_{min} = -10\,^{\circ}C$ is assumed. The temperature difference with respect to STC (25°C) is $\Delta T = T_{min} - 25 = -35\,^{\circ}C$. Due to the negative value of the temperature coefficient, the reduction of temperature leads to the increase of the voltage. Hence, under cold conditions, the voltage will change as follows:

$$V_{OC}(-10\,^{\circ}C) = V_{OC,STC} \cdot (1 + \beta_{Voc} \cdot \Delta T)$$

$$V_{OC}(-10\,^{\circ}C) = 44.40 \cdot (1 + (-0.0024) \cdot (-35)) = 44.40 \cdot 1.084 = 48.13 \text{ V}$$

Therefore, the maximum allowable number of modules in series is obtained by dividing the inverter DC limit by the cold V_{oc}:

$$N_{máx\ series} = \frac{V_{DC,máx}}{V_{OC}(-10\,^{\circ}C)} = \frac{600}{48.13} = 12\ modules$$

- ✓ By designing 8 modules in series, the maximum DC voltage of the inverter is not exceeded. Therefore, the first electrical constraint taking into consideration the low temperature is satisfied.

Moreover, it is verified that the voltage of the cold string is lower than the maximum DC input voltage of the inverter:

$$V_{OC\ string}(-10\,^{\circ}C) = 8\ modules \cdot V_{OC}(-10\,^{\circ}C) = 8 \cdot 48.13\ V \approx 385\ V < 600\ V$$

- ✓ The second electrical condition taking into account the low temperature is satisfied.

Regarding the MPPT range, it is verified that the string operating voltage at maximum power under STC conditions falls within the MPPT range:

$$V_{MP\ string} = 8\ modules \cdot V_{MP,STC} = 8\ \cdot 37.05\ V \approx 296\ V$$

which falls well within the inverter MPPT range $40\ \leq 296\ \leq 560\ V$.

- ✓ The third electrical constraint considering the low temperature has been met.

- ➢ <u>High temperature verification</u>

Along with checking the behaviour of the photovoltaic system at low temperatures, one must investigate the system's operation at elevated temperatures. In contrast to the open-circuit conditions in winter when it is crucial to make sure that the voltage does not become too high, in summer the most dangerous moment is reducing the voltage at the maximum power point ($V_{MP\ string}$), as the voltage of the PV modules decreases with increasing temperature.

To assess the worst-case high-temperature scenario, a conservative cell temperature of $T_{máx} = 70$ °C is assumed. This value represents a realistic operating condition under high irradiance and elevated ambient temperature, considering that module temperature typically exceeds ambient temperature during summer operation. Moreover, the temperature difference with respect to STC (25 °C) is $\Delta T = 70 - 25 = 45\ °C$.

The voltage at maximum power decreases according to the temperature coefficient of voltage, so the voltage at maximum power at 70 °C is therefore estimated as:

$$V_{MP}(70\ °C) = V_{MP,STC} \cdot \left(1 + \beta_{Vmp} \cdot \Delta T\right)$$

$$V_{MP}(70\ °C) = 37.05 \cdot (1 + (-0.003) \cdot 45) = 32.10\ \text{V}$$

Therefore, the minimum allowable number of modules in series is obtained by dividing the minimum MPPT operating voltage by the voltage at maximum power point:

$$N_{mín\ series} = \frac{V_{MPPT,min}}{V_{MP}(70\ °C)} = \frac{40}{32.10} = 1.25 \approx 2\ modules$$

- ✓ By designing 8 modules in series, the first electrical constraint taking into consideration the high temperature is satisfied.

Moreover, given that the selected configuration consists of 8 modules in series, the operating voltage under high-temperature conditions is

$$V_{MP\ string}(70\ °C) = 8\ modules \cdot V_{MP}(70\ °C) = 8 \cdot 32.10\ V \approx 257\ V$$

which falls well within the inverter MPPT range $40\ \leq 257 \leq 560\ V$.

- ✓ The second electrical constraint considering the high temperature has been met.

In conclusion, the photovoltaic generator will operate as a single chain of eight modules connected in series to one MPPT input of the inverter. This arrangement meets all the necessary electrical requirements, including the maximum voltage value at the worst-case winter temperature of −10 °C, while staying within the operating voltage and current ranges supported by the inverter. Now that the electrical compatibility has been ensured, this system parameters can be introduced into PVsyst to carry out performance simulation of the photovoltaic installation.

5.3.4 SIMULATION WITH PVSYST

In order to assess the performance of the photovoltaic installation, the PVsyst software package has been used to carry out a simulation process following a methodical approach which guarantees consistency between the climate conditions, system setup and yearly generated electricity. The role of PVsyst, from a practical point of view, is to evaluate whether a photovoltaic installation has been adequately designed and is technically sound from all perspectives, both electrical and performance.

To begin with, a new grid-connected project was created, where the geographical location of the installation was defined by setting up the coordinates of the installation site (43.274° N, −2.912°). After selecting the site, PVsyst automatically retrieves the meteorological data stored in its database for this exact site, consisting of global horizontal radiation, temperature and wind speed. PVsyst uses these climatic variables to calculate the irradiance and operating temperature of the photovoltaic generator by means of its internal model.

Then the orientation of the photovoltaic generator was set up (Figure 18). A tilt angle of 35° and an azimuth of 0° (south facing) were set. This arrangement yields the highest value of yearly energy generation (*4.2. Solar*). Subsequently, PVsyst uses its transposition model to convert the horizontal irradiance to the irradiance on the plane of array.

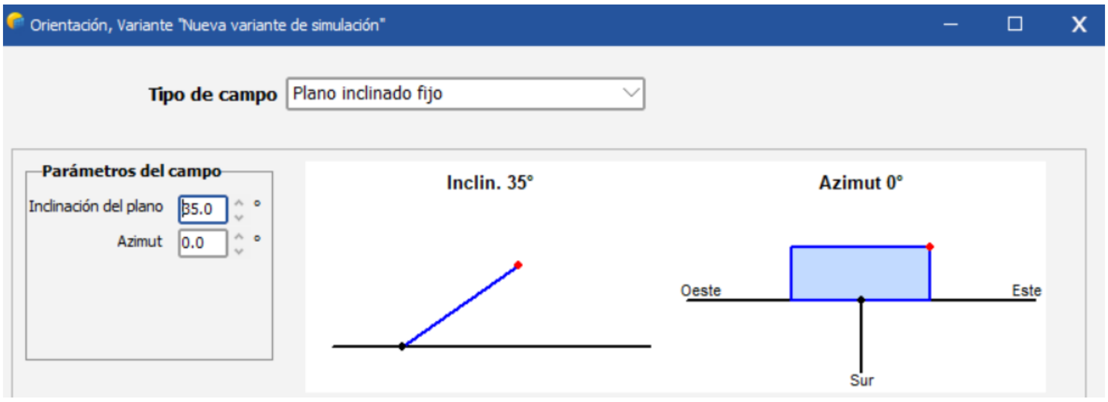

Figure 18: Screenshot of the PVSyst program where the orientation is changed.

Upon setting the site and the orientation, the electrical design was then set up in the section labeled "System." In this instance, a crystalline silicon module was designed as the one selected in *5.3.1.Initial data and components*, along with its electrical characteristics such as nominal power, open circuit voltage, voltage at maximum power, current values and temperature coefficients (Figure 19).

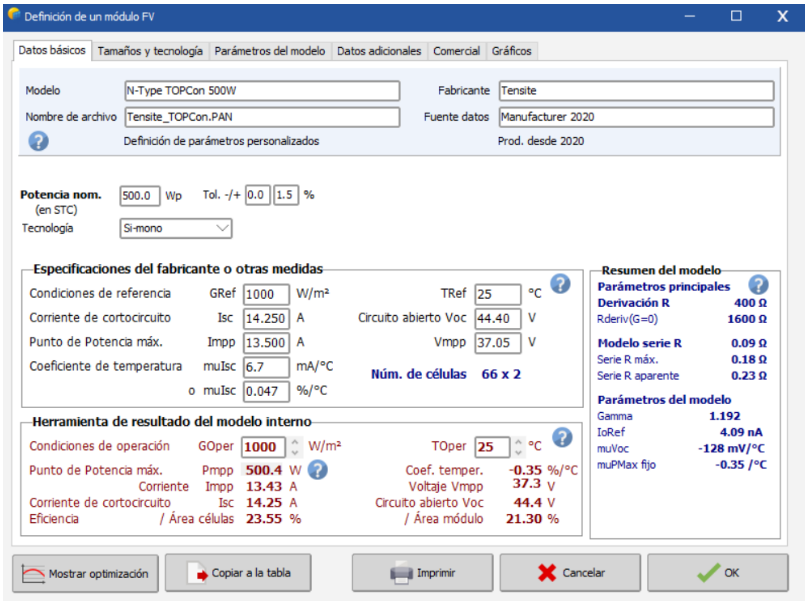

Figure 19: Screenshot of the PVSyst program where the module is created.

Then the inverter was chosen from the database, considering compatibility with the selected module in terms of maximum DC voltage, MPPT voltage range, maximum input current and nominal AC power (Figure 20).

Figure 20: Screenshot of the PVSyst program where the inverter is selected.

The system was set up as one string consisting of eight modules and placed in series, then assigned to one MPPT input. PVsyst checked if the electrical specifications are compatible through comparing the voltage of the string under low temperature to be less than the maximum DC input voltage of the inverter and comparing the operating voltage at higher temperatures to be within the MPPT voltage range. The software calculates the DC/AC ratio and issues warning signs for exceeding the electrical constraint.

Upon completing the setup of the system, the loss parameters were also checked. Standard values were used for losses due to wiring, module mismatch, incidence angle modifier losses, soiling losses and inverter efficiency. Loss parameters are used to simulate practical operations.

In the end, the yearly simulation is run using PVsyst. This software calculates energy balance on an hourly basis using meteorological year with calculations performed for irradiation, module operating temperature, DC generation, inverter losses and final AC energy output.

5.3.5 RESULTS OF THE PVSYST SIMULATION

Based on the information from PVsyst simulation (Figure 21), yearly photovoltaic energy production is equal to 4635 kWh/year. It should be noted that the aforementioned figure is indicative of AC power that comes out of the inverter based on TMY data and all the system losses.

Resultados principales

Producción del sistema	**4635**	kWh/año	Prod. normalizada	**3.17**	kWh/kWp/día
Prod. específica	**1159**	kWh/kWp/año	Pérdidas del conjunto	**0.48**	kWh/kWp/día
Proporción de rendimiento	**0.830**		Pérdidas del sistema.	**0.17**	kWh/kWp/día

Figure 21: Screenshot of the PVSyst program where the principal results are found.

In terms of resource assessment, the simulation shows that annual reference incident irradiation is equal to 3.827 kWh/m²·day (Figure 22). As can be seen from the plot, irradiation demonstrates a characteristic seasonal dependency, low values are registered in winter (December-January), whereas peak values occur in May-July. The highest monthly irradiation is registered in June and July and exceeds 5 kWh/m²·day, whereas the winter irradiation is less than 2 kWh/m²·day. The seasonal character of irradiation explains the monthly change in energy production.

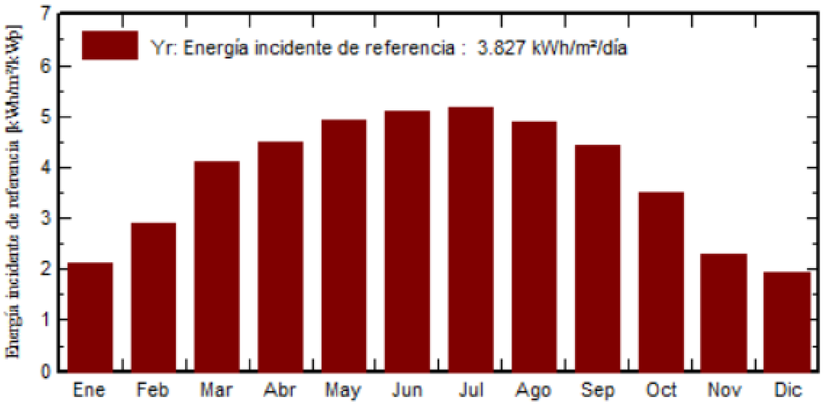

Figure 22: Irradiation diagram obtained from the PVSyst simulation.

Based on the results of the normalized production diagram (Figure 23), it was found that useful energy generated at inverter output is equal to 3.17 kWh/kWp·day, collection losses are 0.48 kWh/kWp·day, whereas system losses are equal to 0.17 kWh/kWp·day. It should be noted that a major part of energy losses is due to thermal effects and optics losses in PV array, which is typical for crystalline silicon panels.

Furthermore, it shows that monthly energy production is highly dependent on seasonality. In particular, energy production starts to increase already in March and reaches its peak in May-August, then the energy production is reduced in October-February months. Thus, it can be concluded that although annual energy balance is acceptable, photovoltaic energy generation occurs only in periods with peak irradiation.

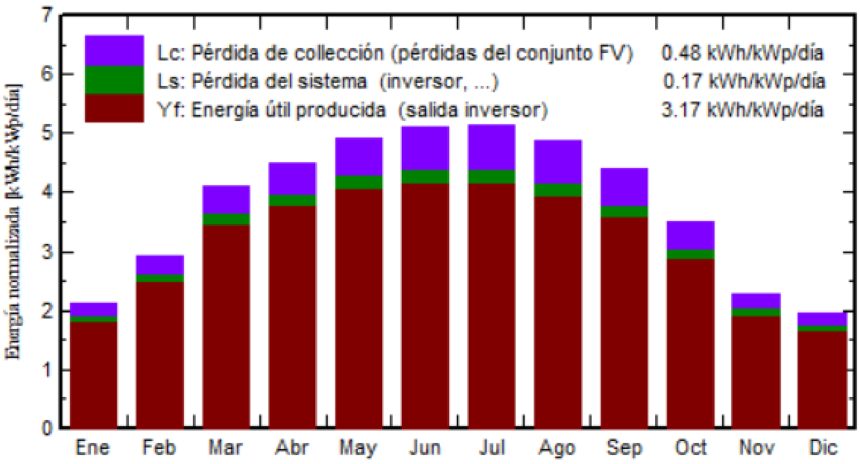

Figure 23: Normalized production diagram obtained from the PVSyst simulation.

In terms of Performance Ratio, its value is equal to 0.83 (Figure 24). The PR parameter stands for the ratio between final useful energy and reference energy and it allows assessing the quality and efficiency of the system irrespective of irradiation level. Thus, based on the PR value of 0.83, it can be stated that the electrical and thermal losses are relatively minor and the design is properly configured [26]. PR values range from 0.80 to 0.86 depending on time of year. The slight decrease of PR in summer is explained by module overheating, which leads to voltage reduction and thus decreases efficiency.

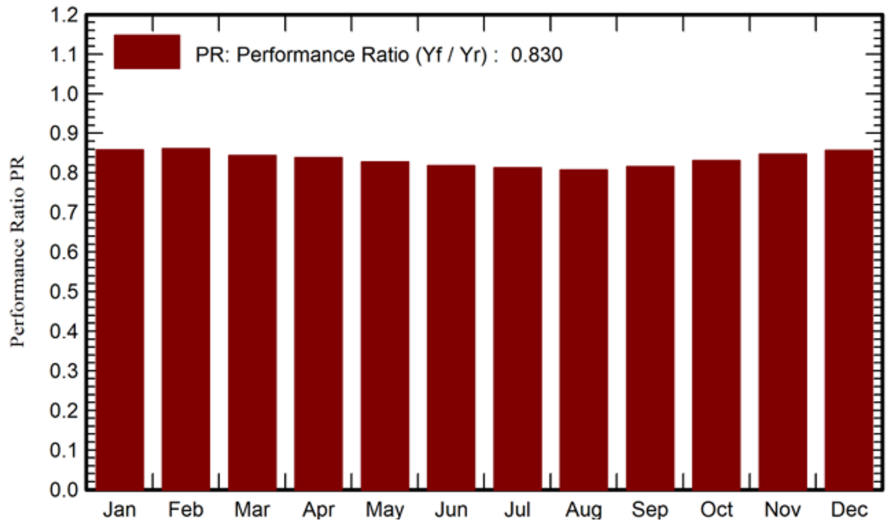

Figure 24: Performance Ratio diagram obtained from the PVSyst simulation.

Moreover, energy input into the grid graph presented in Figure 25 demonstrates a generation surplus during spring and summer months. As the system operates on a grid-tied self-consumption principle with no storage in place, all excesses generated in hours of low consumption are delivered back into the grid. It can be observed especially during April-September period, when the average surplus output exceeds 15-20 kWh/day. However, export volume becomes smaller during winter months due to less sun exposure as well as increased relative coincidence of production and residential demand.

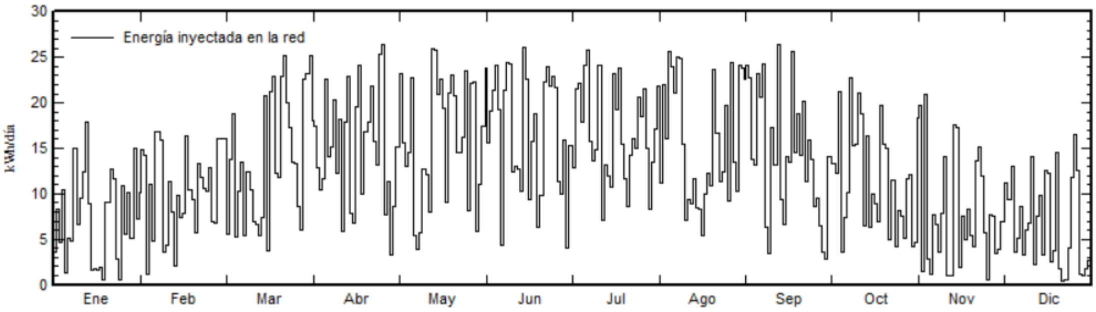

Figure 25: Normalized production diagram obtained from the PVSyst simulation.

Thus, it should be noted that according to the simulation data provided above, the installation can produce a much larger amount of energy compared to the annually designated need of solar contribution. Technically speaking, it means that the project can be said to have been developed correctly in the sense that it will provide enough generation power, increase winter generation capacity, as well as ensure better reliability of PV system performance.

Chapter 6. SIMULATION AND OPTIMIZATION (HOMER PRO)

6.1 SIMULATION METHODOLOGY

Techno-economic evaluation of the proposed solar and wind hybrid energy system will be performed through HOMER Pro software. The latter is widely acknowledged as a reliable platform that allows for simulating and assessing different system alternatives based on their operation over a whole year and the comparison made based on both technical and economic indicators.

In terms of this work, the major purpose of utilizing HOMER Pro is the identification of the best configuration capable of meeting electrical consumption needs of the chosen rural householder. More specifically, this relates to the selection and optimal sizing of all system components, i.e., PV, wind, battery, grid connections and interactions.

HOMER's simulation procedure utilizes techno-economic optimization technique, meaning that many alternative configurations can be evaluated. The program conducts hourly simulation of one year operation period (8760 hours) taking into consideration the variations of availability of renewable resources (sunlight and wind speed) and also the pattern of electrical load. As a result of the analysis, the key performance indicators such as the levelized cost of energy (LCOE), net present cost (NPC), annual energy production and renewable fraction will be estimated. Furthermore, NPC equals the total cost of the system during its lifetime reduced to present value, whereas the LCOE equals average costs of electricity generation per unit of produced energy. These measures provide possibility to compare alternatives.

The basic steps of modelling are associated with setting up certain values of parameters (electric load, renewable resources data, equipment characteristics, economic conditions).

The next step is generating and analysing all the combinations of the above parameters within certain limitations. It means that all possible variants of equipment capacity are taken into consideration. Optimal configuration is selected by minimizing the total cost of the system under required constraints.

Moreover, in addition to the determination of the best configuration, the use of the simulation framework facilitates the comparison of various system configurations, including photovoltaic systems only, wind systems only and hybrid PV-wind systems. Moreover, it is possible to evaluate configurations with and without energy storage and with different strategies for grid connection. Thus, the comprehensive evaluation is aimed at assessing the effects that the application of each technology will have on the overall system performance and profitability.

In summary, the use of the HOMER Pro software enables applying the rigorous process of analysing renewable hybrid systems in order to choose the most appropriate one.

More information available in [23].

6.2 MODEL INPUT DATA

The correctness and adequacy of modelling with the use of HOMER Pro simulation depends on the proper selection of input data for calculations. In the current case study, all the input data was selected considering the sections of the thesis that had been already completed (i.e. resource estimation, demand calculation, components sizing, etc.). Below there are listed and justified the main model inputs.

6.2.1 DEMAND

As for the electrical demand of the rural house, its estimation has been done using the bottom-up approach (*4.4.1.Daily demand*).

The average energy consumption per day comes out to be 7.81 kWh/day. For a year, this would come out to about 2850 kWh/year. Peak demand for the building is estimated to be

3.70 kW, where simultaneity factor of 0.8 has been considered for the total installed load. This estimation is based on the assumption that all household equipment does not use their rated power together at one time.

In HOMER, a representative hourly load curve has been generated that reflects the pattern of energy use in a household building, where high load curves are seen during morning and evening hours while low load curves occur during mid-day and night-time.

6.2.2 SOLAR RESOURCE

The solar irradiation at Bilbao has been studied using PVGIS-SARAH3, a database of validated high resolution solar radiation values for Europe (*4.2.Solar resource*).

The average irradiation at optimum inclination (35° tilt, South-oriented surface) is around 1450 kWh/m²·year, meaning moderate-to-high photovoltaic generation potential in Northern Spain. From this information, a PV generation of 1150 kWh/kWp/year has been estimated after considering the effects of temperature variations, conversion losses from the inverter, etc.

In the HOMER simulation model, the solar data have been provided using monthly average solar irradiation values which are converted internally by means of stochastic algorithms to daily/weekly/hourly irradiation patterns with seasonal variation, meaning higher production in summer months and lower values in winter.

6.2.3 PHOTOVOLTAIC SYSTEM

For sizing the PV generator in HOMER simulations, an excess in the minimum size of the generator has been considered. This is due to the seasonal variation of solar generation and the improvement in system robustness when low irradiation periods occur (*5.3.2.Energy sizing*). The size of the photovoltaic array used in the simulation has been set to 4 kWp, slightly exceeding the minimum size necessary.

This size has been chosen to keep consistency with the technical sizing results and to represent a real residential installation, avoiding the oversizing caused by economic considerations only and especially in grid-tied systems in which the surplus energy is fed to the grid.

Capital, replacement and O&M costs have been defined following market prices.

6.2.4 WIND RESOURCE

The wind resource has been assessed based on the hourly data from ERA5 reanalysis database that provides reliable and consistent information on wind (*5.2.Wind system design*). The wind speeds in the dataset were initially recorded at the 10-meter altitude, but subsequently, the wind speeds were estimated at the turbine hub height following the power-law wind profile. Assuming an optimal turbine hub height of 15 meters for the project location and considering the semi-rural nature of the land area, the wind shear exponent of 0.14 was used.

The resulting average wind speed at the turbine hub altitude was approximately 2.6 m/s, which is low enough for such conditions. Low average wind speed is likely to negatively affect the turbine operation since a significant amount of time will be spent waiting until the wind reaches the cut-in level.

In HOMER, the monthly average wind speeds are introduced to enable the generation of the synthetic wind profiles. Despite being rather poor in comparison with other resources available, the wind resource has been included into the assessment in case it can make a contribution in hybrid systems.

6.2.5 WIND TURBINE

As mentioned above, a small turbine with a rating power of 2 kW has been selected due to its characteristics suitable for residential applications (*5.2.1.Turbine selection*).

The turbine has been chosen because of the relatively low cut-in speed (2.5 m/s) required for operating in low-wind conditions. However, taking into account the wind limitations of the area, the generated energy is not expected to be large enough.

The simulation of the turbine is carried out according to its power curve and, therefore, allows calculating the energy produced by it depending on the profile of wind speeds.

6.2.6 BATTERY STORAGE

Considering that the inclusion of the battery affects the energy balance, this type of equipment can be taken into account as well. Nevertheless, the use of such storage devices becomes less reasonable because the system operates in connection with the electric grid and therefore, the latter can serve as a buffer storing the excess of produced energy. That is why two scenarios, i.e., with and without batteries, were considered during the calculations.

The choice of a battery was conducted from the catalog of HOMER Pro. The selected model is the Discover AES 6.6 kWh 48VDC and based on lithium iron phosphate technology, which is popular among consumers because of its high efficiency, low rate of degradation and reliability.

As for its parameters, the discover AES has a nominal energy capacity of 6.24 kWh and a nominal voltage of 48V; the round-trip efficiency is equal to 95%; a maximal charging current is 150 A; and a maximal discharging current, 600 A.

Economically, the following costs were considered: the capital cost of 7500 € and the replacement cost of 6500 € [27], besides the annual operation and maintenance costs, which were estimated at 25 €. The lifetime of the battery was 10 years and total throughput was 38,000 kWh.

With regard to operation, the battery initially had 100% SOC. At the same time, a minimum level of charge was set at 20% in order to increase the lifetime of the batteries.

6.2.7 INVERTER

The use of a power converter allowed connecting DC elements of the system with AC load and the electric grid; the maximal power of the converter was determined by the peak consumption (*5.3.1.Initial data and components*).

6.2.8 ECONOMIC PARAMETERS

Economic parameters adopted within the HOMER Pro model are based on practical assumptions concerning Spanish residential energy systems and reflect present-day market realities.

The project lifetime is assumed to be 25 years [28], being consistent with the average photovoltaic panel lifetime. Moreover, such assumption provides the possibility to make long-term calculations related to investment profitability evaluation. Discount rate equals 6% and is used in calculations [29]. It reflects moderate financial risk and is considered appropriate for residential energy projects.

Electricity purchasing price from the grid equals 0.22 €/kWh [30]. It covers both energy payment and related payments and is close to the average value in Spain in relation to residential customers. A surplus compensation price of 0.07 €/kWh was assumed for the economic analysis. Such value has been chosen as an example of a typical compensation scheme used for domestic self-consumption facilities in Spain, where the compensation policy is based on the simplified surplus compensation scheme defined by the regulations in force in Spain [1]. This price is relatively low since it concerns energy exportation into the grid that has not so high economic value as electricity consumed from the grid.

In regard to expenses and system costs, it is assumed that PV system capital cost will be equal to 1000 €/kW [3]. It is considered to be a reasonable estimate for residential installations. O&M cost is 10 €/kW/year [27]. Replacement cost will equal the initial capital cost taking into account system maintenance.

Wind turbine capital cost will be 3000 €/kW [27]. Such amount reflects the price of installation per installed kW in small-scale wind projects. Operation and maintenance expenses equal 50 €/year [31] since wind turbine has more moving parts than photovoltaic panels and requires additional maintenance.

Power converter (i.e., inverter) capital cost equals 300 €/kW [27] and its efficiency is approximately 95% [28].

Thus, these parameters have been chosen on the basis of reasonable assumptions and are important for the subsequent NPC and LCOE calculation.

6.3 DEFINITION OF SCENARIOS

To compare the performance of different system designs, several scenarios are developed and simulated via the software package HOMER Pro. These scenarios are aimed at analysing the effect of each technology and system architecture from the standpoint of technical and economic performance.

The simulations are carried out for configurations involving different combinations of photovoltaic generation, wind energy production, energy storage and connection to the grid. Such a strategy will help determine the optimal combination of components for use in this particular case study.

Among the configurations examined, there are:

- **Photovoltaic-only system**

An option featuring a photovoltaic system without any additional equipment (wind generator, battery storage and connection to the grid). It allows determining whether solar energy can supply enough power in light of its seasonality and variability within a day (Figure 26).

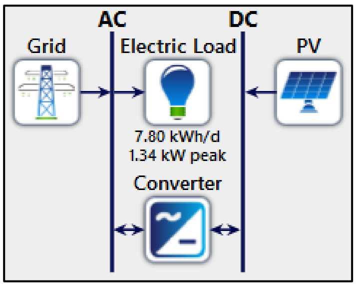

Figure 26: Schematic of photovoltaic-only system configuration.

- **Wind-only system**

This is a design including a small wind generator only. It will make it possible to assess the prospects of such a system for the present location based on existing wind conditions (Figure 27Figure 35).

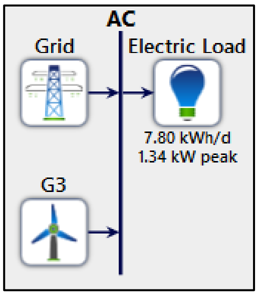

Figure 27: Schematic of wind-only system configuration.

- **Hybrid PV-wind system**

This combination will help exploit the synergy potential of photovoltaics and wind energy and make up for the lack of one source with another one, taking into account their seasonal variations (Figure 28).

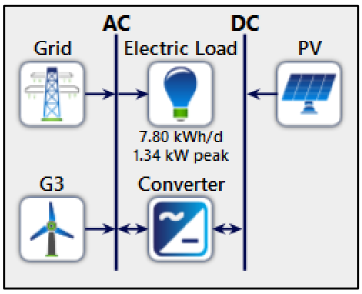

Figure 28: Schematic of hybrid PV-wind system configuration.

- **With and without energy storage**

Some of the scenarios include battery storage while others do not. The latter implies utilizing the grid as a buffer for storing excess energy and receiving electricity when renewables are inadequate (Figure 29).

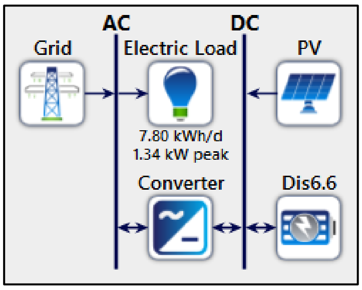

Figure 29: Schematic of PV + Battery (on grid) system configuration.

- **Grid-connected and off-grid configurations**

Grid-connected system scenarios imply connecting the system to the electricity network and thus making it possible to receive electricity through importing and export excess energy (Figure 30).

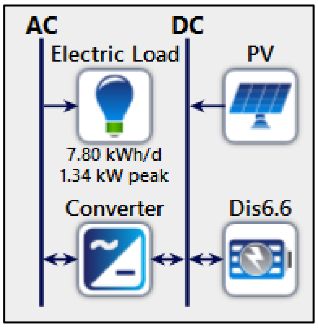

Figure 30: Schematic of PV + Battery (off grid) system configuration.

A summary of the analysed scenarios is presented in Table 4.

Scenario	PV	Wind	Battery	Grid
PV-only	✔	✘	✘	✔
Wind-only	✘	✔	✘	✔
Hybrid	✔	✔	✘	✔
PV + Battery (On grid)	✔	✘	✔	✔
PV + Battery (Off grid)	✔	✘	✔	✘
Hybrid + Battery	✔	✔	✔	✘

Table 4: Characteristics of different scenarios.

As a result, these sets of scenarios create a complete basis for the evaluation of different configurations regarding their technical and economic performance, ensuring an unbiased comparison and identifying the optimal solution.

6.4 SIMULATION RESULTS

6.4.1 SCENARIO COMPARISON

In order to evaluate the performance of the various system configurations described above, a thorough analysis was carried out using HOMER Pro software. All cases were analysed using the same assumptions regarding the technical and economic issues in order to achieve an equal comparison between the alternatives.

For every system, the optimization process carried out by HOMER Pro comprised several combinations of possible sizes for the components. Consequently, only that combination representing the least cost of operation was chosen as the result of optimization. This resulted in exclusion of all those components that were found to be uneconomical and unprofitable under the conditions assumed.

The comparison was based on some key indicators including Levelized Cost of Energy (LCOE), Net Present Cost (NPC), energy produced per year and share of renewables.

These results are presented in Table 5, where all differences in the scenarios analysed can be easily traced.

Scenario	**LCOE (€/kWh)**	**NPC (€)**	**PV production (kWh/yr)**	**Wind production (kWh/yr)**	**Grid import (kWh/yr)**	**Renewable fraction (%)**
PV-only	0.0727	7255	5195	0	1536	52.30
Wind-only	0.22	9866.36	0	0	2847	0
Hybrid	0.0727	7255	5195	0	1536	52.30
PV+Battery (On-grid)	0.0727	7255	5195	0	1536	52.30
PV + Battery (Off-grid)	NO FEASIBLE SOLUTION					

Table 5: Simulation results for different scenarios.

It needs to be said that even though both hybrid and battery configurations have been taken into account, in this case, owing to the low wind resource and economic assumptions made during the research, additional elements have not been required. Thus, optimal systems are the same as the only solar energy generation.

As follows from the results obtained, a significantly high cost of energy in the case of the wind-only scenario (see Figure 31). It is evident that while the other scenarios show a relatively low cost of energy, the wind-only scenario stands out with its significantly higher cost of energy. The reasons for such high cost are associated with insufficient capacity and output of the wind turbine in the local climatic conditions.

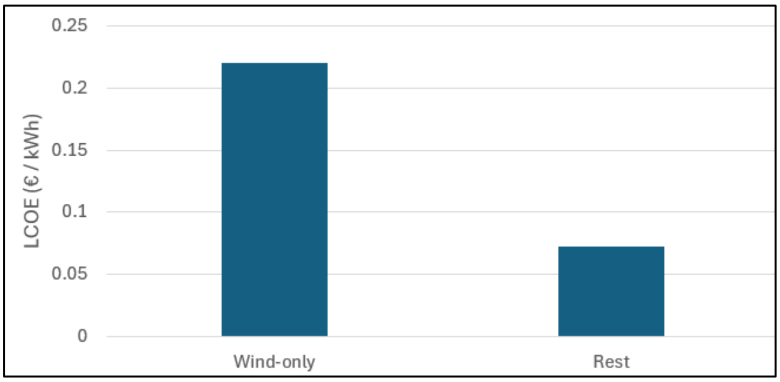

Figure 31: LCOE comparison.

Similar results were obtained in relation to Net Present Cost (NPC) that represents the total cost of system installation (see Figure 32). As seen from the figure provided below, the wind-only scenario is characterized by the significantly highest cost of installation, which is associated with poor economic performance of wind generation in this particular case. All other scenarios demonstrate considerably lower costs.

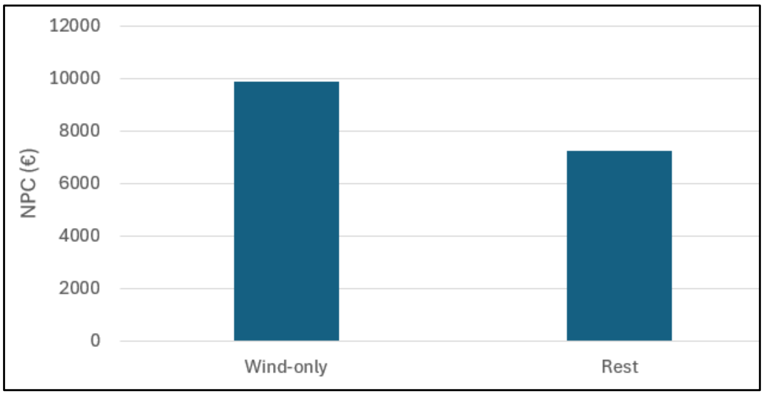

Figure 32: NPC comparison.

Grid Imports (Figure 33) demonstrate that the wind-only scenario uses electricity supplied from the grid to the largest extent among all other configurations. Such a situation is caused by lack of generation from the wind system, while other configurations manage to reduce electricity consumption from the grid thanks to photovoltaic generation.

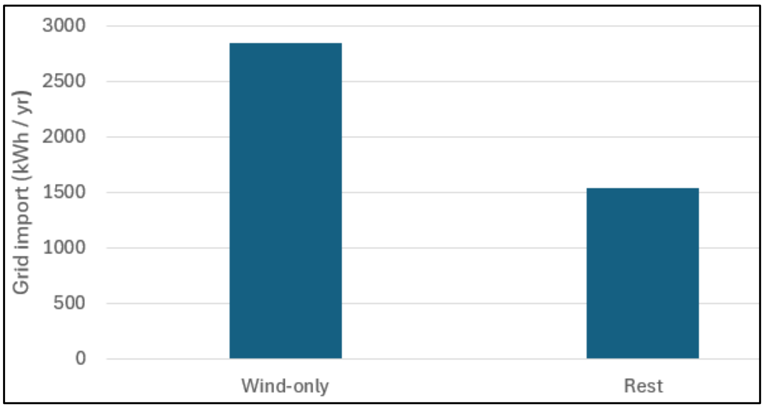

Figure 33: Grid imports comparison.

Finally, as can be seen in Figure 34, about three-quarters of energy demands in photovoltaic scenarios are met by renewable energy sources, whereas the remaining energy is supplied by the grid.

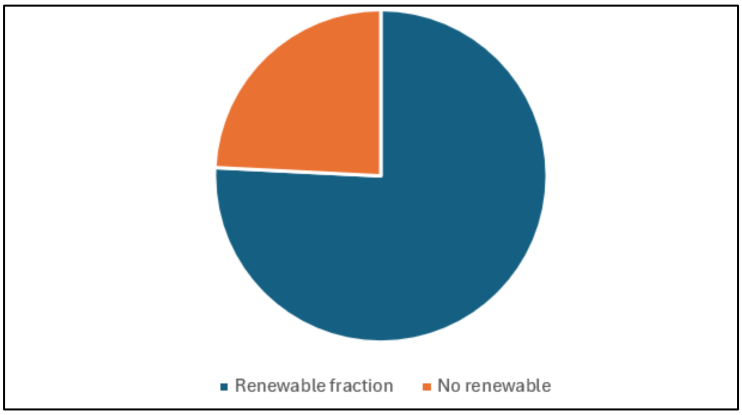

Figure 34: Renewable fraction for photovoltaic scenarios.

6.4.2 ANALYSIS BY CONFIGURATION

- **PV-only configuration**

In addition, the photovoltaic-only setup has excellent performance characteristics both technically and economically. The total electricity production amounts to 5195 kWh/year, while 1536 kWh/year (53.90%) have to be supplied by the grid leading to the renewable's percentage equalling 52.30%. Despite the fact that the annual amount of photovoltaic energy production exceeds the yearly energy consumption of the house, 46.10% of the former are used by the load due to differences in the generation schedule and consumer consumption pattern. If there is too much generation but the load is insufficient, surplus electricity gets sold to the grid; otherwise, the latter has to supply the necessary energy during the nighttime and during periods of lower solar radiation intensity. Hence, solar energy contributes significantly to meeting the requirements despite the presence of some dependency on the grid.

In terms of economics, this setup has resulted in an NPC and LCOE of 7255 € and 0.0727 €/kWh correspondingly, which makes it a quite economical variant to implement in the current situation.

This conclusion can thus be reached that photovoltaic generation can be applied effectively in the chosen area; however, it is not enough to meet the required demand.

- **Wind-only configuration**

On technical and economic levels, wind-only system proves to be totally inadequate. Thus, the power produced is equal to 0 kWh/year; thus, all electricity needs (2847 kWh/year) have to be covered by the grid.

Therefore, the renewable fraction equals 0% and the system becomes 100% dependent on grid electricity. The configuration is also unfavourable economically, as it features NPC equal to 9866.36 € and LCOE equals 0.22 €/kWh, which is worse compared to any other system configuration.

All these results show that wind energy cannot be used as a standalone solution for the analysed location because of a lack of wind energy resource.

- **Hybrid PV-Wind configuration**

In case of hybrid configuration, the results match the ones obtained from analysis of the PV-only configuration. It means that a wind generator is not involved in energy production. The energy produced using photovoltaics equals 5195 kWh/year, whereas wind power generation stays equal to 0 kWh/year.

In such way, the renewable fraction equals 52.30%, whereas 1536 kWh/year (53.90%) are drawn from the grid. Economic indices remain the same: NPC equals 7255 € and LCOE equals 0.0727 €/kWh.

In this case, the addition of wind energy to the energy system doesn't contribute anything to improving the performance of the system in view of the existing resources. As such, this element is not required in the optimization process.

- **PV + Battery (on grid) configuration**

The grid-connected PV + battery energy system shows similar results compared to those for the grid-connected PV only system. This is an indicator that the battery does not serve any role for HOMER in solving the optimization problem.

The total annual energy output of the system is 5195 kWh with 1536 kWh (53.90%) imported from the power grid and meeting only 46.10% of the total load, while the renewable percentage is 52.30% – equal to the PV-only case.

The economics of the system does not change with the introduction of the battery as well. The cost (NPC) remains unchanged at 7255 € while the LCOE remains 0.0727 €/kWh.

It can thus be stated that there are no economic benefits in introducing the battery in the grid-connected situation, as the power grid acts as the energy buffer.

- **PV + Battery (off grid) configuration**

The off-grid energy system is not a viable option in this case.

This suggests that the system cannot cover the demand reliably without the use of the power grid. This means that the photovoltaics combined with battery storage is not enough for guaranteeing the energy supply.

It is evident that reaching complete energy self-sufficiency may prove to be extremely challenging given that there are not much renewable power production and storage of surplus power is difficult.

6.4.3 DISCUSSION OF RESULTS

From the obtained findings it can be seen that the efficiency of each particular installation depends on the characteristics of the renewable resource available on the chosen location.

Photovoltaic energy installation shows stable performance, which is associated with the stability of the resource; moreover, it covers 46.10% of the demand for energy thanks to a relatively high production amount equal to 5195 kWh/year. The dependence from the grid is medium (53.90%) but still provides the renewable fraction of 52.30%. This renewable fraction can be defined as the share of the energy coming from renewable sources in the total supply of energy into the system. The value of this fraction exceeds that of the PV demand cover since a substantial share of produced photovoltaic energy (74.70%) is exported to the grid when household demand is lower while import from the grid is necessary at night and in case of low solar radiation. Generally speaking, it may be concluded that solar energy is the only viable type of renewable energy in this particular situation.

However, the wind energy source adds nothing to the system configuration regardless of how the latter looks like. In this context, the wind turbine generates 0 kWh/year because local winds do not have enough speed to make the wind turbine work properly. Although the preliminary estimate of the wind energy resource gives about 340 kWh/year annually, HOMER simulation shows that there is no wind generation included in the optimal configuration and the wind energy source is excluded because of poor economy of the wind technology, which is not able to compensate additional investment costs by generating enough energy. That is why the wind-only system depends totally on the grid and the hybrid system functions just as well as the PV-only system.

The absence of benefits in the hybrid and wind-only configurations is explained by the inability of the hybrid system to benefit from combining different sources of renewable energy, since both of them should be present in sufficient quantity. Although the PV energy is typically considered complementary to wind energy, it does not apply in the present situation due to the lack of the latter. Therefore, the hybrid system configuration is worse than the PV-only one from the technological and economic points of view.

Moreover, it should be mentioned that the electrical grid works as a buffer that allows storing the excessive electricity generated in the PV system. Thus, the PV + battery configuration gives exactly the same results as the PV-only system because of the non-use of batteries in the optimal solution.

Furthermore, the lack of an effective stand-alone option proves how vital the presence of a grid in this project is. It would be impossible to achieve supply stability based only on photovoltaic energy production and storage options, making full autonomy unachievable.

Thus, as can be seen from this analysis, both hybridization and energy storage have no benefits in this thesis and must be approached based on specific site considerations and project requirements.

Chapter 7. OPTIMAL SYSTEM CONFIGURATION

HOMER optimization produces the PV-only configuration as the most effective one, as this is the most efficient design in terms of cost-effectiveness, while at the same time being quite efficient in terms of renewable energy use in the context of the analysed system.

From a purely technical standpoint, this system is solely powered by photovoltaic generation, as there is not enough wind energy present in this location to generate electricity. The system uses a grid connection, where the electric network serves as an alternative energy supply when solar energy levels are low.

Regarding the components' sizing, the most efficient configuration features PV capacity sufficient for generating up to 5195 kWh/year of electricity or 46.10% of total energy consumption. Moreover, 1536 kWh/year or 53.90% of energy comes from the electric grid.

On an economic aspect, the present configuration presents the best combination in terms of performance, having the NPC and LCOE of 7255 € and 0.0727 €/kWh, respectively. Such results demonstrate that the chosen solution is indeed better than those which include wind energy and batteries as a part of the system.

Finally, the most appropriate solution for the problem at hand takes into consideration both the economic aspects and the great potential of photovoltaic energy at the chosen location as well as the significance of grid connection.

7.1 ENERGY PERFORMANCE ANALYSIS

7.1.1 MONTHLY PRODUCTION

The monthly electricity production of the system is presented in Figure 35. It presents the month-wise electricity generation of the proposed system. It can be seen that photovoltaic generation makes the biggest contribution to electricity production of the system.

It should be noted that maximum electricity generation was achieved between May and August, where photovoltaic power generation made up approximately 0.60-0.65 MWh per month. The reason for that is more sunlight during such periods of the year.

On the contrary, electricity production falls on the autumn and winter months, when photovoltaic generation achieves its lowest monthly production values of approximately 0.40-0.50 MWh.

It must be mentioned that there are also some grid imports all the year round; however, their volume is smaller than that of the PV production. There is an obvious increase in the need for electricity from the grid during the winter months – specifically November, December and January, where there is less solar power produced. In this case, the grid's share grows since it is necessary to compensate for the lack of renewable generation.

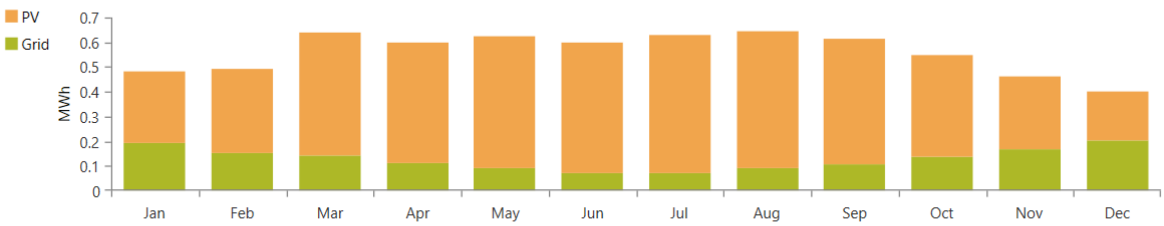

Figure 35: Monthly electric production for scenario PV-only configuration.

In conclusion, it is possible to say that the photovoltaic plant is able to provide quite a high share of annual energy demand; however, it still cannot fully substitute the use of the grid.

7.1.2 GRID INTERACTION

Interaction with the electrical network is one of the major aspects affecting the energy balance of the system. In accordance with the simulation results, the yearly electricity taken from the power grid totals up to 1536 kWh/year or 53.90% of total demand.

From the data above it may be concluded that despite the significant contribution made by the photovoltaic system into meeting the energy requirements, the generated electricity is not enough to supply all the needs completely. Consumption exceeding generation occurs at nighttime and during the winter season when the irradiance level is low and the amount of photovoltaic production is insufficient.

The total annual output of photovoltaics amounts to 5195 kWh/year meaning that the size of the system is determined by the necessity to supply part of the requirements without generating considerable excesses in order to export electricity to the network. The latter happens only when the instantaneous PV output is higher than load during certain periods of time.

This fact can be explained by considering the seasonal availability of solar irradiance shown in Figure 36 where its highest values are observed between April and September.

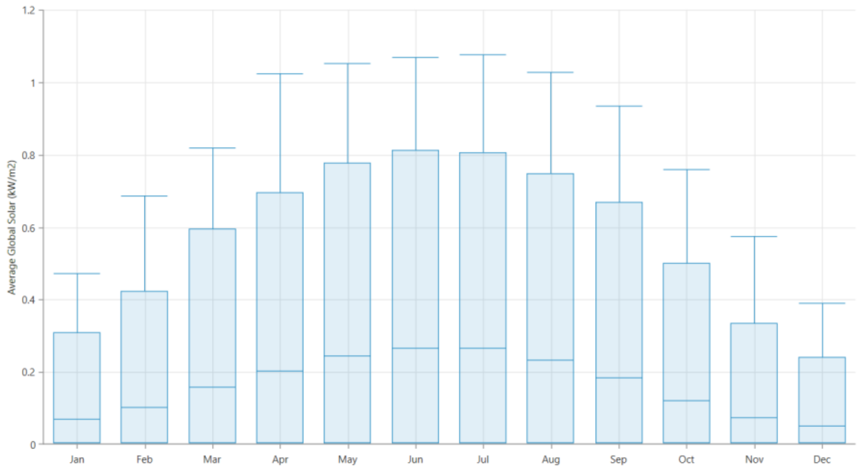

Figure 36: Monthly average grid sales.

During the winter season, especially from November through January, lower amounts of sunlight decrease the efficiency of PVs, thus making the reliance on grid power higher. In that time, the exports become minimal or even zero because the majority of energy produced is used immediately.

Generally speaking, the findings indicate a two-way impact of the electrical grid: it becomes a reserve source of energy in case of insufficient renewable sources, while occasionally, it may also serve as a place where extra energy can be stored.

7.2 ECONOMIC PERFORMANCE ANALYSIS

7.2.1 NPC

For the optimal case, PV-only case, Net Present Cost (NPC) equals 7255 €. This cost covers the overall lifecycle cost incurred when implementing and operating the proposed power generation configuration. NPC is still quite acceptable among alternative cases, especially if wind generation is considered.

The reasons for such a low NPC can be attributed to several circumstances. Firstly, operation and maintenance costs of PV systems are relatively low. Secondly, PV panels produce annually 5195 kWh, satisfying about 46.10% of the annual demand and thus reducing the amount of electricity bought from the external source.

At the same time, in contrast to the previous case, the system will not provide significant energy surplus and thus savings will occur due to its self-sufficiency but not through energy selling. Thirdly, since the system is connected to the grid, there will be no need for any batteries that would add to the total initial investment cost.

Thus, from the financial point of view, such a result means that the chosen configuration can be qualified as economically balanced, providing an appropriate balance between initial costs and reduced energy consumption.

7.2.2 LCOE

In the most favourable case, PV-only case, the LCOE is 0.0727 €/kWh, which is relatively low for a household's electricity cost. This implies that it makes economic sense to produce energy through this method. It means that each kWh of energy generated by the photovoltaic system is cheaper or at least as expensive as energy bought from the grid. The LCOE for a photovoltaic system depends on how the ratio between the cost of the system and the energy produced yearly is optimized. In this case, the system produces 5195 kWh annually, which covers a considerable amount of the load without any overproduction. Therefore, the cost per kWh remains relatively low rather than very low.

In addition, the LCOE shows a good and balanced design. This means that the photovoltaic system capacity was optimized so as to minimize grid electricity consumption without having to use an oversized photovoltaic system.

Conclusively, this implies that photovoltaic generation is technically appropriate and economical.

7.2.3 FEASIBILITY

Therefore, one can state that the PV-only option under discussion may be called economically feasible in the given situation. The installation offers a proper balance between expenses required to buy components and energy produced as a result of the installation operation. Thus, the price of electricity becomes competitive with the electricity cost provided by the grid.

A share of renewable resources used as much as 52.30% shows that the analysed system reduces dependence from grid electricity. Still, in spite of using renewables, some electricity should be bought in order to maintain system efficiency during periods of insufficient solar energy generation. However, this dependence makes it possible to lower electricity costs.

As compared with oversized systems, the given installation requires optimal energy consumption as well as the ability to produce enough energy in order to meet electricity needs. That is why economic efficiency is determined by self-consumption of produced electricity and not export of energy surpluses to the grid.

The absence of battery installation in the analysed system serves as another important point which proves feasibility of the installation. Being connected to the grid, it receives electricity and exports any possible surpluses. Therefore, there is no need to invest additional money in installing batteries that will make a system expensive and provide no economic advantages.

In general, one may say that the considered PV-only configuration is characterized by high financial feasibility.

Chapter 8. ECONOMIC EVALUATION

Economic assessment of the most advantageous system configuration takes place based on the solution with pure photovoltaics, which HOMER suggests as the best option.

8.1 CAPEX AND OPEX

To begin with, the capital investment (CAPEX) required to implement the solution is evaluated according to the power of photovoltaics used and inverter. The power of the photovoltaic system under consideration equals 4 kW, while the price per kW equals 1000 €/kW. Thus, the CAPEX of photovoltaics is estimated as:

$$CAPEX_{PV} = 4 \cdot 1000 = 4000\,€$$

In addition, the inverter is sized to approximately 3.6 kW, with a unit cost of 300 €/kW, leading to:

$$CAPEX_{inv} = 3.6 \cdot 300 = 1080\,€$$

Consequently, the total initial investment of the system is:

$$CAPEX_{total} = 4000 + 1080 = 5080\,€$$

As for operating expenses (OPEX), the main characteristic of photovoltaic power plants can be considered their rather low maintenance needs. In this case, OPEX equal 10 €/kW/year. For a 4 kW system, OPEX will be as follows:

$$OPEX = 4 \cdot 10 = 40\,€/año$$

8.2 COST-BENEFIT ANALYSIS

In order to evaluate economically the efficiency of the system proposed, a cost-benefit analysis can be carried out by comparing the optimal photovoltaic configuration against the base case where the house is powered by the grid.

In the baseline case without solar PV system, with annual energy consumption equal to 2850.20 kWh/year at electricity cost of 0.22 €/kWh, the annual cost is estimated as:

$$Cost_{base} = 2850.20 \cdot 0.22 = 627.04\,€/year$$

The annual energy imported under the optimal photovoltaic configuration is equal to 1536 kWh/year, thus leading to annual cost equal to:

$$Cost_{import} = 1536 \cdot 0.22 = 337.92\,€/year$$

At the same time, annual energy production of the photovoltaic system is equal to 5195 kWh/year. However, as not all this energy will be exported and some energy will be used by the household, the energy consumed by the homeowners will be:

$$Energy_{self-consumed} = 2850.20 - 1536 = 1314.20\,\text{kWh}/year$$

The remaining energy is exported to the grid:

$$Energy_{export} = 5195 - 1314.20 = 3880.80\,\text{kWh}/year$$

Assuming a surplus compensation price of 0.07 €/kWh, the annual revenue associated with exported electricity is:

$$Income_{export} = 3880.80 \cdot 0.07 = 271.66\,€/year$$

Then, taking into account electricity import cost, revenue from export and operation and maintenance cost of 40 € per year, the annual cost of the system can be estimated as:

$$Cost_{net} = 337.92 - 271.66 + 40 = 106.26\,€/year$$

Therefore, the annual net economic benefit is:

$$Benefit_{annual} = 627.04 - 106.26 = 520.78\,€/year$$

This value represents the annual positive cash flow generated by the investment.

8.2.1 NPV

Taking into consideration the time value of money, the NPV (Net Present Value) is estimated for an overall period of 25 years of operation, with a discount rate of 6%.

The NPV is defined as:

$$NPV = -CAPEX + \sum_{t=1}^{25} \frac{Benefit_{annual}}{(1+0.06)^t}$$

Since B_{annual} is assumed to remain constant over time, the NPV can be calculated using the closed-form expression for an annuity:

$$NPV = -CAPEX + Benefit_{annual} \cdot \frac{1-(1+r)^{-n}}{r}$$

Where r is the discount rate (0.06) and n is the project lifetime in years.

Replacing it is obtained:

$$NPV = -5080 + 520.78 \cdot \frac{1-(1+0.06)^{-25}}{0.06} = -5080 + 6657.31 = 1577.31\,€$$

A positive NPV confirms that the investment is economically profitable over its lifetime.

8.2.2 ROI AND PAYBACK

The return on investment (ROI) is calculated as:

$$ROI = \frac{Benefit_{annual}}{CAPEX} = \frac{520.78}{5080} \cdot 100 = 10.25\%$$

That is about 10.25% of the initial cost of investment, which makes the project financially viable based on this information.

Similarly, the simple payback period is:

$$Payback = \frac{5080}{520.78} = 9.75\ years$$

Accordingly, this shows that the system can pay back the initial investment within ten years, which matches common PV residential systems.

8.2.3 COST OF ENERGY COMPARISON

The Levelized Cost of Energy obtained from the HOMER simulation is:

$$LCOE = 0.0727\ €/kWh$$

It is much less than the cost of grid electricity, which costs 0.22 € per kilowatt-hour (€/kWh), thereby showing that it is cheaper to generate electricity through photovoltaic systems.

8.3 OVERALL ECONOMIC ASSESSMENT

On the whole, the cost-benefit analysis shows that the photovoltaic-only solution is a good choice for the analysed building due to the positive yearly income of the system because of the decrease in electricity usage from the power grid and additional money for the exported electricity.

Economically, the considered energy generation system is profitable as the project has the Net Present Value of about 1577 €, meaning that during its lifecycle, the profits of the solution exceed the costs. Additionally, the comparatively low payback period makes the considered solution even more attractive as one can see the payback of the initial investments within a reasonable amount of time.

The economic stability of the system is also worth noting since it allows avoiding electricity price risks through generating renewable energy. Thus, one will have more predictable electricity expenses, which is also important.

To sum up, the considered photovoltaic-only solution seems to be the right choice as the installation will provide not only an environmentally friendly solution for electricity production but also a profitable one.

Chapter 9. SENSITIVITY ANALYSIS AND FUTURE SCENARIOS

Sensitivity analysis and the assessment of future scenarios will be presented in this chapter for assessing the robustness of the proposed system with varying economic conditions. Sensitivity analysis is a useful tool for understanding how changes in key variables affect system performance and economic viability.

All the different variations are applied to the optimal system structure, which was determined in previous chapters, namely solar-only on-grid system. This optimal system configuration is used as a reference scenario for the sensitivity analysis with regard to changes in electricity prices, changes in investment cost and solar resource.

9.1 *ELECTRICITY PRICE VARIATION*

To assess the sensitivity of electricity price on the proposed system economics, sensitivity analysis was performed based on changes in electricity price while maintaining other parameter values constant.

The range of selected electricity prices (0.15-0.40 €/kWh) is chosen due to reflecting possible deviations in Spanish retail electricity prices both in low-price scenarios and possible price rises in the future. The average value (base case) of electricity price is set as 0.22 €/kWh, which is a reasonable average price for electricity for end consumers in Spain.

The most economically relevant indicators that were calculated and discussed in this research include LCOE, NPC, ROI and payback time. The results of the sensitivity analysis can be found in Table 6.

Scenario	**Electricity Price (€/kWh)**	**LCOE (€/kWh)**	**NPC (€)**	**ROI (%)**	**Payback (years)**
Low	0.15	0.0557	5561	8.90	12.00
Medium	0.20	0.0727	7255	9.50	9.75
High	0.30	0.0921	9191	13.00	8.00
Very High	0.40	0.116	11610	16.00	6.60

Table 6: Price variation scenarios.

In this regard, it is obvious that the financial efficiency of the system is greatly dependent on the electricity price level. In particular, as anticipated, the increase in electricity price results in significant improvements in all profitability indicators.

In terms of Net Present Cost (NPC), its level grows when there are higher electricity prices, as it goes up from 5561 € under the low-price level assumption to 11610 € for the very high level of electricity price. This can be attributed, first of all, to the increased cost of the electricity produced from the external grid over the lifetime of the system.

On the other hand, in spite of the growth in the total cost of the system, its profitability grows dramatically. Thus, Return on Investment (ROI) goes up from 8.9% to 16.0%, while the payback period decreases from 12.0 years to 6.6 years. Consequently, the economic efficiency gained as a result of the system self-consumption is increasing along with electricity price.

Finally, regarding the Levelized Cost of Energy (LCOE), it can be seen that it also increases in line with electricity price. However, the relative efficiency of the solar PV system remains higher than that of the grid electricity.

9.2 INVESTMENT COST VARIATION

The cost of initial investment constitutes an important factor in defining the economic viability of renewables systems. With regard to this factor, a sensitivity analysis was performed through a cost multiplier, which is illustrated below in Table 7.

The case of 1.00 cost multiplier defines the baseline cost of the investment, corresponding to the nominal cost of the system. Other cases were designed in order to take into consideration both possible cost reductions and additional cost increases related to the cost multiplier. The values of the cost multiplier ranged from 0.50 to 2.50. Thus, a combination of favourable market trends and negative scenarios of increased costs can be analysed.

Scenario	Capital Cost Multiplier	LCOE (€/kWh)	NPC (€)	ROI (%)	Payback (years)
Very Low	0.50	0.0526	5255	18.00	5.75
Low	0.75	0.0627	6255	12.40	7.70
Base	1.00	0.0727	7255	10.30	9.75
High	1.50	0.130	8492	9.90	11.0
Very High	2.00	0.145	9492	7.90	15.0
Extreme	2.50	0.220	9866	-	-

Table 7: Investment cost variation scenarios.

The findings of the sensitivity analysis reveal that the economic performance of the system is highly sensitive to the initial investment cost. Naturally, a reduction in the initial investment cost leads to better economic performance, while higher investment costs decrease economic viability.

Under the favourable assumptions of a very low initial cost of the system (cost multiplier = 0.50), the system reaches maximum performance, yielding LCOE at 0.0526 €/kWh, ROI of 18.00% and a payback period of 5.75 years. Such high sensitivity of the system to any possible cost reductions in the cost of photovoltaic technology can be explained.

The increase in the initial cost of investment leads to a deterioration of all profitability parameters. In particular, ROI is decreasing from 18.00% (very low investment cost) to 7.90% (a cost multiplier of 2.00). The payback period also increases correspondingly from 5.75 to 15.0 years. The cost of electricity (LCOE) also rises substantially under this scenario.

Notably, for an extreme cost multiplier value of 2.50, there is no integration of photovoltaic technology anymore.

9.3 SOLAR RESOURCE VARIATION

The amount of solar resource is a determining factor in the work of photovoltaics-based systems. For the sensitivity analysis to show how variations in the climatic conditions affect the system, different average levels of the global horizontal irradiance have been considered (GHI).

Base case corresponds to the level of 3.91 kWh/m²/day as a mean annual value, as chosen for the current study location. In order to analyse various possibilities of deviation due to weather changes, uncertainty, or site characteristics, ±40% have been used (Table 8).

Scenario	**Solar Resource (kWh/m²/day)**	**LCOE (€/kWh)**	**NPC (€)**	**ROI (%)**	**Payback (years)**
Very Low	2.35 (-40%)	0.179	9008	9.80	11.00
Low	3.13 (-20%)	0.144	8221	11.90	8.90
Base	3.91 (0%)	0.0727	7255	10.30	9.70
High	4.70 (+20%)	0.0533	6172	12.10	8.65
Very High	5.47 (+40%)	0.0458	5592	12.95	8.10

Table 8: Solar resource variation scenarios.

From Table 8 one can see the significant effect of solar resource availability on system performance. Indeed, an increase in GHI positively affects economic parameters whereas decreased values negatively affect the system profitability.

When analysing the very low GHI scenario, one can observe the worst system performance, as expressed through the highest LCOE value – 0.179 €/kWh and the payback period of 11 years. This is explained by the low energy generation capability resulting in poor economic advantages from using photovoltaic technologies.

The further increase of GHI values results in improvement of system efficiency with the best parameters at a +40% scenario. In this case, the lowest LCOE value of 0.0458 €/kWh indicates extremely efficient energy production while the shortest payback period of 8.1 years also shows a great performance of the system under study.

Net present cost (NPC) also decreases from the 9008 € in the worst scenario to 5592 € at the most effective one due to a lower grid power consumption as the part of load satisfied by photovoltaic generation increases with GHI.

It should be mentioned that ROI does not behave in a strictly monotone way. This pattern is caused by the variation in the optimal system design with the amount of the solar resource used, particularly, in the amount of installed PV capacity as managed by HOMER software.

9.4 DISCUSSION

Conducted sensitivity analysis shows that the economic efficiency of the suggested system depends on both external and internal parameters, but not on any single one. Every variable has a significant influence on the results, but the combination of their values defines the real feasibility of the project.

The economic performance of the photovoltaic system under study is highly influenced by electricity price among all considered variables. The higher electricity price makes the considered photovoltaic system even more economically advantageous without making the system itself more efficient. Thus, the major issue here is that the feasibility of the system depends on the external market conditions and this makes the proposed approach vulnerable to changes in these conditions. In other words, the economic advantages can disappear at any moment and become a disadvantage for the system operator.

In comparison, investment cost can be referred to as an internal parameter and its influence on the results of the sensitivity analysis can be discussed separately from others. As it was mentioned above, the investment cost serves as a boundary line after which the photovoltaic system becomes uneconomic. This finding is especially important in relation to the renewable energy systems since renewable energy cannot be guaranteed to be introduced; its cost-effectiveness should be ensured.

The third important variable is solar resource variability, which represents an element of physical uncertainty of the system under discussion. Unlike two others, solar resource variability does not have as strong an influence on the profit indicators as electricity price and investment cost. It still impacts the indicators, but not that significantly.

One interesting thing is how the system configuration changes according to the conducted sensitivity analysis. Thus, for instance, the optimization performed by HOMER leads to variation of photovoltaic capacity. This explains some non-linear behavior, especially in case of ROI indicator.

Speaking about the general picture, it is obvious that the sensitivity analysis results can serve as a confirmation of how important the consideration of uncertainty is in the early stages of project designing. Indeed, while a solution may be considered perfect for certain conditions, it may fail to be optimal under other circumstances.

Thus, the sensitivity analysis shows that the system's feasibility depends largely on its cost. In this regard, the development of photovoltaic technologies will help improve the economic feasibility of such systems further. At the same time, situations in which high investment cost or low electricity price make the introduction of renewable energy sources uneconomical should also be considered.

Chapter 10. REGULATORY ANALYSIS AND IMPLEMENTATION BARRIERS

10.1 SELF-CONSUMPTION FRAMEWORK

Indeed, the legal framework concerning the electricity self-consumption in Spain represents another essential component which should be taken into account when considering the operational and financial conditions under which the system can be integrated. Although most of the key provisions relating to self-consumption have been described in *3.3. Self-consumption regulation*, this section will focus on the concrete implementation aspects of those regulations.

According to the Spanish self-consumption regulation, which is currently formulated in Royal Decree 244/2019 [1], various technical, administrative and financial requirements to the installation have been established. It should be recalled that the regulation established a simpler regime allowing distributed generation facilities to overcome some obstacles and become more widespread across Spain. Consequently, this section will not discuss the legal aspect of the regulation but will concentrate on its practical application aspects.

First, from an operational viewpoint, the regulation distinguishes two major types of self-consumption: self-consumption without a surplus and self-consumption with a surplus. The choice of one of these two categories directly influences the integration of the system into the grid. In systems without a surplus, the exportation of energy becomes technically impossible due to the anti-export device installation. On the contrary, systems that have surplus allow for electricity surplus to be exported, making possible economic valorisation processes which will be examined further in section *10.2.Net metering and simplified compensation*.

In relation to the case study presented in this dissertation, the system will operate in self-consumption with surplus scheme. This means that firstly, the generated energy is consumed locally, with excesses being fed into the grid. This description is fully coherent with the system dynamics explained before, since the grid not only serves as a reserve energy supplier but also as a surplus consumer.

The particularity of the Spanish legislation is the distinction made between small scale and big scale projects [12]. In particular, systems such as the studied in this dissertation can take advantage of simplified administrative procedures, especially when connected to the network through existing supply points.

From a technical point of view, although there are some simplifications in terms of permits, the fulfilment of the requirements for grid connection cannot be avoided. According to Chapter 3. installation will need to meet grid connection requirements according to Low Voltage Electrical Regulation and Distribution System Operator guidelines.

From an economic standpoint, the notion of self-consumption has a significant effect on the system profitability due to the way electricity flows are estimated. With a higher priority given to the utilization of generated power within the site and low values attributed to the export, it becomes essential to optimize systems in a manner that ensures high self-consumption ratios, which is especially true for the current project due to its specific design.

Moreover, the described regulatory model also incentivizes the use of grid-connected systems over standalone systems since, as seen from the simulated data, the presence of the grid enables to eliminate the necessity of having battery storage as the grid can be used both for the absorption of excess power and provision of additional electricity in cases when its generation is insufficient.

However, one must note that despite the positive influence of the present-day regulations on the economic situation, there still are some shortcomings. In particular, with the help of the simplified surplus compensation scheme, it is possible to generate revenue from the exported energy only up to the amount that is used for compensating its consumption by the producer.

As a result, overproduction will not bring additional income, making it impossible to optimize the economy.

10.2 NET METERING AND SIMPLIFIED COMPENSATION

The economic aspect of the surplus electricity becomes especially significant in the analysis of self-consumption models due to its impact on the economic efficiency of distributed power production facilities. As far as the Spanish regulations in the field are concerned, they substantially differ from the traditional net metering arrangements used in other countries. The mechanism of self-consumption in Spain is based on the simplified scheme of economic compensation introduced by Royal Decree 244/2019 [1].

Classical net metering provides consumers with an opportunity to balance the volume of electricity supplied to the grid and received from it over a certain billing period. Thus, the grid acts as a virtual battery and allows customers to sell excess electricity and buy less of it later in order to cover the expenses related to their consumption. At that, the cost of excess electricity is usually equal to the retail price for consumed energy, thus, allowing customers to minimize their bills to zero or even accumulate surplus.

In Spain, however, a completely different approach is followed. Namely, the simplified scheme of economic compensation provides individuals with an opportunity to gain economic benefits from the surplus electricity they produce yet not being a kind of energy sales arrangement.

In such cases, the price of the energy sold to the grid will depend on the negotiated compensation rate, which will always be less than the retail price of electricity. The compensation amount will be subtracted from the cost of the electricity consumed and paid for from the grid in the same billing cycle. However, the compensation received can never exceed the cost of the energy used. This means that the end-user does not receive any economic benefits, apart from reducing the energy bill to zero.

It should be noted that this particular feature of the compensation regime implies an interesting aspect when considering the optimal design of solar PV systems. For instance, unlike in net metering schemes, where over-sizing the power system can result in an economic benefit, the Spanish model will encourage consumers to avoid excessive capacities. Once the electricity bill becomes zero, all extra energy will lose its economic significance. Therefore, the optimal ratio of energy consumption will play an even more significant role in the design of solar PV power plants than generation capacity.

Moreover, the eligibility criteria for using the simplified compensation mechanism include, but are not limited to, the following aspects. In most cases, consumers should not have the capacity of more than 100 kW, operate on the low voltage grid and be connected with their consumption point. Moreover, a signed contract on compensation rates should exist between the consumer and the energy retailer.

In this thesis, the compensation system considered within the analyses is the one described above. The economic values included in the HOMER simulations represent the regulation, with a cost of grid electricity of 0.22 €/kWh and a price of surplus energy of 0.07 €/kWh. The price asymmetry in this regulation causes some of the most important effects observed in the economic analysis of this thesis.

First of all, a smaller value of surplus energy compensation makes energy export less economical compared to consumption. In consequence, the profitability of the system relies mostly on self-consumption and much less on energy export. This is confirmed by the size of PV systems calculated using HOMER, which ensures a substantial amount of self-consumption while avoiding unnecessary overproduction.

Second of all, the compensation rule strengthens the importance of the electric grid as a complement to the system and not a revenue source. It enables economical use of surplus energy, but at the same time, it does not motivate any energy exports from the system.

Thirdly, the lack of net metering conditions can explain the economic non-optimality of particular configurations of the system, e.g., battery storages. In a situation of net metering, the use of batteries would enable maximization of profits through the optimization of energy export and/or price arbitrage, but in the analysed case, this is not necessary.

However, besides the general description of regulations, it is very important to focus on the economic impact that they have on the optimal configuration of renewable systems.

An economic asymmetry caused by different values of the cost of electricity purchased from the grid (0.22 €/kWh) and the cost of surplus energy (0.07 €/kWh) becomes apparent in the profitability of particular actions performed by the system. From an economical point of view, each kWh produced through self-consumption of generated energy creates the profit corresponding to the value of electricity consumed from the grid, while the exported surplus energy produces only the limited profit corresponding to the value of the subsidy.

Consequently, self-consumption produces approximately three times greater economic effect. This has important implications in the case of the system analysed in this thesis. Despite the capacity to generate a significant amount of surplus energy due to its capacity, the economic effect related to its generation is quite low. Part of the potential of this energy goes unused in terms of profitability.

This regulation is also relevant to the limited economic efficiency of the wind subsystems of the system. Due to a moderate wind resource availability and relatively low value of surplus energy, the investments in generating this type of energy are not economically profitable. Therefore, no economically significant advantage of wind energy use is observable.

More information available in [32]

10.3 SURPLUS ENERGY SALE CONDITIONS

In addition to the rather simple compensation model introduced in *10.2.Net metering and simplified compensation*, under the Spanish regulation, self-consumption facilities can sell their surplus electricity into the market as well. However, unlike the previously discussed method of compensation for surplus electricity, selling surplus into the market is significantly more complex in terms of administration, technology and economics and, thus, not applicable for residential installations like the one used as an example throughout this thesis.

With the introduction of Royal Decree 244/2019, facilities that have surplus can abandon the simplified compensation approach and join the market as power producers. In this mode, surplus electricity will not be compensated via the electricity bill anymore, while the price offered for the sale is determined according to market rates, e.g., in the wholesale electricity market managed by OMIE[1].

To benefit from the surplus sold in the market, several supplementary criteria should be met. At first, the installation itself should be considered an installation that generates electricity [33]. Thus, the installation should be registered in the corresponding administrative registry for electricity production facilities as well as fulfil all fiscal responsibilities for the sales of the produced energy.

Secondly, direct selling in the electricity market requires engaging a market agent or representative ([34] and [35]). Usually, small producers of electricity use some third parties like energy aggregators or retailers who manage transactions, bidding process and settlements on behalf of small producers. Therefore, there will appear some additional cost and loss of revenue associated with this process.

From a technical perspective, additional requirements should be met by installations related to technology and equipment. Besides installing a bidirectional meter, additional meters will be necessary in order to measure and register the energy being injected into the grid.

From the economic perspective, while selling electricity to the market makes it possible to take advantage of potentially higher prices compared to simplified compensation, it also means exposure to fluctuations of market electricity price, since the latter varies hourly

[1] OMIE is the entity responsible for managing the daily and intraday electricity markets on the Iberian Peninsula; it serves as the marketplace where electrical energy is bought and sold for both Spain and Portugal.

depending on supply and demand situation. Besides that, additional costs associated with intermediaries and administration may become significant in the case of relatively small installations.

In respect of household systems, selling energy directly to the power supplier proves to be less economically attractive in comparison with simplified compensation, owing to additional complexity of the process and related expenses, considering the relatively low volume of produced surplus electricity in such cases. It applies to the analysed system in particular, where self-consumption is prioritized.

There is one more crucial point regarding the fiscal consequences of selling produced energy. In contrast with simplified compensation, which results in savings but not profits and does not affect taxation, selling energy is a form of economic activity, hence taxable [36]. Thus, additional tax liability makes energy sale less advantageous for small scale producers in financial terms.

Another alternative approach may imply reaching a bilateral agreement with electricity retailer to sell surplus energy via such agreement with a guaranteed price, thus avoiding direct involvement into wholesale trading. Nonetheless, it implies additional costs related to administrative issues and fiscal aspects as well. Thus, the scenario of selling surplus energy was not taken into account in our analysis.

In conclusion, having accounted for all economic factors it has beem concluded that simplified compensation was the most rational approach for the current case study.

10.4 ENERGY COMMUNITIES AND AGGREGATORS

Indeed, in the recent past, changes in the framework for European energy policy led to the emergence of some new forms of distributed production and management of energy. Moreover, these are the energy communities and aggregators, that have become important players in terms of integration of renewable distributed energy resources and increasing system flexibility. The formation of these entities is closely connected to the regulatory activities of the European Union, in particular through the Clean Energy Package. Energy community can be described as an organizational structure in which different consumers of energy (residences, companies, or governmental bodies) work together to produce, consume, exchange and manage energy. At present, there exist two types of such communities that have been identified at the European level. These include Renewable Energy Communities (REC) [37] and Citizen Energy Communities (CEC) [38], both of which prioritize social, environmental and local economic objectives rather than financial goals.

The development of energy communities in Spain still faces many challenges, but it does take place in an increasing number of locations. This type of organization enables to engage in collective self-consumption, meaning the joint usage of electricity produced in a common renewable energy facility. Such communities are especially useful when operating in the urban or suburban areas, where individual energy facilities cannot be used due to technological limitations.

Speaking about technical peculiarities of the energy communities, one can indicate the fact that the produced energy should be distributed according to the set of distribution coefficients. In this way, it becomes possible to maximize the use of local electricity production and thus increase self-consumption rates. Although the energy generation scheme considered in this thesis relates to a separate household, its features are applicable to any distributed generation system.

However, aggregators function as intermediaries between distributed energy resources and electricity markets. The basic principle of aggregators lies in grouping multiple small generation facilities, energy storages or flexible loads into one virtual facility. As a result, aggregators make it possible for distributed energy resources to participate in electricity markets and grid services that cannot be provided by individual small facilities.

The role of aggregators [39] acquires significance in the context of the increasing share of renewables and the necessity to achieve the appropriate level of system flexibility. In such a manner, it becomes possible for aggregators to provide certain services, including demand response, load shifting and balance support to the grid, which contribute to system stabilization.

At the same time, from the perspective of economics, aggregators may increase value through optimized energy flows and market participation. Namely, an aggregator may manage when and how energy should be consumed, stored or exported, depending on conditions. Nonetheless, such processes imply a developed communication network, ability to process data in real time and access to flexibility markets.

In the current Spanish context, aggregators are in the process of implementation. Although they have not yet become involved in electricity market activities on a large scale due to certain regulation barriers, it is predicted that in the near future they will play an increasingly significant role as the energy sector continues its development.

In relation to the system considered within the framework of this research, energy communities and aggregators are currently not used. To put it differently, the energy system considered in this paper exists as an individual self-consumption facility without any involvement in collective programmes or participation in the electricity market.

Nevertheless, energy communities and aggregators may provide opportunities for future evolution of the energy system considered in the thesis. On the one hand, energy communities may enable the system to share excess generation with other participants. On the other hand, aggregators may create additional value by participating in different markets.

10.5 INCENTIVES AND SUBSIDY PROGRAMS

Not only market conditions and regulation play an important role regarding the economic feasibility of distributed renewable energy sources, but also public support mechanisms, that have been put in place in recent years, can have a big impact in the development of these systems, especially the residential self-consumption model. One of the most influential mechanisms in this regard in Spain, are the different subsidy programs available as a consequence of the financing received from different European recovery instruments, including the Next Generation EU funds promoted by the European Union [40].

These funds intend to encourage the energy transition towards more decarbonized models, reducing green gas emissions, as well as promoting decentralized renewable power generation [40]. Many of the funds generated within these mechanisms have been dedicated to support self-consumption systems and energy storage systems, among other initiatives that contribute to improve the penetration of renewables into the power system in the residential and commercial sectors.

From the national point of view [32], these programs are mainly managed by organizations like *Instituto para la Diversificación y Ahorro de la Energía*, being responsible for the design and management of many of these subsidy programs. Nevertheless, the execution of the programs is often decentralized, as the funding process is managed by each one of the regional governments according to their needs and criteria. Therefore, subsidies may differ from region to region, both in terms of intensity, as well as application criteria and procedures.

The main type of public support is represented by capital subsidies, which consist in subsidies provided directly in order to reduce the CAPEX of the installation [41]. In the case of residential photovoltaic installations, subsidies usually depend on the size and power installed of the system and the possibility or existence of storage. There may be additional support available in some regions, depending on the installation location (rural), making this kind of program extremely relevant for the case studied.

In the case of Basque Country specifically, there are regional subsidies managed by the organization known as Ente Vasco de la Energía (EVE) [42] for supporting residential self-consumption installations. These subsidies usually include capital subsidies per kW of photovoltaic installed, although additional subsidies may be provided if it includes a storage system or it is residential.

Besides the direct incentives in terms of subsidies, there may also be additional economic benefits on the local level in the form of reduction of property tax (IBI), construction tax (ICIO), or any other municipal tax related to installation of the renewable energy equipment. While the types and magnitude of those taxes differ from municipality to municipality, they play a crucial role in making the projects more economically beneficial and shorten payback periods. Some Basque municipalities offer, for instance, IBI reduction of up to 50% during some years for buildings that make use of renewables [47].

From an economical point of view, all those support mechanisms have an immediate effect on some of the most significant indicators, such as NPC, LCOE and payback period. Any cut in upfront cost will positively affect the profitability, as was shown in Chapter 9. in the sensitivity analysis. Thus, the lower cost of installation significantly improves the payback period, as well as increases return on investment.

However, despite their positive impact, subsidy programs also present certain limitations. One of the main challenges is the administrative complexity associated with the application process, which may involve extensive documentation, technical justifications and long processing times. Additionally, the availability of funds is often limited and subject to specific time windows, creating uncertainty for project planning and potentially delaying investment decisions.

Nevertheless, as useful as those tools are, they still have some drawbacks. The first disadvantage of the system lies in the administrative burden involved in applying for them, involving filling out numerous forms, providing extensive technical justification and waiting for approval for months. Besides, the availability of the subsidies is always limited to sometime window and funds.

Another issue related to support measures is their short-lived character. Changes in policies or even budget might influence the future of support programs.

In practical terms, the direct capital subsidies for installation of photovoltaic panels might reach 30% to 50% of the eligible investment cost under favourable conditions [41]. Taking into account the case of the residential photovoltaic system described in this study, which is expected to have the installed capacity of approximately 4 kWp, the total cost of investment might be in the range of 5,000-7,000 €. Under the subsidy rate of 40%, this would lead to the saving of 2,000-2,800 € in the initial CAPEX.

The reduction of initial expenses directly influences the economic parameters of the PV system. From the financial point of view, lower initial investment cost translates into proportionally decreased NPC and LCOE, however the strongest impact is produced on the payback time. Depending on the initial conditions of operation, the payback time might be lowered to the tune of several years due to the use of subsidies. For instance, the system with the current payback time of 8-10 years may become profitable within the timeframe of 5-7 years due to these incentives.

In addition to capital subsidies, other financial incentives may be used in the form of local fiscal advantages such as reduction of the property taxes (IBI). For instance, if the property owner receives 50% reduction of IBI for the period of 3-5 years, this may mean that hundreds of euros will be saved during this time. However, while useful, they are less powerful in terms of impact on the initial payback time than capital subsidies.

It should be mentioned that despite having strong influence on the initial costs of installation, subsidies do not change the operating economic parameters of the PV system under analysis. In other words, their introduction does not change the major structural constraints, such as price of electricity, degree of self-consumption, surplus compensation policy, etc., thus the economic efficiency of the system in the long term.

Thus, despite the fact that introduction of subsidies enhances the economic attractiveness of PV system, it does not change the basic conclusion regarding the optimal configuration: photovoltaic only system has greater economic efficiency in comparison with others. However, this statement relates to the case analysis where no subsidies are considered in order to ensure unbiased analysis. In a practical application in the Basque Country, the combination of different subsidies at all levels (European, national and regional) will decrease the initial investment costs significantly.

10.6 BARRIERS TO IMPLEMENTATION

10.6.1 ADMINISTRATIVE AND LICENSING BARRIERS

Even with the new simplifications that have been introduced recently, the administrative and regulatory barriers continue to present themselves as significant obstacles for the implementation of self-consumption facilities in Spain. Even though the Royal Decree 244/2019 significantly reduced some of these barriers (explained in Section 3.3), there are other challenges presented by the complexity and the lack of normalization of these procedures.

The major challenge is presented by the differences in administrative requirements on the local level. Based on the place where one intends to install their facility, there will either be a need to get a building license, or alternatively, a simple prior declaration, criteria which have not been unified yet, making it quite difficult for users to determine which steps to take.

Furthermore, even when there are simplifications in terms of obtaining the legalization of the facility, there are other procedures involved that include certification, documentation and registration of the system.

Among others, there is an important characteristic that minimises the influence of the above-mentioned issues. Specifically, as stated in Section *3.1.Grid access conditions*", installations with installed power up to 15 kW and connected to the electricity supply system at existing power points are exempted from the official procedure of getting access and connection permits (A&C).

It should be noted that it is applicable for the installation being considered in this thesis, which has an installed power below the aforementioned limit. Therefore, this feature eliminates the need for going through one of the most complicated official procedures, simplifying implementation of the system significantly. However, it does not mean that the process will be devoid of administrative problems.

In particular, it should be pointed out that system registration, checking of its compliance with requirements and cooperation with the distribution company have to be arranged anyway and will require additional time.

As far as administration barriers are concerned, one should note that in most cases it is not their existence that matters, but the fragmented way they are carried out and excessive length of related procedures that make it hard for potential users to use the system.

To conclude, although the current regulations have helped to reduce administrative barriers, they are still present. However, for those installations that have installed power under 15 kW and are connected to existing electricity points, there are no such requirements anymore.

More information available in [12].

10.6.2 GRID CONNECTION CONSTRAINTS

Grid constraints constitute another important constraint that affects the implementation of renewable energy systems alongside the administrative one discussed above. Despite being set in a favourable regulatory framework like in the case of Spain, grid constraints might have a significant impact on the feasibility and efficiency of self-consumption systems [11].

One of the main challenges faced in the implementation of renewable energy systems relates to the hosting capacity of low-voltage distribution grids. The existing low-voltage grids have been developed to facilitate unidirectional power flow from central generating stations to customers, which means that they may not always be able to cope with distributed power injections into the grid. Such problems include voltage rise, congestion and power quality problems, as mentioned by CNMC.

The problem becomes even worse when considering the implementation of renewable energy systems in highly penetrated areas by photovoltaic generation facilities, especially in rural/semi-urban locations. In these places, the injection of surplus power by different customers simultaneously becomes a serious problem, especially at noon when there is high radiation from the sun. Under these circumstances, DSOs might impose new connection or reinforcement constraints on renewable energy projects.

Another constraint in relation to the connection and technical conditions set by the DSO should be noted. It is important that despite the possibility of small-scale installations to be connected without going through the whole access process and obtaining permits to connect, in accordance with the topic discussed in *10.6.1.Administrative and licensing barriers*, the DSO defines all technical specifications for connecting to the grid, such as voltage requirements, protection systems and metering equipment installation.

In light of the system analysed within the framework of this work, it should be stated that the analysed system uses the concept of grid connection as the basis of its operation. In accordance with the data obtained based on simulations of the system operation, the grid provides for import into the analysed system of 53.90% of the total consumed electricity per year, whereas, in periods of excess photovoltaic power, an equal amount of electricity is exported.

Nevertheless, the lack of battery storage in the system under analysis implies dependence on the electrical grid for the surplus energy to be transferred to the grid in order to balance out the excess production and for additional electricity importation when there is a shortage in the system. In case any grid-related restrictions are encountered and it cannot be transferred, the excess generation will be reduced in its volume.

Besides, taking into account the insufficient remuneration received in exchange for the export of generated electricity (see *10.2.Net metering and simplified compensation*), there are no financial incentives to do so in an unlimited manner.

The other issue to consider here is the cost of reinforcement which could be associated with grid issues. If the grid was not able to provide additional power generation capacity, then a certain amount of costs will be incurred by the end-user for grid reinforcement. Although this is generally a problem faced by bigger projects, it remains an issue, nonetheless.

Having said all that, the effect that such an arrangement could have on our system would still be fairly small. Firstly, our project is not large, meaning that the demand put onto the grid will not be too much. Also, due to our exempt status regarding access and connection permits, this process will be much easier to achieve.

On the other hand, however, grid constraints are a crucial point in relation to wider deployment of renewable energy sources in terms of self-consumption.

10.6.3 MARKET ACCESS LIMITATIONS

Market constraints associated with limited opportunities for selling surplus electricity are a challenge for small renewable systems [43]. Despite the regulatory environment of Spain offering several options for assessing excess electricity value, individual consumers cannot fully engage in electricity trading markets due to specific restrictions.

One of the reasons why it is challenging for individuals to engage in energy markets is related to their technical and regulatory characteristics, aimed at large-scale production. For example, wholesale markets, run by OMIE, involve specific minimum bid amounts, energy forecasting capabilities, real-time connection and other technical and financial prerequisites, which are too complex to meet for small residential units.

In this case, participants are not able to use wholesale markets but have limited means of participating in other simplified ways, namely the net metering method discussed in Section *10.2.Net metering and simplified compensation* or aggregation, considered in Section *10.4.Energy communities and aggregators*. However, both options reduce economic opportunities for the user in contrast to direct sales via energy market platforms.

An additional limitation relates to the discrepancy between the retail and surplus energy price, which significantly affects the economic benefit gained from using renewable generation. According to the analysis conducted in Section 8, imported energy was estimated as being worth 0.22 €/kWh, while excess generation was worth 0.07 €/kWh. Therefore, despite being possible, active involvement in electricity trading would hardly be economically justified because of a relatively low value of surplus energy.

Additionally, the regulatory framework makes it difficult to produce revenues through simplified compensations that have been discussed above. Thus, it prevents small users from being producers of electricity and makes them only consumers with some generating capabilities. Even though the scheme of operation described earlier is quite straightforward and does not entail market manipulations, it also imposes certain restrictions on economic efficiency of distributed generation.

Access to the energy market is another aspect where the role of residential users becomes limited by the fact that the energy prices are regulated and, thus, do not vary significantly depending on supply-and-demand balance. Residential users usually face fixed tariffs which means that their consumption decisions are not affected by the prices in the energy market. In other words, users do not have any incentive to make flexible decisions regarding their electricity consumption.

The fact that demand-side participation in the electricity market is not widespread means that small users are unable to participate in various market schemes related to energy provision. Although aggregators should make it possible for residential consumers to use services like demand response or provide energy during periods of peak loads, this function is not currently being exploited.

These market limitations are taken into account while designing a system to be used for fulfilling this thesis' purpose. The photovoltaic panels are adjusted for producing the highest amount of electricity that could potentially be consumed. Selling excess electricity is not a very promising activity since selling tariffs are quite low due to market conditions.

However, some further regulatory and technological innovations might positively affect the market penetration rate of small-scale systems in the future. Namely, the increasing digitization of the energy system, smart meter technology and flexibility markets are considered to offer new perspectives for distributed energy sources.

Besides, it is necessary to consider the potential economic implications related to the mentioned obstacles to implementation.

Additional costs related to regulatory and technical challenges, such as those linked to engineering work, consultations, administrative processes, or delays, may become an indirect cost which was not taken into account when calculating the initial cost-benefit relationship. The time lost while waiting for the necessary approvals results in delays of the system implementation and, accordingly, its commissioning. It means that the start of earning money from the operation of the installation is postponed, thus, stretching out the payback period even further.

Moreover, the simplified surplus compensation scheme limits the economic attractiveness of the generated output from distributed energy resources because it prevents the generation of a net economic profit. Therefore, since the compensation for the surplus energy production remains relatively low, there is no incentive to oversize installations in order to generate as much electricity as possible.

The absence of certainty in the legislation concerning distributed energy resources also adds to the economic risks and it negatively affects the willingness to invest. Uncertainty regarding the compensation policy, electricity prices and other incentives may hinder investments in such projects because they increase the riskiness of the venture. This aspect may be understood as an implicit cost related to the increased risks.

With respect to the results obtained in the course of this research, such economic constraints help explain why certain types of systems do not provide improvements in economics. For instance, although hybrid PV-wind or PV systems with battery storage can provide certain technical benefits, the combination of these aspects does not result in economic gains.

10.6.4 CRITICAL ASSESSMENT OF IMPLEMENTATION FEASIBILITY

Despite the Spanish regulatory approach to self-consumption being generally positive and clear, its effects on small-scale residential systems will vary depending on the specifics of installation.

In terms of the particular system studied, the low installed capacity (under 15 kW) greatly facilitates the whole process. Namely, the absence of access and connection permits makes the procedure of realization much easier as it lacks the most important bureaucratic component associated with implementing distributed generation projects. Consequently, the overall number of regulations will decrease, making the realization more flexible.

As far as economics is concerned, the simplified process of compensation of surplus generation is rather convenient and predictable. At the same time, such an arrangement entails certain limitations in terms of economic efficiency since all surplus generation will not bring any profit and thus make economic optimization impossible. It means that oversized equipment and the participation in the electricity trading will be highly unlikely.

As for technical issues, there is only one possible problem related to grid integration. Namely, it can arise from the necessity to connect to the electric grid and export surplus generation and import electricity when necessary. In general, however, it should not be expected due to the fact that the installation works under standard conditions. Also, since there is no capacity for storage, the system will heavily rely on the grid.

From the market perspective, there are no advantages in terms of obtaining additional services and possibilities. Namely, there will be no way of participating in various flexibility markets or engaging in demand response, aggregations and other activities. While such limitations will have little effect on the possibility of implementation, they present a missed opportunity in today's digitized world.

10.7 OPPORTUNITIES FOR DEPLOYMENT

Although regulatory, technical and market barriers discussed above exist, there are significant opportunities for the installation of renewable energy systems on a distributed basis in the current energy transition context in Spain. Opportunities include advancements in technologies, favourable policy measures and changing energy markets' dynamics.

First, the cost of photovoltaic technologies continues to decrease, as seen in Chapter 8. of the economic analysis conducted in this thesis. Specifically, photovoltaic systems have already reached a level of maturity when their electricity generation becomes economically competitive, or even cheaper, than retail electricity prices. The ability to provide cost-competitive power at relatively low O&M costs makes photovoltaics a perfect solution for residential use.

Second, volatile and rising electricity prices present another incentive to engage in renewable energy production through self-consumption. As proven by the sensitivity analysis (Chapter 9.), electricity price increases lead to improved economic performance of self-consumption installations. The ability to produce one's own electricity is a great way to avoid future price hikes.

Furthermore, the regulatory measures implemented through Royal Decree 244/2019 have addressed most of the issues related to self-consumption in the past, removing barriers to its use while providing a legal framework for its economic success. Even if certain limitations still exist, the current regulatory regime is definitely supportive of distributed generation.

Moreover, public subsidies and other support programs make investments in self-consumption installations even more appealing, as they reduce upfront expenses and payback periods, as described in *10.5.Incentives and subsidy programs.*

On another front, technological advances also present opportunities for deployment of the technology [44]. With the growing accessibility of sophisticated inverters, smart meters and energy management systems, there are now better ways of integrating renewables with consumer energy consumption.

Furthermore, the distributed energy resources concept is becoming relevant with the integration of additional complimentary technologies like battery storage and EVs. While the use of battery storage cannot be economically justified in the current setup analysed in this research work, future reduction in costs associated with the technology or regulatory changes could improve its economic attractiveness, especially if there was considerable variability in the prices of electricity in the area under consideration, or insufficient capacity in the power grid.

In addition to that, there are opportunities emerging with the advent of energy communities and energy aggregators discussed in detail in Section *10.4*. These are useful in improving the role of small consumers of energy in the system, with the possibility to implement collective self-consumption and access new market mechanisms, which would increase the potential of distributed energy production.

Regarding the particular example examined in this research work, it can be confidently stated that photovoltaic energy installation can provide for an effective solution in this particular situation. In the analysed case, the degree of renewables penetration reached approximately 52.30%, while grid dependency became greatly diminished. Therefore, it can be concluded that similar solutions can be effectively deployed in other areas that have similar conditions.

In addition to that, grid-tie system provides a very effective framework for implementing and maintaining distributed energy generation. Here, one should pay attention to the fact that electricity grid works both as a source of energy and as its sink, making it unnecessary to incorporate sophisticated storage devices to run distributed energy installations.

Moreover, on a larger scale, the implementation of distributed energy solutions can lead to various benefits for the energy system as a whole. These include lower greenhouse gas emissions, lesser need for energy production from centralized sources, improved reliability of the electrical system and decreased load on the power transmission infrastructure.

Chapter 11. CONCLUSIONS

After the exhaustive elaboration of the master's Thesis project concerning the techno-economic assessment of distributed renewable energy systems for residential self-consumption in a grid connected rural environment, several significant conclusions were reached, which provide a greater insight into energetic, economic and regulatory behaviour of different hybrid configurations involving PV and wind energy systems. In general, this thesis includes all stages related to the development of distributed renewable systems, including resource characterization, determination of residential electricity demand, energy simulations, economic calculations and the analysis of Spanish regulation concerning self-consumption. The following sections contain the most important conclusions extracted from the research performed and indicate potential future lines of work which might lead to further improvement in the integration of distributed renewable systems in the residential sector.

Regarding Objective O1, it could be concluded that there was a high level of solar energy availability at the selected location, since the solar resource showed a great annual stability and a good energy yield despite the existence of some variability throughout the year. Photovoltaic energy thus appeared to be the most reliable renewable energy source in the selected location. On the contrary, it could be seen that the wind resource was characterized by moderate-low annual availability and by significant hourly and seasonal variation in the availability, which decreased the reliability and predictability of its output generation. Even though wind energy may serve as a complement in a hybrid configuration, especially in periods when solar energy is not available, its potential remains limited under the analysed conditions.

By estimating the residential electricity consumption, it was possible to obtain an hourly consumption profile. Nonetheless, the mismatch between generation of energy and consumption caused that the self-consumption ratio achieved was relatively low, being only 46.10%. Even though a PV system generated sufficient energy to cover the total annual demand of the building, only a part (namely, 46.10%) of it came directly from photovoltaics, while the other part (that is, 53.90%) was imported from the grid. Additionally, approximately 74.70% of photovoltaic generation had to be exported to the grid in periods of maximum irradiation and low household consumption. It could therefore be stated that generation sizing alone does not guarantee maximum renewable energy utilization, because the consumer's demand plays a key role.

With respect to the technical performance of the wind turbine component, it was observed that it behaved rather irregularly. It could be seen that, although it contributes only about 8% of the total annual energy consumed, the wind subsystem compensated in particular months the decrease of solar energy generation. When there were low wind speed periods, the wind turbine operated at much lower capacity than nominal and, according to the performed simulations, did not contribute with any renewable energy generation in some periods. Thus, despite being useful in some particular moments, the wind subsystem did not provide a significant contribution to the hybrid PV-wind configuration compared to the photovoltaic subsystem alone.

Economically speaking, although the introduction of a wind turbine into the system would increase the overall annual energy generated, it would also cause an increase of surplus energy. In an optimal configuration, that is photovoltaic-only, approximately 74.70% of the energy produced by photovoltaic technology is injected into the grid, due to the before mentioned mismatch between production and consumption. While surplus energy injection helps to improve the economic efficiency of the installation, it does not bring many benefits to the user, as the price per kilowatt-hour for sold energy is considerably smaller than that for bought energy. Excessive oversizing, therefore, is not economically effective.

All of the above leads to the conclusion that photovoltaic systems are currently the most balanced choice for residential self-consumption under the analysed Spanish conditions. Even though wind-based hybrid configurations seem to be potentially interesting under certain conditions (particularly in locations with high-quality wind resources), their advantages are not universal and their benefits should be verified beforehand. Taking this information into account, it can be stated that **Objective O1 can be considered successfully achieved.**

With respect to Objective O2, economic performance indicated that grid-connected photovoltaics currently constitute a feasible solution in Spain. The steady fall in photovoltaic system costs in conjunction with the rising prices of electricity in Spain resulted in a significant increase in the economic attractiveness of self-consumption installations in recent years. The photovoltaic-only system proved to be the most economic among the alternatives tested, achieving the lowest payback period of less than 10 years and the minimal levelized cost of energy (LCOE), with a cost of 0.0727 €/kWh. These results suggest that, despite being environmentally driven originally, residential self-consumption of photovoltaics has become an economically competitive and lucrative long-term investment option as well.

Hybrid photovoltaic-wind energy systems demonstrated weaker economic performance under the tested conditions. Even though the integration of small-scale wind energy generation helped achieve a minor increase in the amount of renewables generated during some months, the additional costs resulting from integrating a wind subsystem led to a higher overall cost of the energy generating system. In this scenario, an improvement in economic performance could not be achieved due to the low wind resource present at the studied location and unpredictable operation of the wind generator during different months. Therefore, the economic feasibility of hybrid configurations was inferior to the photovoltaic-only variant. Indeed, all the solutions recommended by HOMER were photovoltaic-only and did not account for a wind generator due to its relatively low economic attractiveness.

The use of simplified compensation of surplus energy by the Spanish regulatory framework had a positive impact on all the tested scenarios. Economic compensation of excess energy generation contributed to an improvement in annual savings and a substantial decrease in payback periods of installations. In the optimal scenario, a photovoltaic system was expected to reach a payback period below 10 years due to the current surplus compensation scheme. Otherwise, without surplus energy compensation, a payback period of approximately 20 years would have been required, which would have doubled the investment recovery period.

Hence, it can be concluded that self-consumption of electricity regulation in Spain had a major influence on the improvement of the economic performance of PV systems. At the same time, the amount of surplus energy compensation remained significantly lower than the retail prices of electricity. Maximizing direct self-consumption would thus remain the optimal solution from an economic standpoint.

Moreover, sensitivity analysis revealed that the economic feasibility and performance of a photovoltaic system depended greatly on external economic conditions such as electricity prices and capital costs. The latter parameter had the strongest effect on profitability because high grid electricity prices meant higher value of energy generation and self-consumption in this system. On the other hand, low investment costs proved essential for the economic feasibility of renewables-based energy generation, as adverse scenarios might lead to a preference of conventional energy generation methods over renewables. While the impact of the variability of solar radiation also existed and affected system performance, the market situation proved crucial. In conclusion, it should be noted that uncertain economic conditions should be taken into account at the planning stage. Future reductions in photovoltaic costs and further electricity price increases will undoubtedly boost economic feasibility.

Consequently, **Objective O2 can be considered successfully accomplished**, demonstrating the techno-economic feasibility of distributed renewable systems for residential applications under the current Spanish self-consumption framework.

Concerning Objective O3, the regulatory analysis revealed that the Spanish regulatory system regarding self-consumption has become significantly since the approval of the Royal Decree 244/2019. In particular, the removal of significant barriers such as administrative or economic constraints resulted in the stimulation of installation and usage of renewable technologies. Simplified surplus compensation was identified as one of the most essential improvements. In such a way, the process of implementation of PV power plants has been made more economically attractive for end-users, which allowed integrating the renewable energy generation into households.

Moreover, public subsidies or other incentive programs played an important role in the improvement of investment attractiveness. In certain cases, subsidies were able to decrease initial investments into the project up to 40%. Thus, it is possible to state that, without such instruments, small installations would not have attractive financial performance.

However, several barriers were recognized during the research as those that could prevent large-scale implementation of distributed energy generation. Complex administrative procedures in certain regions or in case of using hybrid systems or those having specific requirements can be listed among those factors. Also, inconsistency between autonomous communities, related to regulations, can be considered a barrier that causes uncertainties. Finally, low-voltage grids require future improvement considering rapid penetration rates.

It is also worth noting another issue recognized throughout the research process, namely uncertainty in the regulatory area. Profitability of renewable self-consumption highly depends on regulatory stability in the long run. Changes in the field might drastically affect the investment conditions; therefore, consistency should be preserved to maintain investors' confidence.

Finally, the following research directions can be proposed. Implementation of battery storage systems might bring significant benefits to consumers. In such a way, they allow minimizing the amount of surplus energy injected to the grid and reaching self-consumption ratios above 80-90%. Nevertheless, the economic feasibility of such technology still requires improvement. Thus, **objective O3 can be considered reached successfully**.

Regarding future research lines, it would be interesting to continue studying the effect that the progressive electrification of the residential sector will have, in particular by means of introducing electric vehicles and heat pumps for heating and air conditioning applications. Such new electrical load types can affect the demand patterns and enhance the use of renewable generation within the households.

Further research may also concern the dynamic study of smart energy management approaches using optimisation procedures and intelligent control systems. Active demand response, meteorological prediction and control strategies may enhance self-consumption and optimise the performance of small-scale renewables within residential settings.

It would also be very useful to evaluate energy community schemes and shared self-consumption approaches, considering technical, economic and regulatory considerations. Such schemes are expected to play an increasingly important role in the sustainable evolution of energy systems.

Chapter 12. BIBLIOGRAPHY

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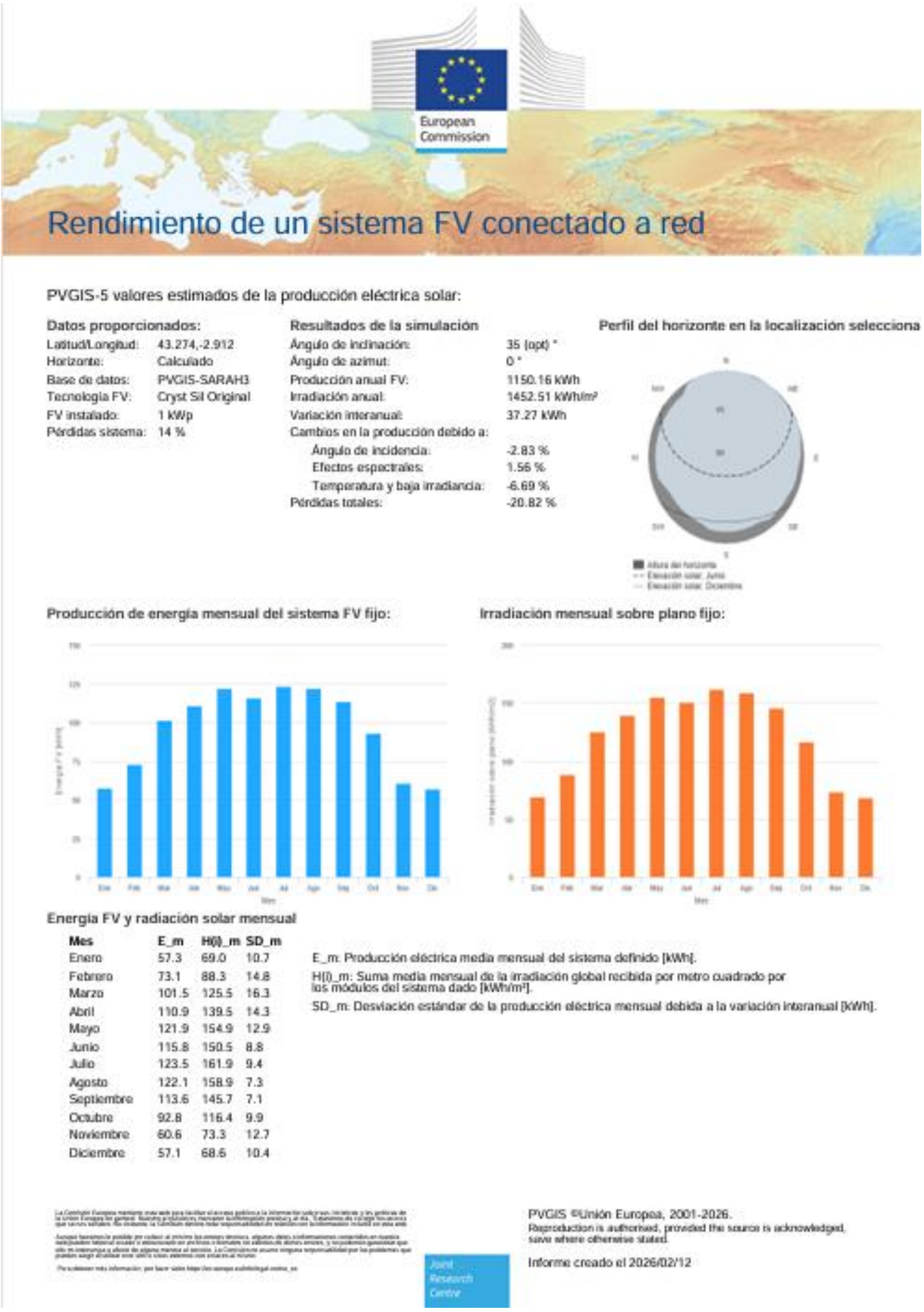
APPENDIX

PVGIS-SARAH3 database



European Commission

Rendimiento de un sistema FV conectado a red

PVGIS-5 valores estimados de la producción eléctrica solar:

Datos proporcionados:

Latitud/Longitud:	43.274,-2.912
Horizonte:	Calculado
Base de datos:	PVGIS-SARAH3
Tecnología FV:	Cryst Sil Original
FV instalado:	1 kWp
Pérdidas sistema:	14 %

Resultados de la simulación

Ángulo de inclinación:	35 (opt) °
Ángulo de azimut:	0 °
Producción anual FV:	1150.16 kWh
Irradiación anual:	1452.51 kWh/m²
Variación interanual:	37.27 kWh
Cambios en la producción debido a:	
Ángulo de incidencia:	-2.83 %
Efectos espectrales:	1.56 %
Temperatura y baja irradiancia:	-6.69 %
Pérdidas totales:	-20.82 %

Perfil del horizonte en la localización selecciona

Producción de energía mensual del sistema FV fijo:

Irradiación mensual sobre plano fijo:

Energía FV y radiación solar mensual

Mes	E_m	H(i)_m	SD_m
Enero	57.3	69.0	10.7
Febrero	73.1	88.3	14.8
Marzo	101.5	125.5	16.3
Abril	110.9	139.5	14.3
Mayo	121.9	154.9	12.9
Junio	115.8	150.5	8.8
Julio	123.5	161.9	9.4
Agosto	122.1	158.9	7.3
Septiembre	113.6	145.7	7.1
Octubre	92.8	116.4	9.9
Noviembre	60.6	73.3	12.7
Diciembre	57.1	68.6	10.4

E_m: Producción eléctrica media mensual del sistema definido [kWh].

H(i)_m: Suma media mensual de la irradiación global recibida por metro cuadrado por los módulos del sistema dado [kWh/m²].

SD_m: Desviación estándar de la producción eléctrica mensual debida a la variación interanual [kWh].

Joint Research Centre

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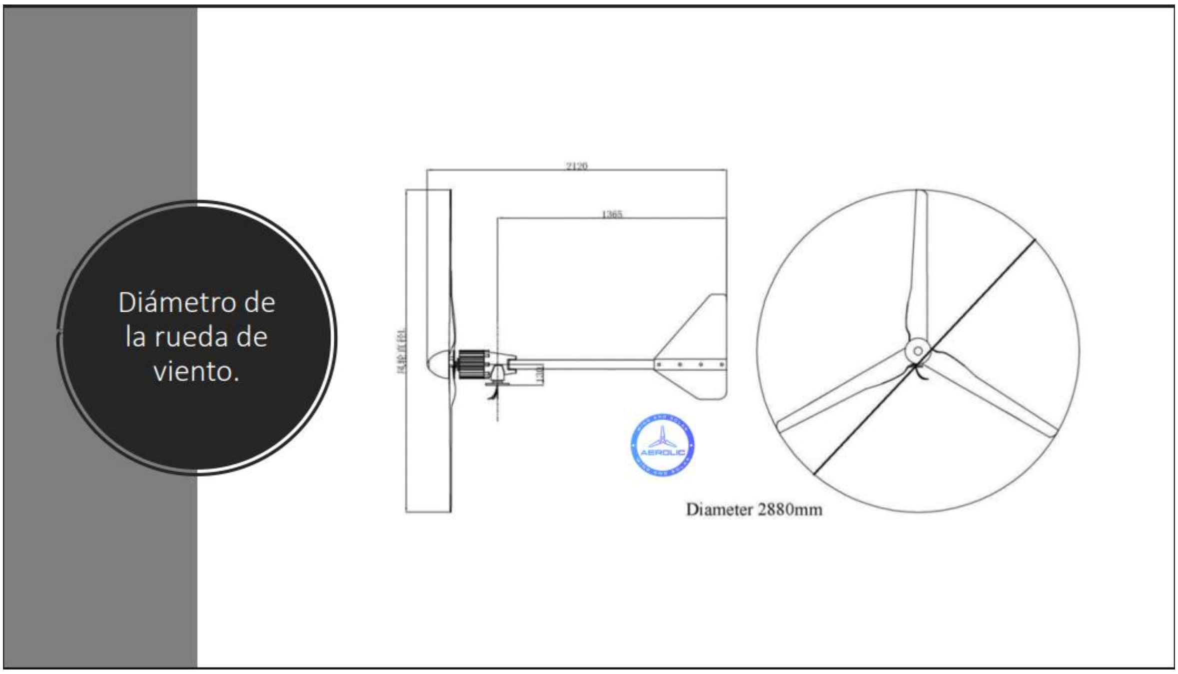
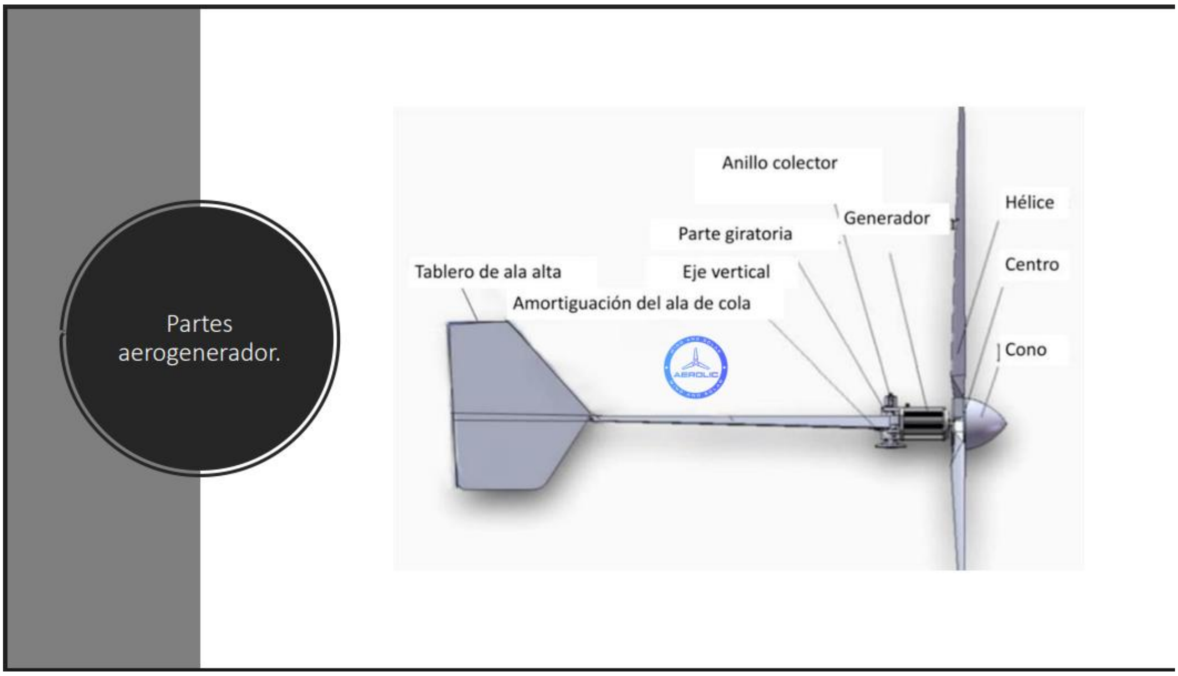
Informe creado el 2026/02/12

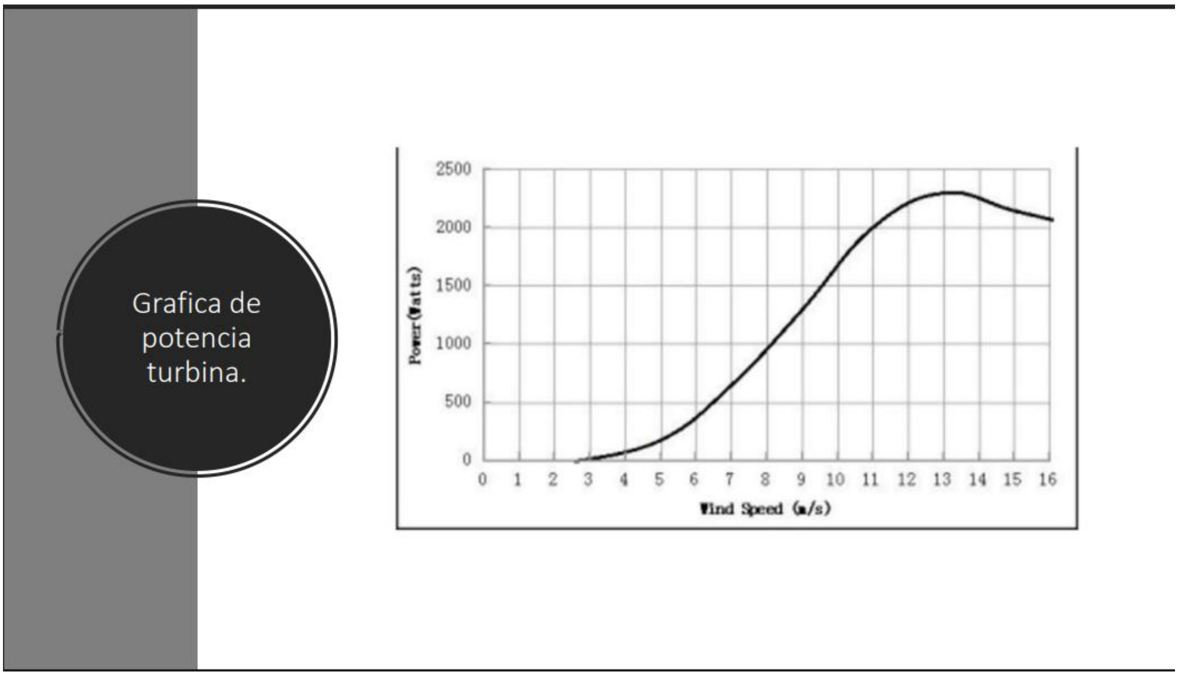
OpenWindMap

Small Wind turbine

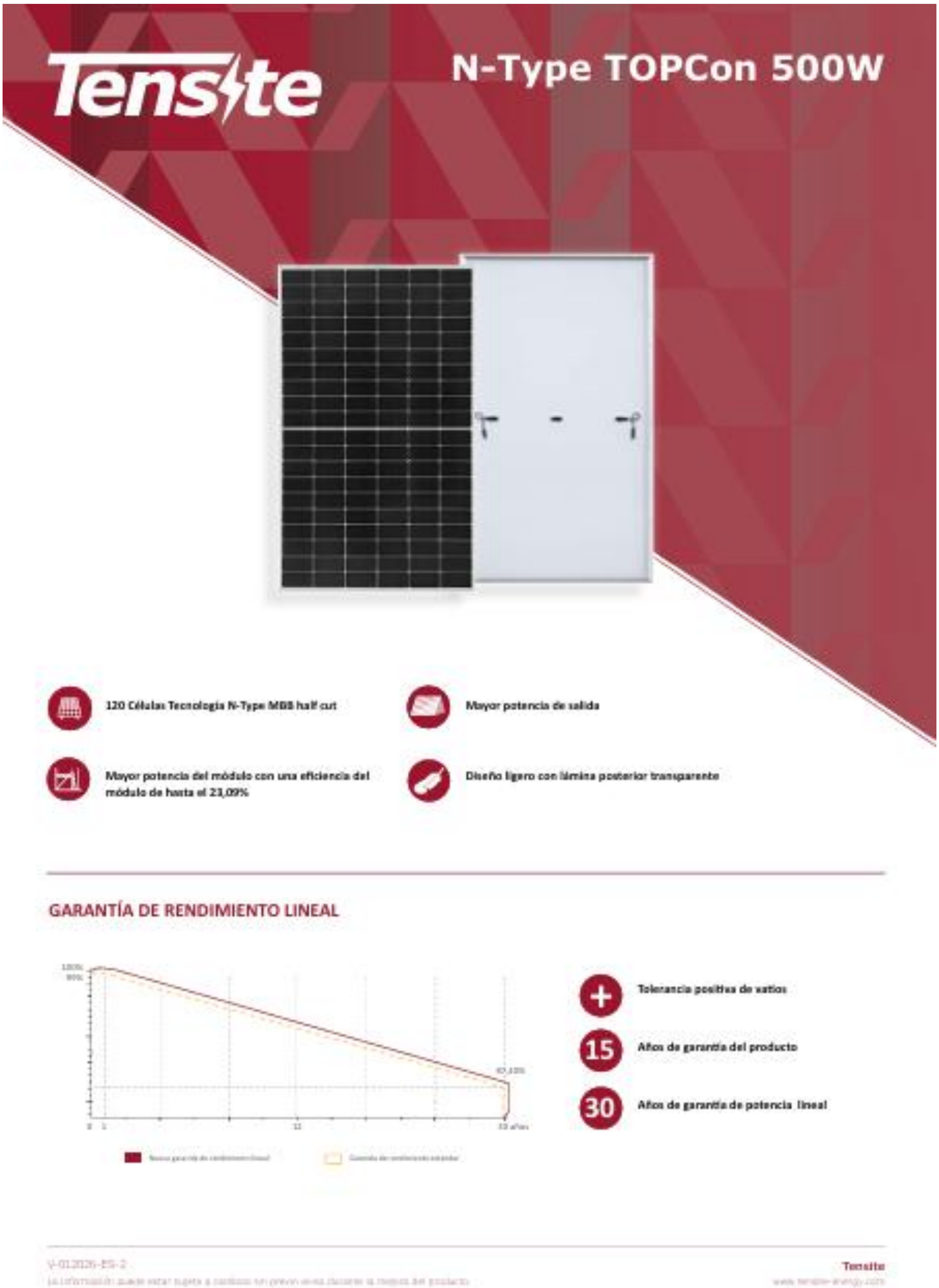




Potencia promedio	2000w
Potencia máxima	2300w
Voltaje promedio	48 – 220v
Viento inicial	2.5m/s
Viento para 2000w	11m/s
Viento máximo	35m/s
Peso	70kg
Diámetro de la rueda de viento	2880mm
Longitud de cada hélice	1400mm
Altura torre sugerida	6m
Tipo de torre	TZ 35 - 40
Cantidad de hélices	3
Material de hélices	Fibra de vidrio
Generador	Trifásico ac imanes permanentes
Método de protección	Frenado electromagnético / Bloqueo manual
Temperatura de trabajo	-40 °C -- 100°C


Grafica de potencia turbina.
Power(Watts)
2500
2000
1500
1000
500
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Wind Speed (m/s)

Solar panel technical specifications



Tensite N-Type TOPCon 500W

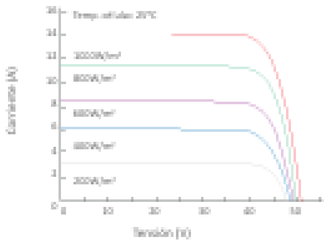
Datos Eléctricos STC	N-Type TOPCon 500W
Máxima potencia (P_{max}/W)	500W ±3%
Corriente de potencia máxima (I_{mp})	13,50A
Voltaje de potencia máxima (V_{mp})	37,05V
Corriente de cortocircuito (I_{sc})	14,25A ±5%
Voltaje de circuito abierto (V_{oc})	44,40V ±4%
Eficiencia del módulo	22,25%
Capacidad máx. fusible en serie	25A
Número de diodos	3
Tolerancia positiva en vatios	0 ~ +5W
Condiciones de prueba estándar	1000 W/m², 25 °C , AM 1.5
Tensión máxima del sistema	1500Vdc
Coeficiente de temperatura I_{sc}	0,043% / °C
Coeficiente de temperatura V_{oc}	-0,24% / °C
Coeficiente de temperatura P_{mp}	-0,30% / °C
Rango temperatura funcionamiento	-40°C / +85°C
Temperatura operación célula (TONC)	45°C
Capacidad de carga cubierta del módulo	5400Pa (IEC61215) (nieve)
Capacidad de carga cara frontal/trasera	2400Pa (IEC61215) (viento)

[illegible]

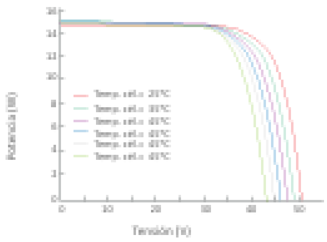
Rendimiento Eléctrico (TONC)	
Potencia máxima (P_{max}/W)	382W
Voltaje de potencia máxima (V_{mp})	33,85V
Corriente de potencia máxima (I_{mp})	11,28A
Voltaje de circuito abierto (V_{oc})	40,5V
Corriente de cortocircuito (I_{sc})	11,89A

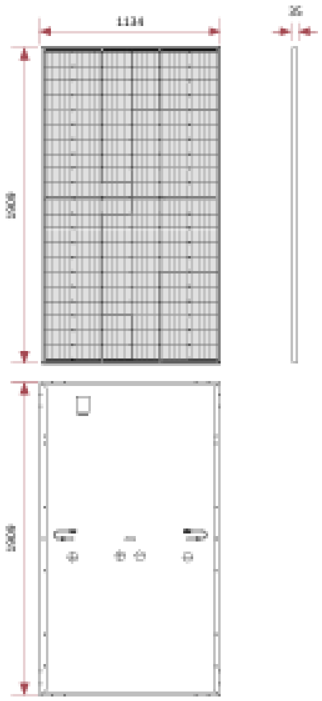
Características mecánicas	
Tipo de célula	N-Type
Peso del módulo	23kg
Dimensiones del módulo (L/W/H)	1909x1134x35mm
Cubierta frontal/trasera (material/grosor)	Vidrio templado / 3,2mm
Células (cantidad/dimensiones)	120(6x10x2)
Marco (material/color)	Aleación de aluminio anodizado/plata
Grado protección caja de conexiones	≥IP68
Cables y conectores	4mm², 1200mm en longitud
Clasificación de calidad	Clase A
Clase de protección eléctrica	Clase II
Clase de seguridad contra incendios	Clase C

Características temperaturas @25°C y niveles variables de irradiancia



Características temperaturas variables e irradiancia constante de 1.000 W/m²





V-012026-ES-2
La información puede estar sujeta a cambios sin previo aviso durante la mejora del producto.

Tensite
www.tensite-energy.com

Inverter technical specifications

SH3.0/3.6/4.0/5.0/6.0RS

Residential Hybrid Single Phase Inverter

NEW

FLEXIBLE APPLICATION

- 80–460 V wide battery voltage range
- Ideal for both retrofitting and new installations
- Built-in smart PID recovery function

ENERGY INDEPENDENCE

- Seamless transition to backup mode, for protection against power outages
- Fast Charging or discharging, enabling higher self-consumption results
- Built-in EMS with advanced customization

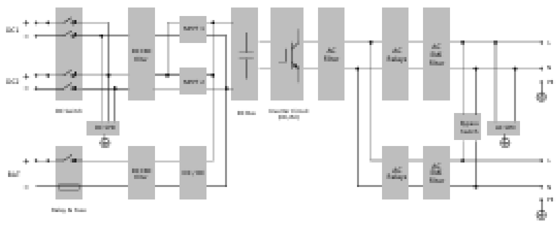
USER FRIENDLY SETUP

- Plug and play installation
- iSolarCloud monitoring available on App and Web
- Lightweight and compact, optimized for heat-dissipation

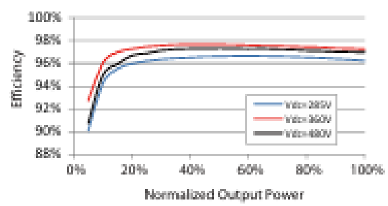
SMART MANAGEMENT

- Real time data (10 seconds refresh sample)
- 24/7 live monitoring both online and with integrated display
- Online IV curve scan and diagnosis

CIRCUIT DIAGRAM



EFFICIENCY CURVE



SUNGROW
Clean power for all

Type designation	SH3.0RS	SH3.6RS	SH4.0RS	SH5.0RS	SH6.0RS
Input (DC)					
Recommended max. PV input power	10000 Wp	10700 Wp	11000 Wp	12000 Wp	13000 Wp
Max. PV input voltage	600 V				
Min. operating PV voltage / Start-up input voltage	40 V / 50 V				
Rated PV input voltage	360 V				
MPP voltage range	40V – 560 V				
No. of independent MPP inputs	2				
Default No. of PV strings per MPPT	1				
Max. PV input current	32 A (16 A/16 A)				
Max. DC short-circuit current	40 A (20 A/20 A)				
Input / Output (AC)					
Max. AC input power from grid	10000 VA	10700 VA	11000 VA	12000 VA	13000 VA
Rated AC output power	3000 W	3680 W	4000 W	5000 W*	6000 W
Max. AC output power	3000 VA	3680 VA	4000 VA	5000 VA*	6000 VA
Rated AC output current (at 230 V)	13.1 A	16 A	17.4 A	21.8 A**	26.1 A
Max. AC output current	13.7 A	16 A	18.2 A	22.8 A**	27.3 A
Rated AC voltage	220 / 230 / 240 V				
AC voltage range	154 V – 276 V				
Rated grid frequency / Grid frequency range	50 Hz / 45 – 55 Hz 60 Hz / 55 – 65 Hz				
Harmonic (THD)	<3 % (of rated power)				
Power factor at rated power / Adjustable power factor	>0.99 at default value at rated power (adj. 0.8 overexcited/leading to 0.8 underexcited/lagging)				
Feed-in phases / connection phases	1 / 1				
Efficiency					
Max. efficiency / European efficiency	97.4 % / 97.0 %	97.5 % / 97.1 %	97.6 % / 97.2 %	97.7 % / 97.3 %	97.7 % / 97.3 %
Protection & Function					
Grid monitoring	Yes				
DC reverse polarity protection	Yes				
AC short circuit protection	Yes				
Leakage current protection	Yes				
Surge Protection	DC Type II /AC Type III				
DC switch(solar)	Yes				
DC fuse(battery)	Yes				
PID recovery function	Yes				
Battery input reverse polarity protection	Yes				
Battery Data					
Battery type	Li-ion battery				
Battery voltage	80 V – 460 V				
Max charge / discharge current	30 A / 30 A				
Max charge / discharge power	6600 W				
General Data					
Dimensions (W * H * D)	490 * 340 * 170 mm				
Weight	18.5 kg				
Mounting method	Wall-mounting bracket				
Topology (Solar / Battery)	Transformerless / Transformerless				
Degree of protection	IP65				
Operating ambient temperature range	-25 ℃ to 60 ℃				
Allowable relative humidity range	0 % – 100 %				
Cooling method	Natural convection				
Max. operating altitude	4000 m				
Display	LED digital display & LED indicator				
Communication	RS485 / Ethernet / WLAN / CAN				
DI / DO	DI * 4 / DO * 1 / DRM				
DC connection type	MC4 (PV) / Sunclix (Battery)				
AC connection type	Plug and Play				
Grid compliance	IEC/EN 62109-1, IEC/EN 62109-2, IEC/EN 61000-3-11, IEC/EN 61000-3-12, EN 62477-1, AS/NZS 4777.2, EN 50549-1, CEI 0-21, G98 / G99				
Backup Data (on grid mode)					
Rated output power for backup load	6000 W				
Rated output current for backup load	27.3 A				
Backup Data (off-grid mode)					
Rated voltage	220 V / 230 V / 240 V (±2 %)				
Frequency range	50 Hz / 60 Hz (±0.2 %)				
Total output THDv for linear load	< 2 %				
Switch time to emergency mode	< 10 ms				
Rated output power	3000 W / 3000 VA	3680 W / 3680 VA	4000 W / 4000 VA	5000 W / 5000 VA	6000 W / 6000 VA
Peak output power	8400 VA, 10s				

* AS4777.2 4999W, 4999VA ** AS 4777.2 :Rated and Max. AC current is 21.7A

PVSyst simulation result

Version 7.2.3

PVsyst - Simulation report

Grid-Connected System

Project: LanderProyecto

Variant: Nueva variante de simulación

No 3D scene defined, no shadings

System power: 4000 Wp

Bilbao/Sondica - Spain

Author

Project summary

Geographical Site	**Situation**		**Project settings**	
Bilbao/Sondica	Latitude	43.30 °N	Albedo	0.20
Spain	Longitude	-2.93 °W		
	Altitude	34 m		
	Time zone	UTC+1		

Meteo data
Bilbao/Sondica
Meteonorm 8.0 (1995-2013) - Sintético

System summary

Grid-Connected System — **No 3D scene defined, no shadings**

PV Field Orientation		**Near Shadings**	**User's needs**
Fixed plane		No Shadings	Unlimited load (grid)
Tilt/Azimuth	35 / 0 °		

System information

PV Array		**Inverters**	
Nb. of modules	8 units	Nb. of units	1 Unit
Pnom total	4000 Wp	Pnom total	3600 W
		Pnom ratio	1.111

Results summary

Produced Energy	4635 kWh/year	Specific production	1159 kWh/kWp/year	Perf. Ratio PR	82.96 %

Table of contents

Project: LanderProyecto
Variant: Nueva variante de simulación

PVsyst V7.2.3
VC0, Simulation date:
25/02/26 13:38
with v7.2.3

General parameters

Grid-Connected System | **No 3D scene defined, no shadings**

PV Field Orientation

Orientation		**Sheds configuration**	**Models used**	
Fixed plane		No 3D scene defined	Transposition	Perez
Tilt/Azimuth	35 / 0 °		Diffuse	Perez, Meteonorm
			Circumsolar	separate

Horizon
Free Horizon

Near Shadings
No Shadings

User's needs
Unlimited load (grid)

PV Array Characteristics

PV module		**Inverter**	
Manufacturer	Generic	Manufacturer	Generic
Model	N-Type TOPCon 500W	Model	Solar Inverter SOLIVIA 3.6 EU G4 TR
(Custom parameters definition)		(Original PVsyst database)	
Unit Nom. Power	500 Wp	Unit Nom. Power	3.60 kWac
Number of PV modules	8 units	Number of inverters	1 units
Nominal (STC)	4000 Wp	Total power	3.6 kWac
Modules	1 String x 8 In series	Operating voltage	160-480 V
At operating cond. (50°C)		Pnom ratio (DC:AC)	1.11
Pmpp	3652 Wp		
U mpp	271 V		
I mpp	13 A		

Total PV power		**Total inverter power**	
Nominal (STC)	4 kWp	Total power	3.6 kWac
Total	8 modules	Nb. of inverters	1 Unit
Module area	18.8 m²	Pnom ratio	1.11
Cell area	17.0 m²		

Array losses

Thermal Loss factor
Module temperature according to irradiance
Uc (const) 20.0 W/m²K
Uv (wind) 0.0 W/m²K/m/s

DC wiring losses
Global array res. 333 mΩ
Loss Fraction 1.5 % at STC

Module Quality Loss
Loss Fraction -0.4 %

Module mismatch losses
Loss Fraction 2.0 % at MPP

Strings Mismatch loss
Loss Fraction 0.1 %

IAM loss factor
Incidence effect (IAM): User defined profile

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

PVsyst V7.2.3
VC0, Simulation date:
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with v7.2.3

Project: LanderProyecto

Variant: Nueva variante de simulación

Main results

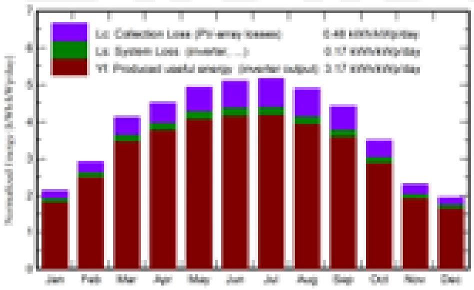
System Production

Produced Energy 4635 kWh/year

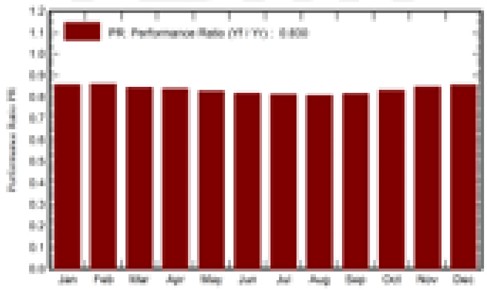
Specific production 1159 kWh/kWp/year

Performance Ratio PR 82.96 %

Normalized productions (per installed kWp)



Performance Ratio PR



Balances and main results

	GlobHor	DiffHor	T_Amb	GlobInc	GlobEff	EArray	E_Grid	PR
	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²	kWh	kWh	ratio
January	41.6	25.49	9.13	65.9	64.9	239.8	226.3	0.858
February	58.6	35.49	9.28	81.5	80.3	295.8	280.5	0.861
March	103.4	52.15	11.89	127.7	125.5	453.5	430.7	0.843
April	125.8	69.00	13.34	135.2	132.2	477.5	453.2	0.838
May	156.8	83.53	16.23	152.8	149.4	533.3	505.8	0.827
June	162.4	87.52	19.38	152.9	149.5	527.6	500.3	0.818
July	167.9	95.80	21.75	159.9	156.3	547.4	519.6	0.813
August	146.5	74.56	22.00	151.7	148.5	516.1	489.7	0.807
September	114.0	58.09	19.59	132.5	129.9	455.1	432.1	0.815
October	80.4	44.24	17.07	108.1	106.5	378.1	358.9	0.830
November	44.9	25.58	12.05	68.4	67.4	245.5	231.5	0.846
December	36.2	22.28	10.06	60.1	59.2	218.6	206.0	0.857
Year	1238.6	673.74	15.18	1396.7	1369.7	4888.4	4634.6	0.830

Legends

GlobHor	Global horizontal irradiation	EArray	Effective energy at the output of the array
DiffHor	Horizontal diffuse irradiation	E_Grid	Energy injected into grid
T_Amb	Ambient Temperature	PR	Performance Ratio
GlobInc	Global incident in coll. plane		
GlobEff	Effective Global, corr. for IAM and shadings		

Project: LanderProyecto

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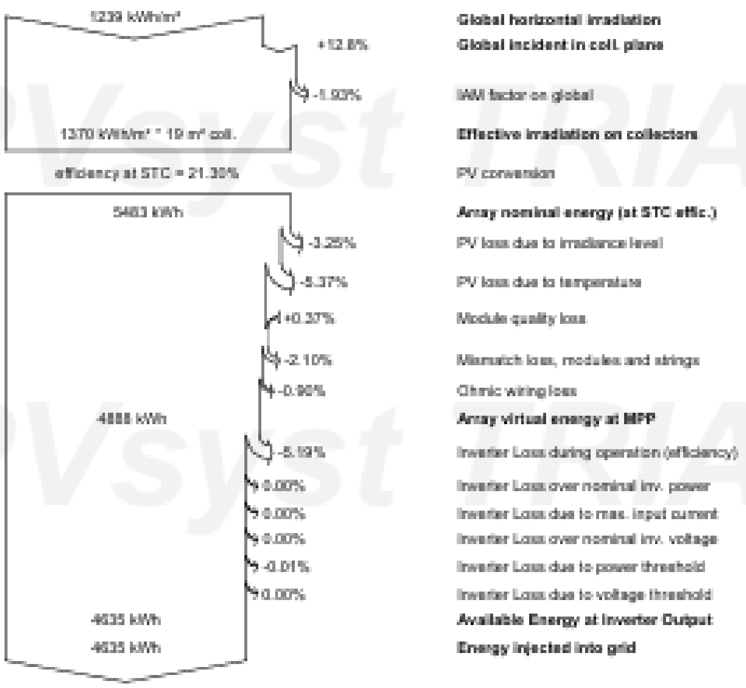
PVsyst V7.2.3
VC0, Simulation date:
25/02/26 13:38
with v7.2.3

Loss diagram



25/02/26 PVsyst Evaluation mode Page 5/6

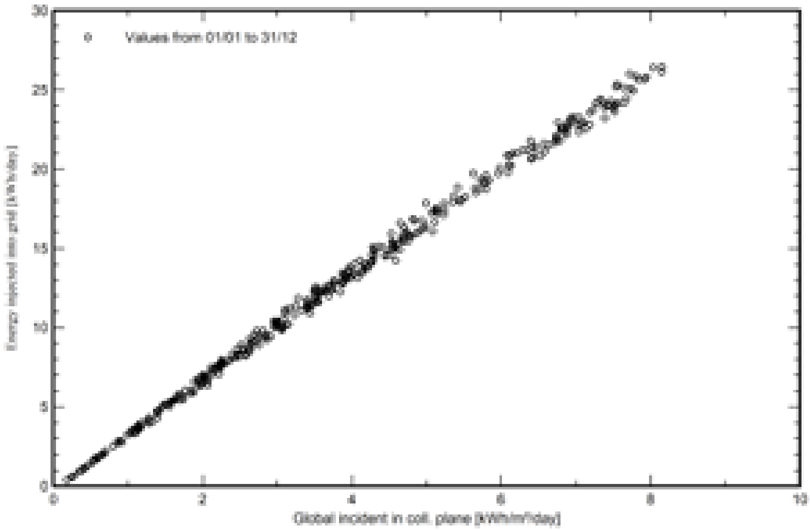
Project: LanderProyecto

Variant: Nueva variante de simulación

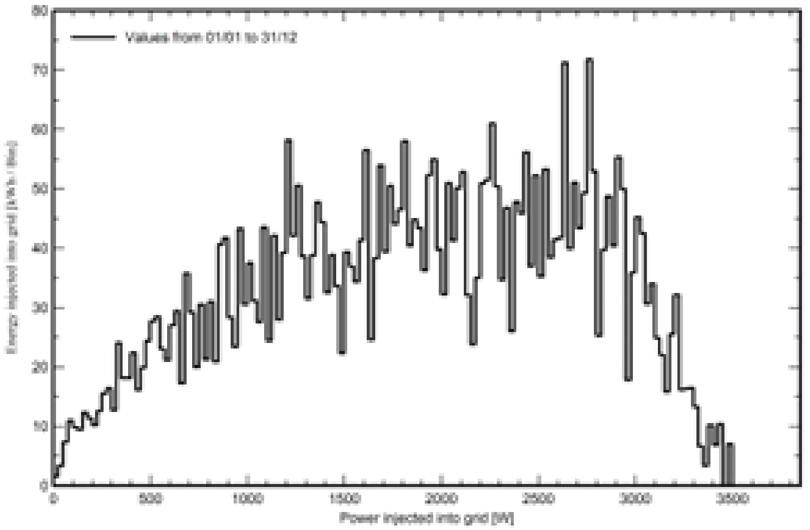
PVsyst V7.2.3
VC0, Simulation date:
25/02/26 13:38
with v7.2.3

Special graphs

Diagrama entrada/salida diaria



Distribución de potencia de salida del sistema



25/02/26 PVsyst Evaluation mode Page 6/6