uc3m | Universidad Carlos III de Madrid

Bachelor's Degree in Energy Engineering

2020-2021

Bachelor Thesis

"Analysis of the techno-economic viability of a solar wind hybrid power plant"

María Baquedano Aísa

Tutor: Jaime Manuel Alonso-Martínez de las Morenas

Director: Ana Patricia Talayero Navales

Leganés, 2021

SUMMARY

The transition towards an electricity system based on renewable energies leads the battle to mitigate greenhouse gas emissions already reflected in the 2015 Paris Agreement, and it is a key line of action to comply with the international commitment to deal with the social, economic and environmental challenges of globalization, the 2030 horizon.

Given the fossil fuels depletion and their polluting effect, renewable energy sources are today a clean, sustainable and inexhaustible generation alternative, where wind and photovoltaic energy, two of the most competitive renewable technologies, play a fundamental role.

In Spain, single-resource renewable generation plants, such as a solar field or a wind farm, are fundamental to the modern renewable energy economy, especially in the context of one of the countries in Europe with the most people living in condominium, a housing typology that creates more barriers for the implementation of distributed generation systems in the cities.

An important problem as the penetration of wind and photovoltaic energy increases lies in their intermittency, since this energy is conditioned by wind and solar resources, subject to variation in climate and time, which makes it difficult to integrate the electrical production of these sources in the electricity management and distribution system.

A tool that is presented as effective to deal with this problem resides in solar wind hybrid power plants, based on the space-time complementarity of wind and solar resources. These facilities seek a less intermittent and more optimized power generation, thus supporting the reliability, profitability and stability of the network system.

The design of individual solar and wind power plants involves a large number of design variables, constraints and complex physical factors, so this new paradigm creates an opportunity for the development of new integrated design approaches in which the knowledge of the resources and technologies, as well as the regulatory framework, will be essential.

Key words: Climate change; Renewable energy sources; Hybrid power systems; Energy efficiency; Power system reliability

CONTENTS

1. INTRODUCTION

1.1 Presentation of the problem and objectives

Although the increasing penetration of renewable energies in the electrical system is a determining factor for the fulfillment of the objectives set by the National Energy and Climate Plan (NECP) carried out by the Ministry for Ecological Transition and Demographic Challenge (MITECO) in Spain, this generation deployment can bring with it problems such as saturation and speculation in the requests of the limited access and connection points to the network, overloads in the evacuation nodes of the electrical grid, or modifications in the structure of the electricity market. [1]

With the aim of providing an integrative solution to the issues described, this document explores the opportunities presented by wind and photovoltaic hybrid generation power plants (HPPs), as well as the understanding of the spatial and temporal variation of wind and solar resources, a key factor for the technologies hybridization potentiality. [2]

Currently, the number of these plants operating or under development in Europe is very limited, therefore, although their business case is still under development or evaluation, the benefits are promising.

For the resources and the wind and photovoltaic technologies integration studies, it has been counted on the cooperation of the Energy Resources and Consumption Research Centre, CIRCE [03], from which seeking to provide innovative solutions in the sustainability and efficiency resources field, a multitude of data and tools have been provided to carry out the present project. The initial proposal of the final degree project came from the centre, and it has been taking shape with its development.

The achievement of the same is divided into two more specific objectives, which will help to know and deepen in a better proposal, and they are the following:

- Carry out an analysis of solar and wind resources from a global vision to a local scale in order to have a greater overview of their potential and their possible spatial and temporal complementarity, thus helping to understand the development of the study proposed later.
- Performing a viability study of a solar wind HPP under two different scenarios covered by the current regulatory framework, using it as a possible solution to the problems described above, and as a market-oriented technology transfer tool.

In addition, the work is carried out synchronously on the following Sustainable Development Goals, SGD, included in the 2030 Agenda, [4]:

- Goal 7: “Ensure access to affordable, reliable, sustainable and modern energy for all”.
- Goal 9: “Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation”.
- Goal 13: “Take urgent action to combat climate change and its impacts”.

1.2 Methodology and chronogram

Regarding the methodology proposed for the project, several ways of working will be differentiated, which will depend on which of the two main objectives the work is done.

In the first place, although it has not been included as the main objective of the project, achieving a contextualization around the problem will be essential for its understanding. The main tasks in this case will be:

- Search for information on the field to be addressed through the Internet, using sources that are reliable and useful.
- Summarize said information so that it is clear and precise to the reader.
- Organize it capturing the interest and the attention of the receiver.

For the first proposed objective, the analysis of wind and solar resources, the tasks to be performed will be:

- Bibliographic review of the resources studied.
- Selection of different sites of interest for the graphic analysis of the behavior patterns of these resources both nationally and internationally. As search tools, different networks and databases in which CIRCE participates will be used, as well as other free databases.
- Data treatment in Excel sheets and creation of graphic material that is visually appealing for the reader and may be useful for a better understanding of the previously exposed theory.
- Analysis and description of the selected sites.

Finally, to achieve the objective of the proposed solution, the following tasks will be carried out:

- Bibliographic review of the generation technologies studied.
- Choice of different wind farm projects and adaptation of the technical specifications to study, and subsequent selection of the photovoltaic projects databases for the approach of the HPPs, again making use of various tools and databases of the centre.
- Large volume data treatment through Excel programming sheets for the hybrid power plants production estimation, given different percentages of photovoltaic (PV) installed power attached to the wind projects, and creation of graphic material that reflects the calculations and the work carried out for an easier understanding of the project scope.
- Analysis of the Levelized Cost of Electricity (LCOE) of the solar plants in order to reflect the economic viability of the hybrid projects.

The planning followed for the development of the project is displayed in *Figure 2.1*, where the project schedule divided by milestones has been represented.

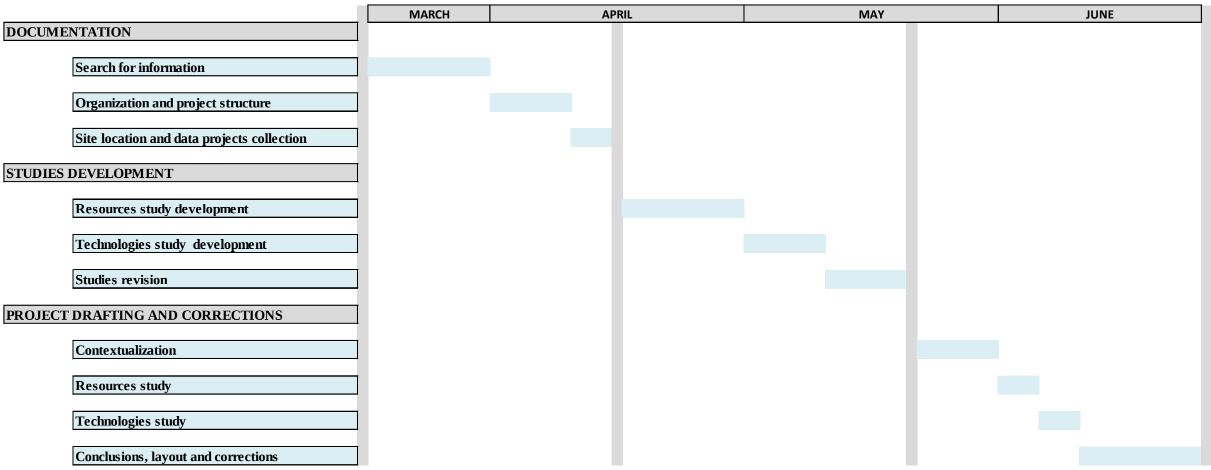

Fig 2.1. Project schedule

1.3 Project structure

This report describes the Final Degree Project carried out through the following chapters:

- Chapter 1: Contextualization:
  - Explanation of the fields close to the need that has motivated the project.
- Chapter 2: Integration of wind and solar resources:
  - Study of the resources and their potential complementarity from the hybrid generation point of view.
- Chapter 3: Integration of wind and photovoltaic technologies:
  - Study of the technical-economic viability of a hybrid generation power plant under two different scenarios covered by the new legal framework.
- Chapter 4: Summary and future lines:
  - Summary and conclusions of the work carried out, socio-economic impact, project budget, and future lines of work.
- Bibliography
- Annex

2. CONTEXTUALIZATION OF THE FIELDS TO BE ADDRESSED

In order to address the problem, it is necessary to initially analyze the current scenario, putting in context all the essential areas to be able to provide a solution that is at the level of the issue raised.

The energy sector is undergoing a strong transformation, a change of model to a sustainable and renewable model. In this new model, energy efficiency and the deployment of large-scale renewable energy generation, with wind and photovoltaic energy being of especial relevance, will play a fundamental role in keeping the global temperature increase below 2 degrees and closer to 1.5 degrees, in line with the set of scenarios outlined in the 2018 Special Report of the Intergovernmental Panel on Climate Change (IPCC). [5]

Under this transformation scenario, it will be necessary to carry out innovative solutions that try to turn the weaknesses of renewable systems into strengths, such as solar wind HPPs.

2.1 Decarbonization of the energy sector and CO_2 emission reduction

An efficient energy transition entails the maximum decarbonization of the energy sector, and thanks to the growing penetration of renewable energies in the generation mix, it is expected that the established objectives will be achieved immediately and competitively.

According to the route established by Spain in the NECP for the 2021-2030 period, it is expected to reach around 74% of renewable electricity generation in 2030, in addition to 42.5% on the final use of energy, which together with the objective of a 39.5% improvement in energy efficiency could allow a 23% reduction in greenhouse gas (GHG) emissions compared to 1990. All this requires certain commitments such the following:

- Promote Renewable Energy Systems (RES), encouraging competitive mechanisms and investment in R+D+i.
- Integrate and optimize RES in the electrical network through the necessary infrastructures for the evacuation of their generation.
- Reduce GHG emissions derived from start-up activities.
- Protection and integration with the environment and communities through environmental impact studies, reforestation and collective consensus.
- Expand the electrification of the national energy system to facilitate the use of RES in a greater number of uses, such as the penetration of the electric vehicle.
- Improve the use and capacities of infrastructures, achieving their more efficient use.
- Promote efficient storage to facilitate the management of the high penetration of renewable technologies. [2]

2.2 Renewable generation growth in Spain

Renewable technologies produced in 2020 the 43.6% of all electricity in Spain, achieving its largest share in the recorded generation mix.

Thus, Spain generated 109,269 GWh of electricity from renewable sources in 2020, 11.6% more than in 2019; despite the fact that the total electricity production was 4% lower, also due to a lower demand caused by the health emergency situation derived from COVID-19.

Wind energy, with a demand coverage of 21.7% and around 27.5 GW of installed power, was the renewable with the greatest presence in the national energy mix, followed by hydro (11.9%) and solar photovoltaic which, with an interannual increase in its generation of 65.9%, closed the year with a penetration rate of 6.1% and an installed power close to 12.5 GW.

Another of the player technologies of the year and not exactly renewable was coal, which cut its production by 60% compared to the previous year, registering its annual historical minimum of production and participation (2%).

These results show the beginning of the progress of the energy transition in which the Spain Government is immersed, however, the objectives proposed by the NECP for 2030 are still far, where a total installed power of 161 GW is expected in the electricity sector (from the current 105 GW), of which 50 GW would be wind energy and 39 GW solar photovoltaics. Therefore, a greater deployment of renewable energies is required in the next decade. [6][7]

2.3 Impact on the deployment of renewables

Despite the need for an imminent transformation of the energy sector, the deployment of renewable energies can trigger changes in the operation of the electricity system and in the current market, such as those described below [1]:

- **Saturation in the request for new access and connection points to the electricity grid:**

  Most of the electricity network connection nodes are saturated due to renewable generation projects in service or that already have access and connection permits for the transmission grid or acceptability for distribution grid connection.

  According to the latest data from Red Eléctrica de España (REE) [8], at the end of April 2021 projects for 93.1 GW of new photovoltaic power would have been denied compared to 65.4 GW already granted, 6.1 GW still in process and 11.1 GW that are in service; In the case of wind power generation, projects for 20.9 GW would have been denied, 19.5 GW would have been granted, 6.8 GW would be pending and 27.5 GW in service.

  In short, considering only the connected wind and solar powers and those that have the granted access permit, the values would amount around 47 and 76.5 GW respectively, figures that currently would be touching even exceeding the established objectives in the case of PV by the NECP.

The sector associations had been warning of saturation or inflationary trend in access and connection requests without viable projects behind. In this sense, with the publication of Royal Decree-Law 23/2020 that regulates access and connection permits to electricity transmission and distribution networks, an orderly generation deployment is expected that eliminates speculation according to MITECO. [9]

- **Overloads in the power grid evacuation nodes due to renewable generation excess:**

  Overloads can be generated in certain nodes of the network due to the enormous integration of renewable generation, which would give rise to technical restrictions that would cause the partial loss of the energy produced. Therefore, a parallel synergy is necessary in time between the penetration of renewable technologies and investments in the development, digitization and technological improvements of the network that alleviate the loads on the nodes.

- **Changes in the structure of the electricity market:**

  The increase in renewable generation will lead to greater variability in the supply and the electricity price, which creates new challenges and scenarios in the market, such as the following [10]:

  - Changes in the market that ensure the efficient integration of renewables, including for example a capacity market.
  - Decrease in the wholesale market price: because the cost of the raw material of renewable energies such as wind and PV is zero, the producers of these energies can offer electricity at a lower price than others. For this reason, the price of the electricity market drops in hours of high renewable generation, displacing technologies with more expensive fuels. Therefore, due to the high penetration of renewable technologies, the situation where they cover the 100% of the demand may arise, producing very low-price scenarios. This fact was reflected in the context of the 2020 health emergency, where demand was drastically reduced due to the slowdown in the economy, in line with a drop in oil prices and a greater contribution from renewable energies.
  - Increase in the price of adjustment services: RES, especially wind and photovoltaic, differ from conventional generation in terms of variability and predictability of their production, which can make it difficult and more expensive to provide flexibility services to the electrical system operation.
  - Load factor [1]: this variable is important in all technologies, however it is even more relevant in renewable generation sources such as PV and wind energy since due to the low cost of operation and maintenance, a higher load factor will be directly translated into higher income without higher expenses. These technologies had an average load factor

[1] Load factor: for a renewable generation plant, it is defined as the quotient between the real energy generated by the corresponding technology during a certain period of time and the theoretical maximum energy if working according to the nominal power during said period, and it is translated as the use of production capacity over time, that is, the percentage of hours of use in the analyzed period.

between 2019 and 2020 of 18.6% and 23.4% respectively [8], low but common figures for RES due to their intermittency and irregularity. [11]

Under the possible impacts previously mentioned, the market price, the inability to schedule all the energy produced and the difficulty to participate in adjustment services, as well as the inability to evacuate the energy produced due to the overload of the system, could reduce the generators revenues and make new investments unattractive.

In this context, it should be noted that the improvement of the load factor, in addition to maximizing the benefits of the facilities and optimizing the relative electrical infrastructures, would help to reduce a large part of the impacts previously described. [1]

2.4 Renewable hybrid generation

To contribute to the efficient integration of renewable projects, optimizing existing network infrastructures, earlier amortizing the investment in common infrastructures, and alleviating the pressure on new access and connection requests, the Spanish government encourages through the publication of Royal Decree Law 23/2020 renewable hybridization, which is presented as a technological solution to the issues described above.

In this context, a renewable hybrid generation plant is defined as the combination of two different generation technologies - such as wind and photovoltaics in the case of this project - that share a single access and connection point to the grid, in order to maximize generation and inject it into the electrical network in an optimized and controlled manner.

Definition given by Royal Decree-Law 23/2020, of June 23, which approves measures in the energy field and in other areas for economic reactivation:

> *"Access to the same point of the network of facilities that use different generation technologies whenever this is technically possible. To this same end, section five of the first final provision modifies the current wording of Law 24/2013, of December 26, to allow the authorization of facilities with an installed power greater than the access and connection power granted, always that these evacuation limits are respected in the operation of the plant. Thus, an unjustified regulatory restriction that prevented the efficient design of the facilities for optimal use of the renewable resource is eliminated." [9]*

There are other combinations of hybrid installations, such as PV and storage, PV and hydraulic, solar thermal and biomass ... However, this document will focus on photovoltaics and wind as the object of study.

Hybrid installations can also be differentiated according to the type of grid connection, such as on-grid installations, connected to the transmission or distribution grid and subject to the field studied, and off-grid installations, those not connected to the grid oriented towards self-consumption.

In addition, these plants can be designed from zero, which corresponds to the name greenfield project, or more commonly an existing and operating plant that can be hybridized by adding a new generation technology, which is known as a brownfield project.

To focus on what concerns this project, from now on whenever hybrid generation plants are named, it is being talked about wind farms to which photovoltaic technology is added.

There is also the possibility of locating a wind farm to an operational PV plant, however, wind farms in addition to requiring potentially windy sites, usually take more years to develop due to greater limitations than in the case of solar farms. Therefore, this scenario will not be considered in this project.

Hybrid installations take advantage of the complementarity between the resources generation profiles, since they do not have to coincide in time (both on an hourly scale and on a seasonal scale), a greater “anti-correlation” will make it possible to take advantage of the gaps in which the production of the original source is low, optimizing the evacuation of energy and increasing the load factor of the plant, achieving greater use of the existing network, a more predictable generation with less intermittency, higher base loads at the nodes and higher environmental synergies. [1][12][13][14]

2.5 Advantages of hybrid power plants

As anticipated in the previous section, in addition to a series of benefits associated with the optimization of the plant evacuation capacity, there are a large number of cost and time efficiencies mainly associated with the common use of infrastructures and grid connection agreements by the generating technologies.

These advantages will be very specific depending on the location of the plant, the type of project and its design variables, so it will be essential that developers study well the design opportunities of each site for a better optimization of the facility. Some of the general benefits that HPPs present will be the following [1] [15]:

- Site: for an existing wind farm or brownfield project, as many site-related studies such as design considerations or environmental impact studies were completed during the park development, the new PV plant may only require upgrades. Regarding the land use, as the terms for an existing generation plant have already been identified in negotiations with the landowners, it is likely that the extension of the existing contractual relationship will be simplified. For both old and new projects, the use of the land will be optimized requiring a smaller area than in the case of having two facilities without a common access point to the network, thus reducing the environmental impact.
- Infrastructures: for brownfield projects, the existing wind farm substation can be used with the corresponding technical adaptations, instead of having two separate connections that considerably increase the cost. In the same way, it is likely that works, services and equipment belonging to the wind farm can be used for the new PV plant, such as access roads, drainage, monitoring buildings, communications... In the case of new design or

greenfield projects, the aforementioned aspects can be planned from scratch, optimizing the design and considering the services shared between the two technologies, thus being able to achieve even greater savings.

- Operation and Maintenance: joint work to carry out minor maintenance activities that do not require special knowledge in the different technologies, such as cleaning, civil maintenance, security and monitoring, will result in a cost reduction in both scenarios. In addition, in the case of greenfield projects, efficiencies in the workforce associated with the construction period could be achieved.
- Administration: in both modalities, efficiencies can be found in the general administration of the assets associated with licenses, planning, accounting ... It is worth highlighting the savings in time and economic cost associated with access and connection to the network permits, which, being relative to the same evacuation line, in the case of brownfield projects they will be greatly reduced, simply having to update them, and in the case of new design projects, the expenses will be shared between the two sources of generation, alleviating in all cases the saturation issue.
- Others: reducing intermittency in generation can reduce buyers and developers negotiation risk, which could improve bids in Power Purchase Agreements (PPAs). In addition, the improvement in the load factor of the facility would increase the possibility of obtaining additional income through participation in adjustment markets.

2.6 Challenges

HPPs generate advantages both for promoters and developers as well as for the electricity system and society, however, they entail some barriers and challenges that could limit these benefits, and are described below [1][15]:

- Site: in general terms, PV plants are located in fields of clear terrain, while wind farms are often located on elevated ridges where there is a greater wind resource and a more complex orography, which can be difficult for the location of solar modules, in the supposed case of having limited land, which in addition the shadow casting by power lines, wind turbines, or colliding hills, can have a negative impact on the photovoltaic production. Therefore, it will also be a challenge to find sites where both resources are favorable since, in the case of having a lower production compared to facilities with a single technology, but a more abundant resource, the savings of the hybrid plant would have to compensate the reduction in production.
- Operation and Maintenance: the control and monitoring of the HPP will request a synchronization of the activities related to the wind farm and the solar plant for both design scenarios, which will require either specialized personnel in the case of greenfield projects or the training of personnel and the network operator for brownfield projects.
- Permits: for brownfield projects, it is likely that the different agreements with the land owners, suppliers, and financing entities will require a renegotiation of the terms, posing another challenge. Furthermore, although an agreement would have been reached with the communities at the time of development of the wind facility, a new consultation and

acceptance will be required before the start-up of the new PV plant. The newly designed projects will also require environmental feasibility studies and the approval of the communities for their development.

- Generation limit: an analysis of the expected generation losses due to the excess of simultaneous generation by the two technologies that conform the HPP and the capacity of the evacuation line to the network, will be essential to determine if the construction and operation cost savings is compensated, in addition to being an essential point for determining the optimal photovoltaic power to install in relation to the wind installed power. Moreover, it should be highlighted that injecting wind power and reducing solar power under this scenario of excess generation is the preferred option for brownfield projects due to technical issues. [16]
- Others: The profitability of the hybrid project will be essential to guarantee its development and also its bankability. Thus, from public bodies, legal guarantees must be given that favor investments in these installations.

2.7 Analysis of best practices

2.7.1 Potential studies

The Massachusetts Institute of Technology (MIT) carried out a study in 2014 where the benefits of the co-location of solar installations with wind facilities in Europe were analyzed, where it was determined that the wind and solar potentials complement each other on seasonal and monthly time scales, and that with the co- location energy availability increases. [12][17]

Another study of interest was carried out by the Australian Government in 2016, in which the scenarios of a brownfield project and a greenfield project were analyzed, making, among other aspects of interest, an estimate of the savings involved in installing the new PV plants taking advantage of the infrastructures of the wind farms. [15]

2.7.2 Existing projects

Renewable energy developers around the world are beginning to pursue hybrid projects that profess to unlock the value of grid connection and unleash the potential of resources and technologies. [18]

There are currently some wind and photovoltaic HPP projects under development and in operation at an international and European level, and some examples of interest are set out below:

- The Port Augusta project located in Australia and planned to be promoted in 2021, would consist of 50 wind turbines, each with a capacity of 4.2 MW, making up a total of 210 MW of wind energy, and 250,000 solar panels equivalent to 107 MW of photovoltaic energy that would give rise to one of the biggest solar wind hybrid power plants in the world, counting on the participation of global, local and Spanish suppliers. [19]

- The project carried out by Hero Future Energies has turned out as the first large-scale solar and wind hybrid energy project in India.

  Located in Kavithal state, the project included an existing 50MW wind farm, to which a neighboring 28.8MW photovoltaic solar park has been added, forming a hybrid system. The evacuation capacity of the project remains at 50MW, since the main objective is the best integration of the grid energy due to the variability of the wind resource, taking advantage of the complementarity of the solar resource. [20]

- The Vattenfall wind project in Wales, Parc Cynog, has 11 turbines in operation for more than 10 years, with an installed capacity of 8.4MW. Furthermore, in 2016 it became a HPP with the addition of a 4.99MW photovoltaic installation that would share the connection point to the grid. [1]

  The pilot project was designed to test how the generation profiles of the two technologies complement each other, and after more than 18 months of operation the results were more than successful. A Power Plant Controller (PPC) was installed to operate within grid constraints, so that when the combined production of wind and solar energy would reach the maximum level of grid capacity, something that only a few times happens, the PPC would be activated to reduce the solar farm, considered technically easier than limiting wind production. [16]

Spain has several pilot projects in operation, small-scale and off-grid, however, it is expected that with the recent approval of the policy that promotes and regulates these utility-scale facilities, these types of projects will begin to be boosted.

3. INTEGRATION OF THE RESOURCE: WIND AND SOLAR RESOURCE COMPLEMENTARITY

The main objective of this chapter is getting to know the temporal behavior of wind and solar resource for different locations for a better understanding of the techno-economic viability of a solar wind hybrid power plant.

In the first place, the wind will be analyzed, how it behaves on a global scale and what parameters affect its behavior, as well as the effects at a local level that determine its variability and its evolution over time.

Secondly, solar radiation is studied, its components, the atmospheric factors that alter it and the amount of irradiance that impacts on the different points of the earth's surface depending also on the time of year, due to the rotational and translational movements that the earth performs around the sun.

Finally, two studies with measured data and reanalysis databases will be carried out for a better illustration of the described resources.

It should be noted that in this chapter the resources are going to be discussed as sources of energy, so both wind speed and solar irradiation are not directly proportional to wind energy and photovoltaic solar energy respectively. Later in the following chapter, the wind power potential and the photovoltaic power potential will be appropriately discussed.

3.1 Wind Resource

3.1.1 Global wind patterns

The energy of the sun together with the tilt and displacement of the earth and the existence of continents and oceans, generates uneven heating that circulates air masses, raising the warmer air of lower pressure and leaving voids for high-pressure cooler air.

This phenomenon occurs on a global scale due to the unequal heating of the earth’s atmosphere by the sun, which causes wind. Therefore, wind energy can be considered as an indirect form of solar energy.

The air in the equatorial region heats up more strongly than in other latitudes (the Poles receive the least sunlight while the Equator receives the most), so it becomes lighter and less dense. The rising air creates a circulation cell, called a Hadley Cell, in which hot air rises and flows towards the poles, where air near the surface is cooler. This movement causes the air to begin to cool, causing a return to the equator.

Figure 3.1 shows the global wind belts. Each of these wind belts stands for a "cell" that circulates air through the atmosphere from the surface to high altitudes and back again. The cells on both sides of the Equator are called Hadley cells and result in the Trade Winds on the earth's surface.

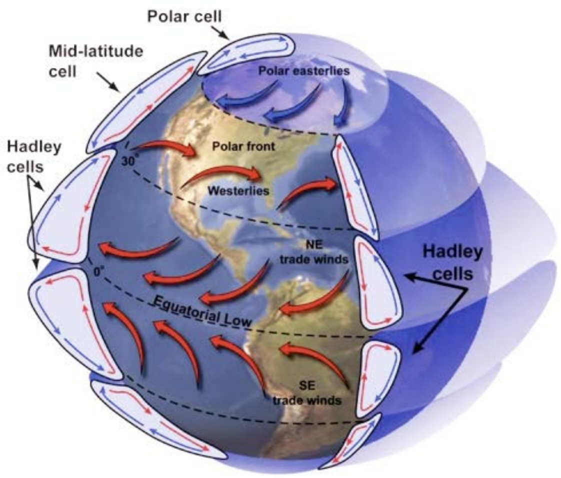

Fig 3.1. Global wind patterns [24]

Air pressure depends on elevation or altitude, the average air temperature over a particular location, and what the composition of the air is. Also, as elevation or altitude increases, the air presents a lower density.

The areas of the world globe where the air descends are zones of high pressure, and where the air is ascending, low pressure zones are formed. A horizontal pressure gradient is formed that drives airflow from high to low pressures, which determines the speed and initial direction of air movement.

Global winds do not move directly from north to south or south to north, as soon as wind movement is established, a deflective force is produced due to the rotation of the earth, which alters the direction of the wind movement, called Coriolis.

The Coriolis effect is a phenomenon that causes fluids like water and air to curve as they travel across or above the surface of the earth. The terrestrial globe is constantly spinning around its axis from West to East, but because earth is a sphere, and wider in the middle, points in the Equator are spinning faster around the axes than points near the poles. As a result, the rotation causes the air flowing from the Equator to the Poles to be diverted to the East, and the return flow from the Poles to the Equator to be diverted to the West, as it could be seen in *Figure 3.1*.

Winds have a specific pattern across the earth, called the global circulation patterns. Near the Equator, there are Trade Winds that blow from East to West. Doldrums is an area located right along the Equator, between the northern and southern part of the trade and it is characterized by light winds. This air belt around the equator receives much of the radiant energy from the sun, and the area is known as the Intertropical Convergence Zone (ITCZ). A low-pressure area is formed by the rising of warm and humid air, extended many kilometers north and south of the equator. Further North and South the wind blows from West to East.

In regard to the Iberian Peninsula, it is found for most of the year within the zone of westerly winds of the mid-latitudes of the Northern Hemisphere. The winds from the peninsula are therefore greatly influenced by the seasonal displacement of the zone of high subtropical pressures; in summer, the peninsular area is totally or partially outside the zone of winds from the west, so that during this season there is a decrease in the intensity of the winds. [24][25]

3.1.2 Local wind effects

In addition to this global wind circulation there are multitude of local effects. The different warming of the land and the sea also produces changes in the general wind flow. The nature of the terrain, local obstacles such as buildings and trees, etc. they have a major effect on the wind. Roughness is determined based on the type of terrain elements such as forest, land without vegetation, seas and lakes…

In *Figure 3.2* the vertical wind profile in function on the different roughness surfaces is displayed.

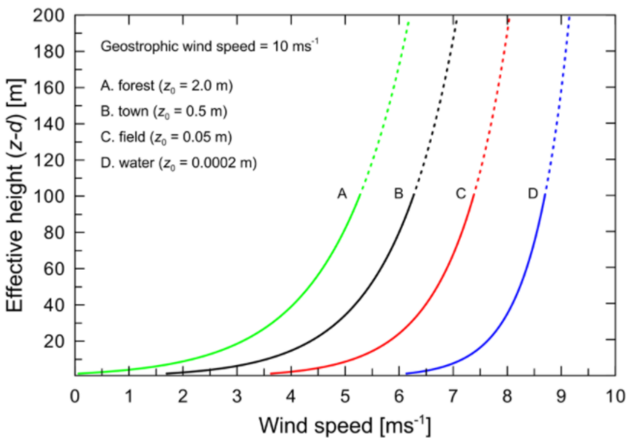

Fig 3.2. Different surface roughness lengths result in different vertical profiles of wind speed [34]

The local characteristics of each area also determine the wind in a very important way, such as:

- Breeze: as the land warms more than the sea, during the day the wind blows from the sea towards the land, known as land breeze. Similarly, as the land cools more quickly at night, it blows from the land into the sea, known as sea breeze.
- Valley-mountain currents: due to the uneven insolation that the different sides of the valley receive during the day an air rise is originated, known as valley currents. Overnight the cooling of the slopes causes the descent of air, known as mountain currents.
- Canneling: due to the acceleration suffered by the wind when entering between two obstacles.
- Terrain morphology and obstacles: soft slopes can accelerate the wind while sharp slopes or mountain ridges may stop the wind, as it can be observed in *Figure 3.3*.

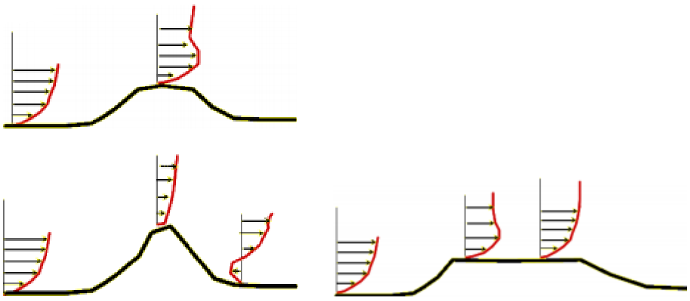

Fig 3.3. Terrain morphology and local surface wind profile [26]

Therefore, the variables that will define the wind regime that will exist in an area will be its geographical location, local climatic characteristics, the topographic structure of the area, specific irregularities on the terrain, the height above ground level...

3.1.3 Time-scale variability of the wind

The wind speed at a given location varies continuously. There are changes in the annual average speed from year to year, seasonal changes, due to the weather (synoptics), on a daily basis, or from second to second (turbulence).

The evolution of the wind speed against time can be analyzed by the Van der Hoven spectrum, showed in *Figure 3.4*, which gives the variation of the wind speed associated with a particular time scale (frequency).

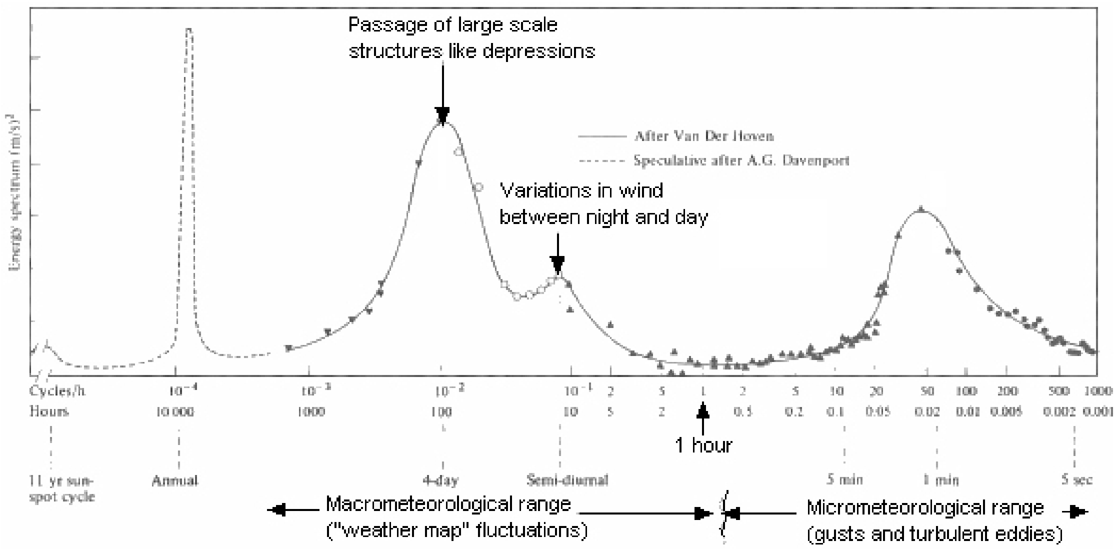

Fig 3.4. Energy spectrum of wind speed at 100 meters above the ground, Van der Hoven [27]

From the Van der Hoven spectrum, as observed in the *Figure 3.4*, a certain periodicity can be deduced every 4 days and every minute. This result is used so that, when taking measurements, do not use any of these intervals between measurements, as they could give misleading results.

There is a spectral gap separating the turbulent variation from the slower variations, in the range of 10 minutes to an hour. Therefore, all wind statistics are based on the average values of measurements of 10 minutes or one hour.

There is also a periodicity with day and night, also each annual cycle. The measurements that are made today must comprise at least one annual cycle.

Wind, considered as an energy resource and from the point of view of its availability, it is a source with substantial temporal variations on a small and large scale of time, and spatial variations both in surface and in height. [26]

3.2 Solar resource

3.2.1 Radiation

The Sun is the primary source of all known forms of energy. Solar energy results from the continuous nuclear fusion reactions that take place in the sun, by which hydrogen combines to form helium. This combustion result in electromagnetic energy that the sun delivers directly and indirectly to the earth in the form of electromagnetic waves. These waves have electrical and magnetic components that allow them to travel through the vacuum at the speed of light, transporting energy and momentum to the receiving source.

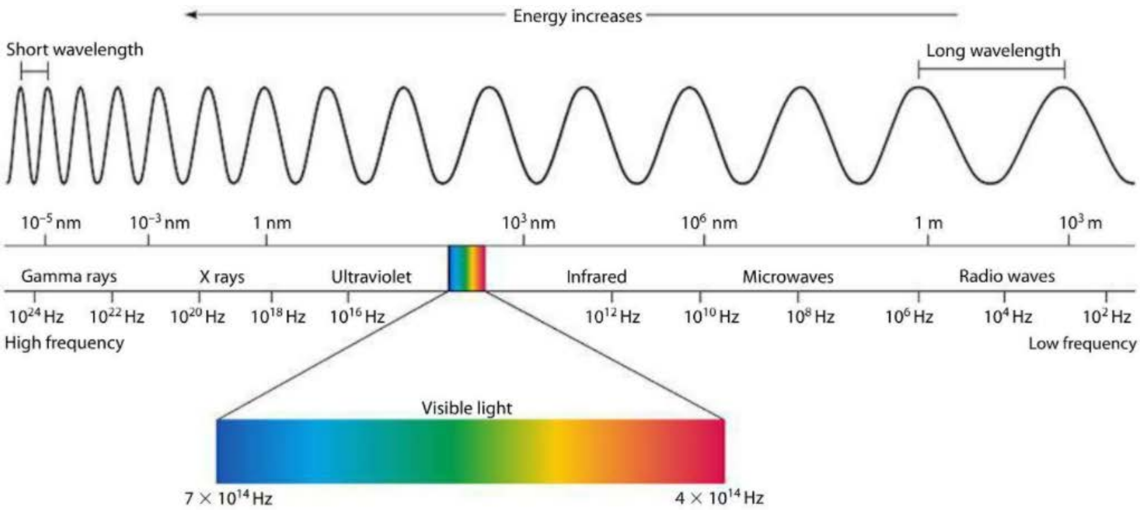

Fig 3.5. The Electromagnetic Spectrum [28]

The solar radiation that reaches the surface of the earth spans a range of wavelength that goes from 0.1um (ultraviolet radiation) to 3um (infrared), therefore from the large amount of electromagnetic radiation emitted by the Sun, only a small part of the electromagnetic spectrum, showed in *Figure 3.5*, arrives to our planet.

The solar radiation that reaches the surface of the earth varies widely from the radiation received by the atmospheric outer layer. This energy loss is mainly due the transmission through the atmosphere, where radiation is partially absorbed and scattered by components of the atmosphere such us refraction and absorption, which convert solar radiation into heat.

The solar radiation that is captured on the surface of the earth, also called irradiance, can be divided into three components based on its trajectory:

- Diffuse solar radiation, G_d: The solar radiation received from the sun after its direction has been changed due to scattering by the atmosphere (sky radiation). It depends on environmental conditions, especially cloud cover.
- Ground reflected radiation, G_r: The solar radiation that comes from reflection produced by the elements of the earth's surface. The value of this reflection will depend on the reflection coefficient or albedo present in the area, which quantifies the number of elements able to reflect waves.
- Beam solar radiation, G_b: The solar radiation received from the sun without having been scattered by the atmosphere (direct solar radiation).

The irradiance at a particular location is roughly altered by the atmospheric effects previously named and also by local variations in the atmosphere such as pollution, cloud cover, water vapor… In addition, the latitude of a location, the time of the day and seasonality will largely contribute to the irradiance rate variation, which is related with the earth rotation. [29]

3.2.2 Sun motion

The earth rotates on its own axis counterclockwise making a complete turn in 24 hours, and the axis of the earth has an inclination of 23.5 degrees. The earth also makes a translation movement of 365 days around the Sun, which gives rise to seasonal variations. Due to these rotations, the motion of the sun from the celestial vault of an observer on earth will be discussed below.

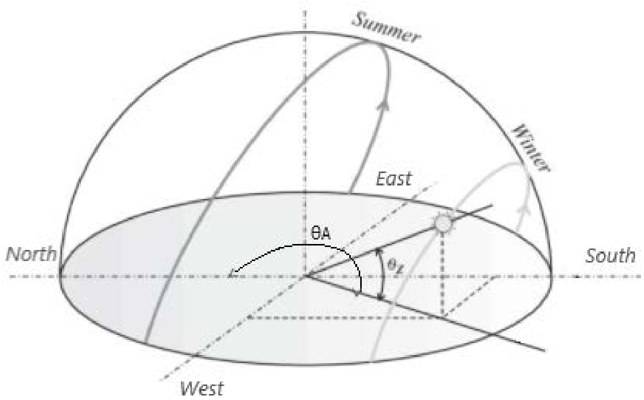

Fig 3.6. Typical behavior for the sun path [30]

In *Figure 3.6* the apparent motion of the sun across the sky dome is represented. The line projection connecting the observer (center point of the sphere) with the sun makes the azimuth angle (θ_A) with North. This line makes the altitude angle (θ_Z) from the horizon as the sun rises in the Easter horizon and sets in the Western.

In the Northern Hemisphere the sun is seen on the southern the sky while on the Southern Hemisphere the sun is seen in the northern sky. As the earth's axis is tilted relative to its orbit by 23.5 degrees (declination angle), in summer the altitude of the sun will increase while it will decrease in winter.

At sunrise, due to the earth's rotational movements the altitude will gradually increase as the sun moves up in the sky and the azimuth will increase towards South if the observer is in the Northern Hemisphere. After noon, as the sun goes down the altitude will decrease and the azimuth will increase towards West.

The azimuth will also change due to the translational movements of the earth, being lower in sunrise and higher in sunset in summer, which will result on a higher number of sun hours. The opposite effect will occur in winter. For the Northern Hemisphere, the sun will reach its maximum altitude the 21st of June (summer solstice) and its lowest the 21st of December (winter solstice). In the equinoxes the length of night and day become equal in each hemisphere, and together with the solstices are displayed in the ecliptic plane of the earth in *Figure 3.7.*

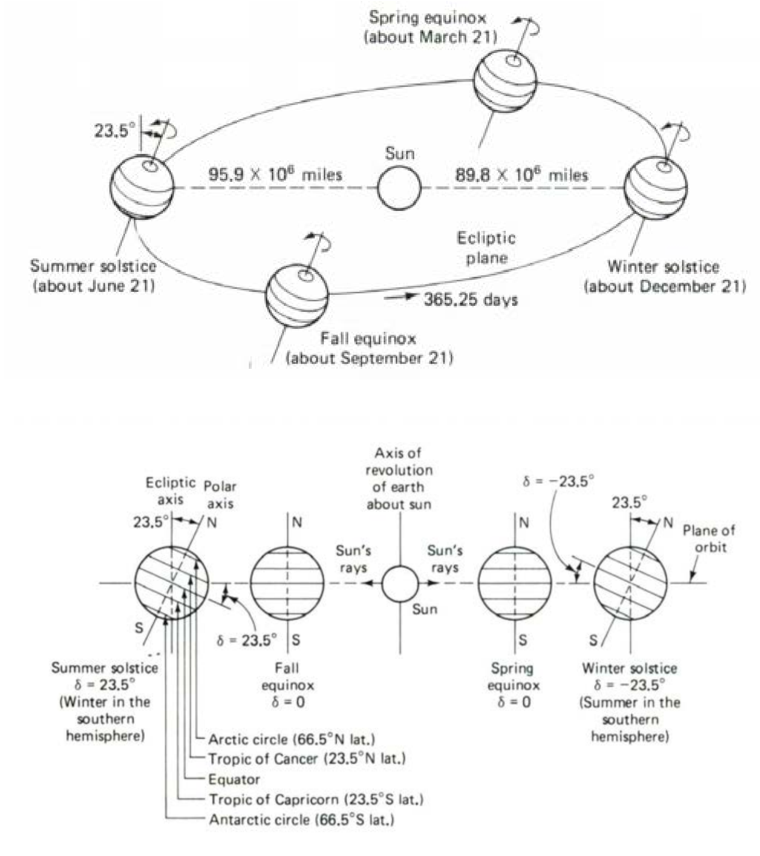

Fig 3.7. Ecliptic plane of the Earth about the Sun. [31]

In addition, different locations on the surface of the earth will receive different amount of solar radiation. Lower latitudes will get the most solar energy while higher latitudes will get the least amount of energy since latitude determines the inclination with which the sun's rays fall (altitude) and the difference in the length of day and night (azimuth). The more directly solar radiation hits the earth's surface, the more concentrated will be heated, however when the sun's rays strike with a greater inclination, they are scattered and dispersed over a wider area because they must pass through a greater amount of atmosphere, heating up to a minor extent.

All in all, it is easy to understand that solar radiation on the surface of the earth will depend on the time of the day, the day of the year, the latitude of the observer and the local variations in the atmosphere. [29][32]

3.3 Resources study

3.3.1 Study Prodecure

In order to see graphically both the wind and sun radiation behavior described above, different locations are going to be analyzed in the present study. Two scenarios are going to be the object of this study, global and regional. For the global study, radiation data from reanalysis sources has been downloaded while wind data is available from meteorological tower measurements. In the case of the regional study wind reanalysis databases with mesoscale and microscale modelling will be used.

Available data:

- PVGIS has been the application chosen for solar radiation analysis. The software provides free and open access to PV potential for different technologies and configurations, solar radiation and temperature as monthly averages or daily profiles, full time series of hourly values, Typical Meteorological Year (TMY) data, solar resource maps... For the present study, TMY databases have been downloaded. For more information on the methodology used by this application, see Annex B. [33]
- The data pertinent to meteorological tower measurements has been the object of a wind resource assessment, therefore the data has been previously filtered with other purposes. Annex A discusses in detail what does the measurement in a meteorological tower consist of, and which methodology and parameters are considered to carry out a resource assessment with the measured data. For the present study, the treated data has been exported from the Windographer software (further information in Annex B) for its later analysis.
- In the case of wind reanalysis databases, The Global Wind Atlas (GWA) has been used, a free web-based application developed to help identify high wind areas for wind power generation in a preliminary manner, nearly anywhere in the world. It facilitates online consults and provides free downloadable data sets based on the latest input data and modeling methodologies. For more information on the methodology used by this application, see Annex B. [34]

The given and downloaded data processing has been made through the Excel tool, as well as all the graphs showed in the case studies.

3.3.2 Global study

As it was introduced before, this first study is developed with wind data measured over a certain period of time with meteorological masts and TMY for solar radiation. Three different locations are going to be analyzed:

- Desertic coastal area of flat terrain in the Southern Hemisphere.
- Mountain ridge on a range area with short vegetation in the Northern Hemisphere.
- In land area with controlled vegetation in the Tropics.

Since the overall project is focused on the wind and solar resource space-time complementarity, the hourly pattern that both the wind speed and solar irradiance present is going to be the subject of study, being displayed for different time frames and locations. In addition, the seasonal behavior will also play a great role in the study.

When talking about "complementarity", this should not imply that both resources are compatible or not for the generation of electric energy independently, but that they are compatible for a hybrid project. This means that from now on, when discussing about wind and solar complementarity, it is done from the perspective of making the most of a common evacuation power line for a possible wind and photovoltaic hybrid generation plant, where both resources do not collapse in the space time and expand the plant factor.

3.3.2.1 Southern Hemisphere area case

As it was reflected in the Van der Hoven spectrum in *Figure 3.4*, wind varies continuously and also seasonally, however there is a certain periodicity or trend in the diurnal profile, also associated with the sun behavior.

In order to see graphically all these variations, the mean diurnal profile of the wind speed in each month of the measured period has been represented in *Figure 3.8* for the Southern Hemisphere area case. The available measured long-term representative period is from 04/17 to 10/20. In each graph, the y-axis corresponds to the mean wind speed [m/s] and it has been bounded on a scale of 5 to 11 m/s for a better representation. The local hour of the day is delimited from 0 to 23 and it is adjusted to the x-axis.

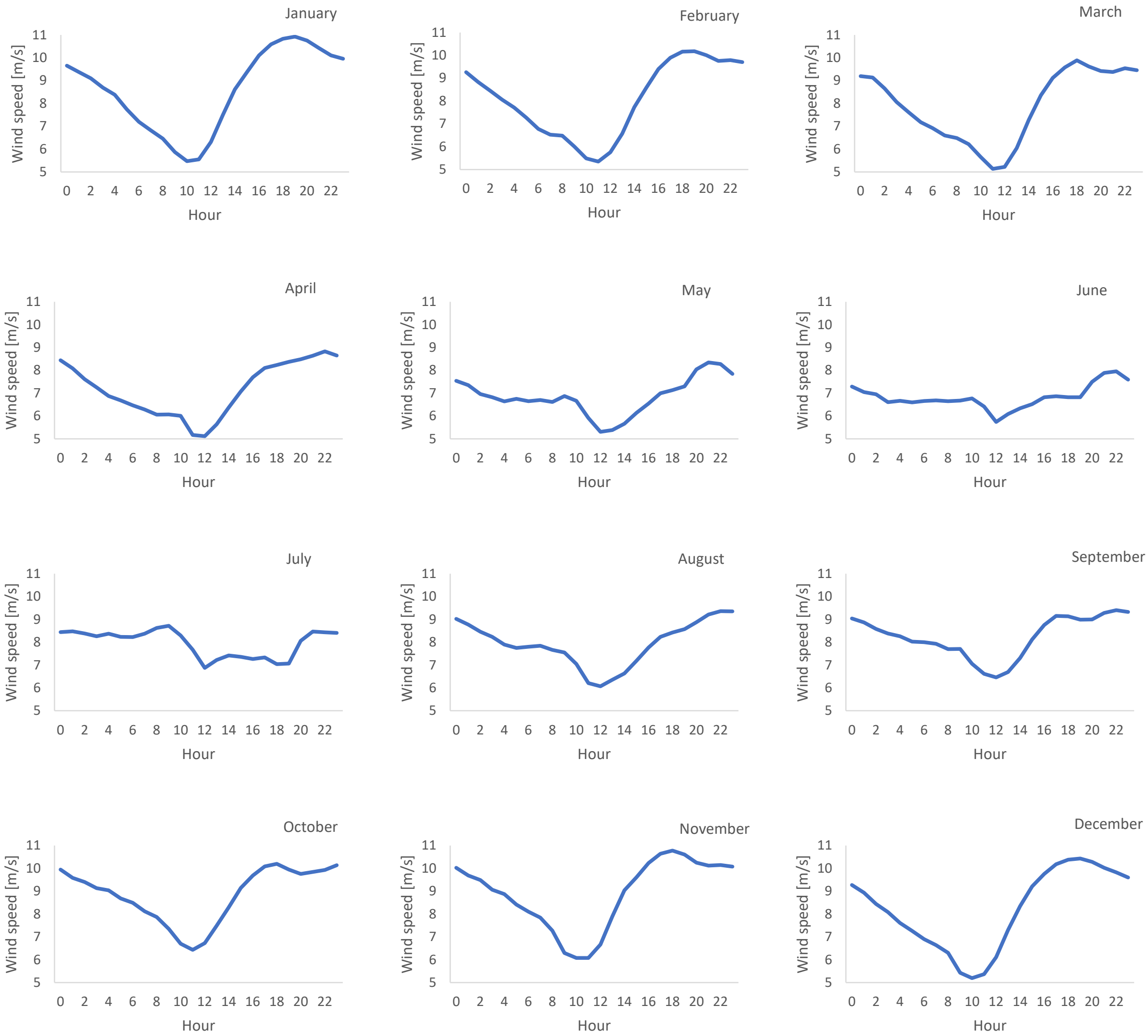

Fig 3.8. Wind speed mean diurnal profile for each month of the period; Southern Hemisphere area case

From *Figure 3.8* a general descending trend in the middle of the day can be observed. This tendency is further accentuated by the first and last three months of the year, corresponding also to months of higher mean wind speed. In the Southern Hemisphere, this windy period coincides with summer and spring respectively.

Following the mid-day downward trend, the overall wind speed mean diurnal profile for the whole period is then displayed in *Figure 3.9*, as well as the mean wind speed values by month and its variation respect to the average in *Table 3.1*.

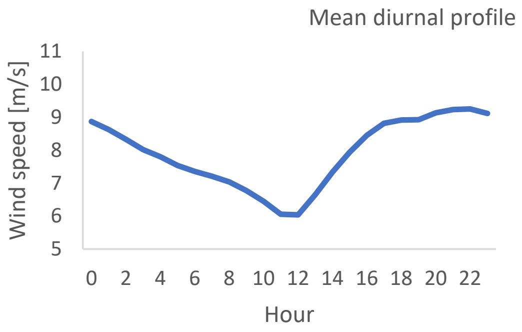

Fig 3.9. Wind speed mean diurnal profile for the whole period; Southern Hemisphere area case

Table 3.1. Mean wind speed values; Southern Hemisphere area case

Month	Mean Wind Speed [m/s]	Variation %
January	8.6	7.2%
February	8.1	1.4%
March	9.2	13.2%
April	7.2	-10.9%
May	6.9	-16.1%
June	6.8	-16.4%
July	8.0	0.0%
August	7.9	-0.3%
September	8.2	3.5%
October	8.8	9.9%
November	8.9	10.5%
December	8.2	3.0%
Average	7.96	

It is worth highlighting that the monthly and overall tendencies do not correspond to the wind behavior of each day of the year. As demonstration of it, 6 random days from the measured period have been chosen for their diurnal profile to be displayed in *Figure 3.10*:

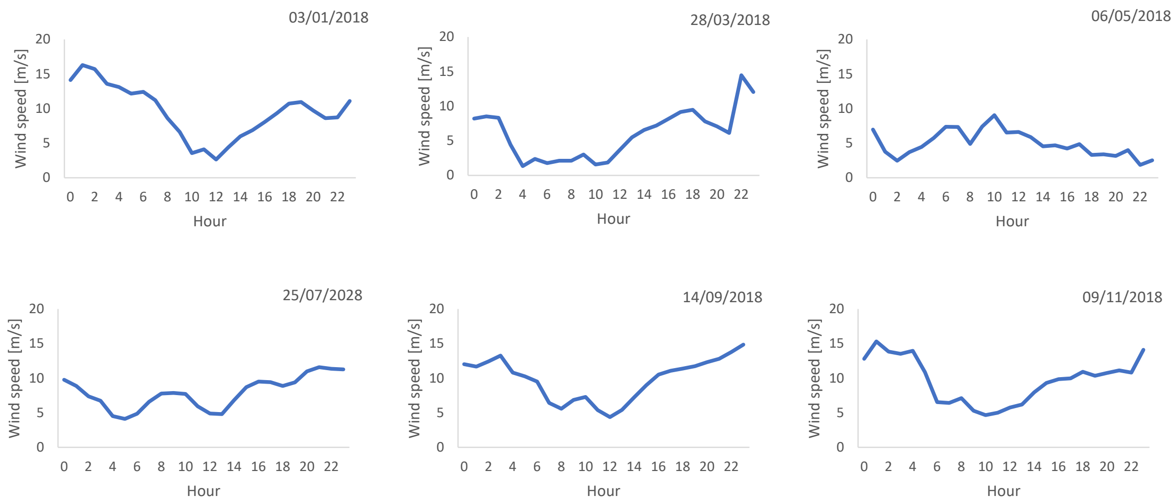

Fig 3.10. Wind speed mean diurnal profile for different days; Southern Hemisphere area case

As it can be seen in *Figure 3.10*, some days follow the trend, especially those subjected to the windiest months, however in the days of May and July (wintertime) there is no mid-day downward tendency.

Related to solar radiation, it was seen before that it will have a widely seasonally variation depending on the latitude, in this case around 30º far from the Equator. Unlike wind, the sun is more constant in its hours of shine, for this reason months have been grouped by seasons for their representation in *Figure 3.11*, where sum of the beam and diffuse irradiance on the horizontal plane have been displayed for each month of the TMY in the Southern Hemisphere area case.

The period covered by TMY is 2007 to 2016. In each graph, the y-axis corresponds to the total irradiance on the horizontal plane [W/m²] while the x-axis relates to the local hour of the day.

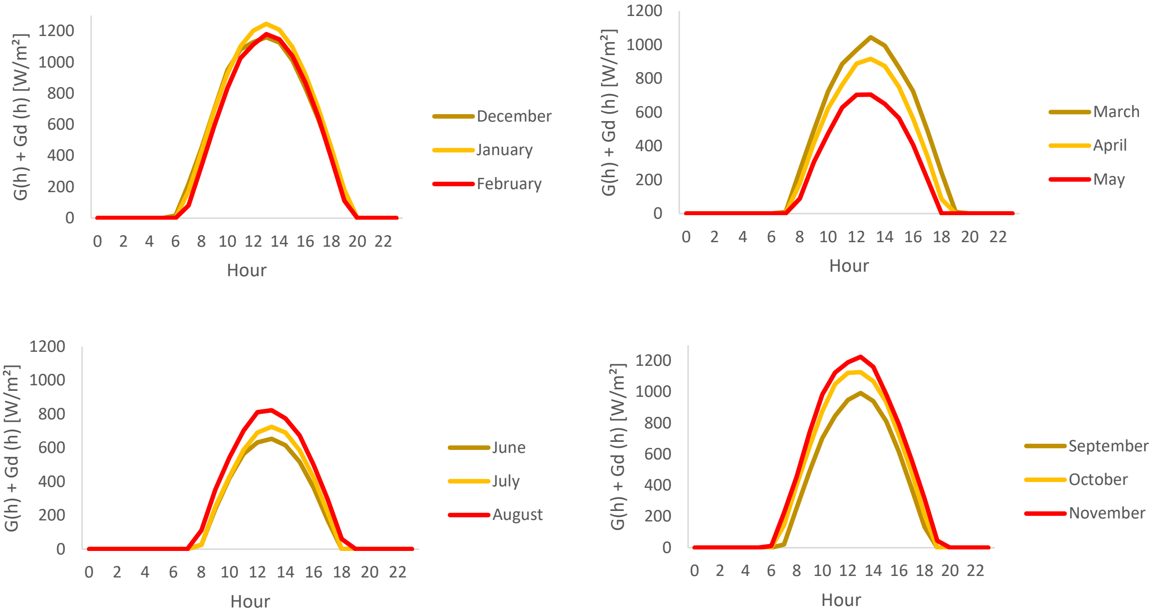

Fig 3.11. Irradiance mean diurnal profile for each month of the period; Southern Hemisphere area case

From *Figure 3.11* as it was to be expected, the irradiance starts increasing gradually from sunrise as the sun moves up in the sky and always achieve the maximum level of irradiance in the middle hours of the day. Then, as the sun goes down it will descend with sunset. As it happened with the wind speed in this particular location, there are both higher irradiance rates and more hours of sun from October until March, coinciding with summer and months close to it, when the sun's rays strike more directly to the surface of the earth.

It is worth stressing that in the same way that happened with the wind speed, the irradiance monthly behavior do not coincide with the irradiance behavior of each day of the month due to the abovementioned atmospheric condition. However, this trend is much more constant and along the time than wind speed variability.

The overall irradiance mean diurnal profile of the whole period is then displayed in *Figure 3.12*, as well as the mean total irradiance values by month and its variation respect to the average in *Table 3.2*.

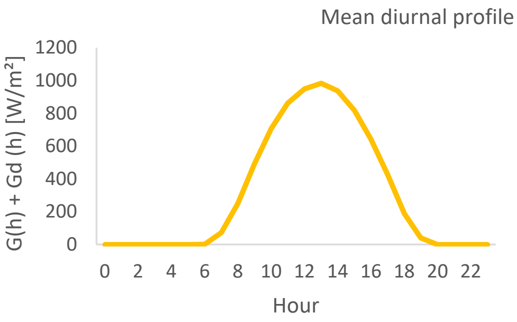

Fig 3.12. Irradiance mean diurnal profile for the whole period; Southern Hemisphere area case

Table 3.2. Mean irradiance values; Southern Hemisphere area case

Month	Mean Irradiance [W/m²]	Variation %
January	390.3	21.1%
February	390.3	21.1%
March	350.8	12.2%
April	266.9	-15.3%
May	197.2	-56.1%
June	175.3	-75.6%
July	192.9	-59.6%
August	235.4	-30.8%
September	297.6	-3.5%
October	366.3	16.0%
November	409.0	24.7%
December	410.8	25.1%
Average	307.83	

Once studied the behavior of the sun and the wind in this location, it can be concluded that both resources could complement each other well.

Regarding the 24 hours of the day, wind speed tends to be lower in the middle hours while sun irradiance reaches its maximum values. On the other hand, when there is no irradiance at all (between sunset and sunrise) the wind speed tends to stay high, therefore in the usual mean diurnal profile the sun would complement the wind very well.

With respect to seasonality, both resources have a higher incidence in the summer months, and a lower incidence in the winter months, so at first glance this would not be an advantage. However, we have seen that in some months corresponding to winter the daily wind speed profile did not tend so much downward in the middle hours of the day, so thinking about the production of energy through these resources, their coincidence in that space of time would not be of great inconvenience since their incidence is much lower than in other months and there would not be an excess of energy generation in that time frame.

Finally, the weighted average of both resources has been displayed for each month of the overall measured period (all the months adding up a total of 1) in Figure 3.13, being lower the contribution of the coldest months of the year due to the scarcity of both resources.

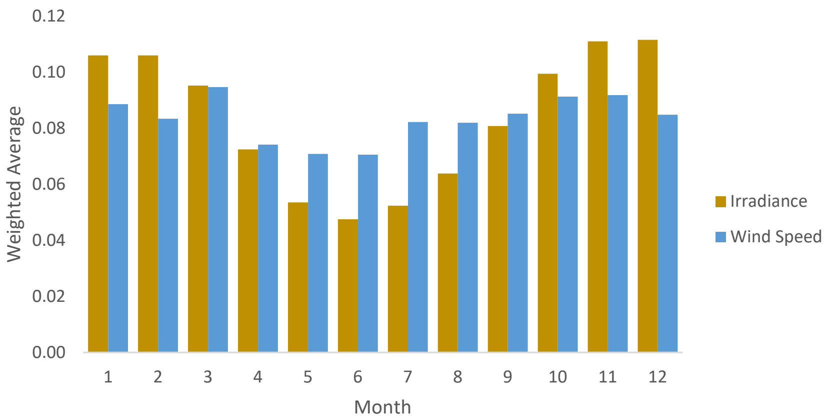

Fig 3.13. *Wind speed and Irradiance weighted average by months; Southern Hemisphere area case*

3.3.2.2 Northern Hemisphere area case

Following the same line of work, the mean diurnal profile of the wind speed in each month of the measured period has been represented in *Figure 3.14* for the Northern Hemisphere area case. The available measured long-term representative period is from 06/10 to 06/12. In each graph, the y-axis corresponds to the mean wind speed [m/s] and it has been bounded on a scale of 4.5 to 10.5 m/s for a better representation. The local hour of the day is delimited from 0 to 23 and it is adjusted to the x-axis.

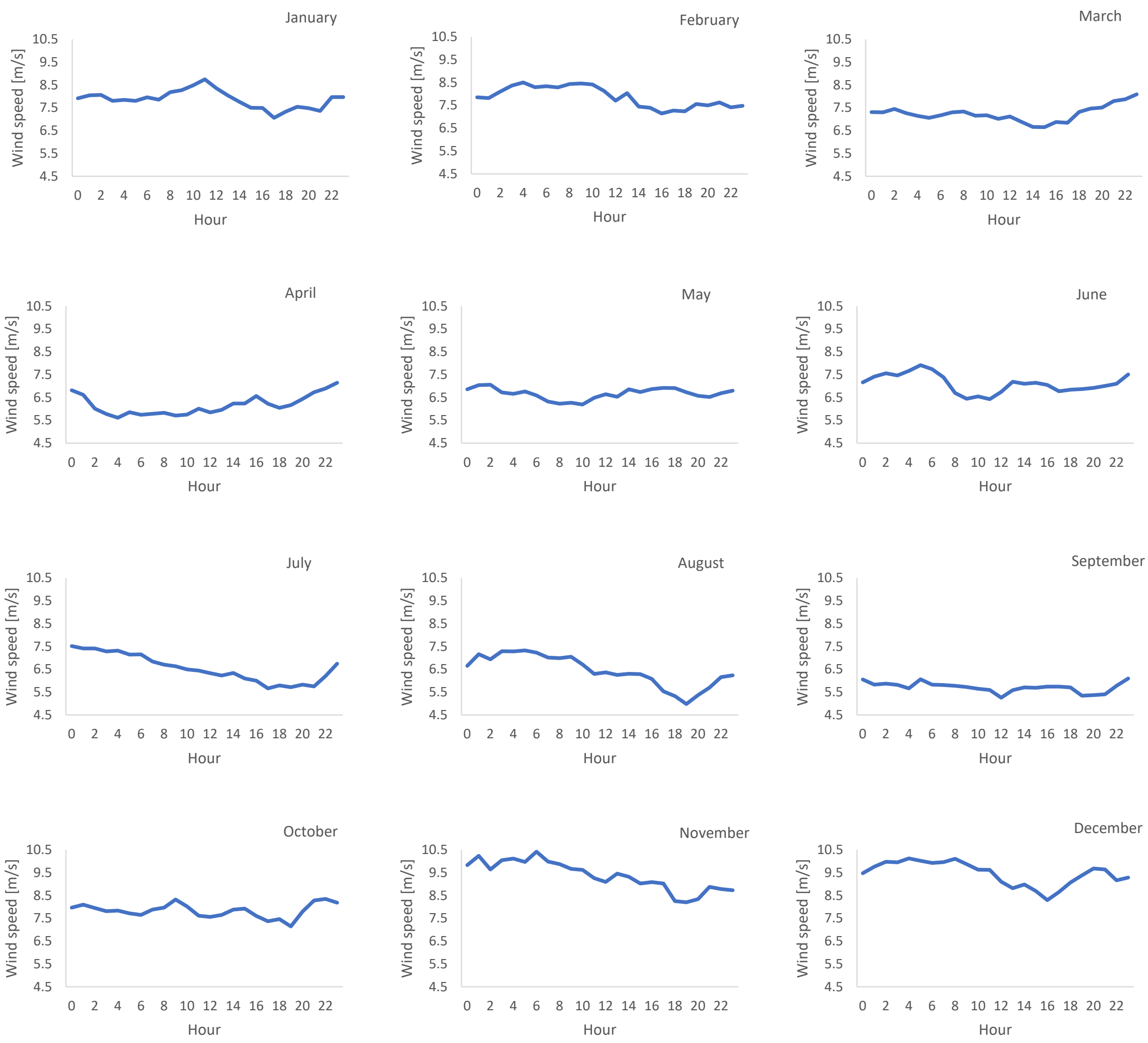

Fig 3.14. Wind speed mean diurnal profile for each month of the period; Northern Hemisphere area case

From *Figure 3.14* it can be observed that the wind speed is roughly constant throughout the day, with a small descending trend as the day passes for a few months. In addition, this constant speed is higher much higher from October to March, corresponding with a colder climate in the Northern Hemisphere. This windy period coincides with the one studied in the Southern Hemisphere, however this time it corresponds to autumn and wintertime.

The overall wind speed mean diurnal profile for the whole period is then displayed in *Figure 3.15*, where a slight decrease in the mean wind speed from 10 to 20 hours can be noted. In addition, the mean wind speed values by month and its variation respect to the average are available in *Table 3.3*.

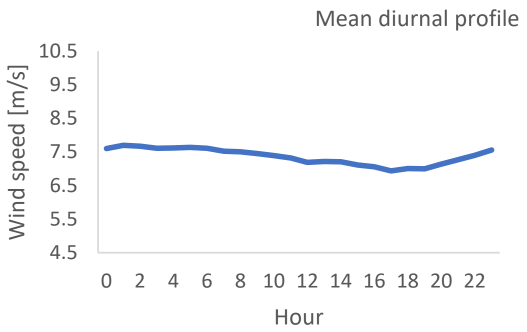

Fig 3.15. Wind speed mean diurnal profile for the whole period; Northern Hemisphere area case

Table 3.3. Mean wind speed values; Northern Hemisphere area case

Month	Mean Wind Speed [m/s]	Variation %
January	7.9	6.5%
February	8.1	8.8%
March	7.3	-0.7%
April	6.2	-19.3%
May	6.7	-10.4%
June	7.1	-3.4%
July	6.5	-12.4%
August	6.4	-14.2%
September	5.7	-28.8%
October	7.8	6.1%
November	9.4	21.5%
December	9.5	22.3%
Average	7.36	

Related to solar radiation, in this case with a latitude around 40º far from the Equator and following the previous procedure, months have been grouped by seasons for their representation in *Figure 3.16*, where sum of the beam and diffuse irradiance on the horizontal plane have been displayed for each month of the TMY in the Northern Hemisphere area case.

The period covered by TMY is 2007 to 2016. In each graph, the y-axis corresponds to the total irradiance on the horizontal plane [W/m²] while the x-axis relates to the local hour of the day.

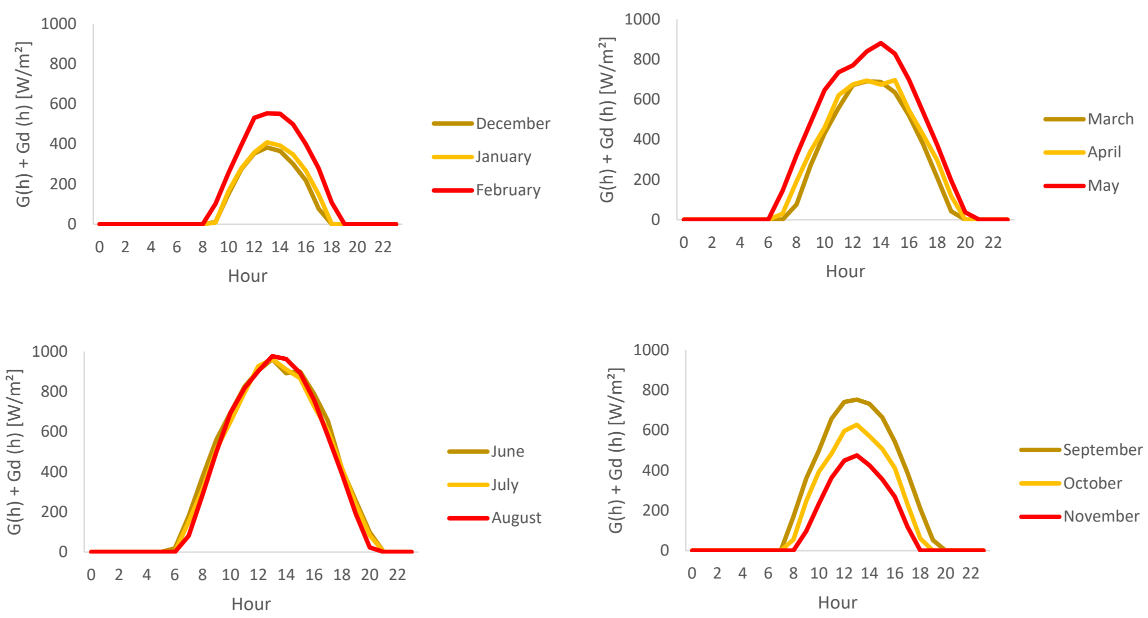

Fig 3.16. Irradiance mean diurnal profile for each month of the period; Northern Hemisphere area case.

As *Figure 3.16* reflects the sun path along the day does barely differ from the previous case. The only appreciation with respect to the Southern Hemisphere case lies with the number in hours of sunshine, that do not result in higher radiation rates. This is due to the 10 degrees of difference in the latitude with respect to the Equator. As it was explained before, the closer from the Equator the more concentrated the irradiance, and the farther from the Equator the more inclined the sun's rays which together with the translation of the earth will result in less sunshine hours in winter and more during summer. This event is very illustrative in the case of both Poles, where there is six months of the year when the sun does not rise above the horizon and another six months when the sun does not go below the horizon

In this location, contrary to the wind speed there are higher irradiance rates and more hours of sun from March until September, coinciding with summer and months close to it

The overall irradiance mean diurnal profile of the whole period is then displayed in *Figure 3.17*, as well as the mean total irradiance values by month and its variation respect to the average in *Table 3.4*, where is apparent that the irradiance variation from summer to winter is very pronounced due to the latitude of the location

Table 3.4. Mean irradiance values; Northern Hemisphere area case

Month	Mean Irradiance [W/m²]	Variation %
January	99.1	-124.6%
February	153.1	-45.4%
March	235.0	5.3%
April	240.4	7.4%
May	312.2	28.7%
June	355.5	37.4%
July	340.3	34.6%
August	335.9	33.7%
September	240.3	7.4%
October	174.3	-27.7%
November	116.0	-91.9%
December	88.9	-150.3%
Average	222.63	

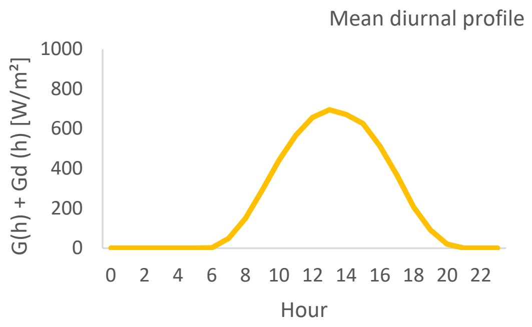

Fig 3.17. Irradiance mean diurnal profile for the whole period; Northern Hemisphere area case

The conclusion for this location after seeing the tendencies of both resources is that despite the fact that their complementarity is not entirely clear on the daily basis, both resources could complement each other quite well regarding seasonality.

Although it has been seen that the wind speed trend for this site is quite constant during the day, there was a slight rate decrease in the hours of sunshine for some months that could be seen as a positive fact. In addition, there is wind at night hours so that compensates the lack of radiation.

Regarding the resources seasonality, they clearly complement each other really well since wind speed has a higher incidence in the winter months and irradiance counts on its highest rates on the summertime frame. This occurrence is well represented in *Figure 3.18*, where the weighted average of both resources has been displayed for each month of the overall measured period.

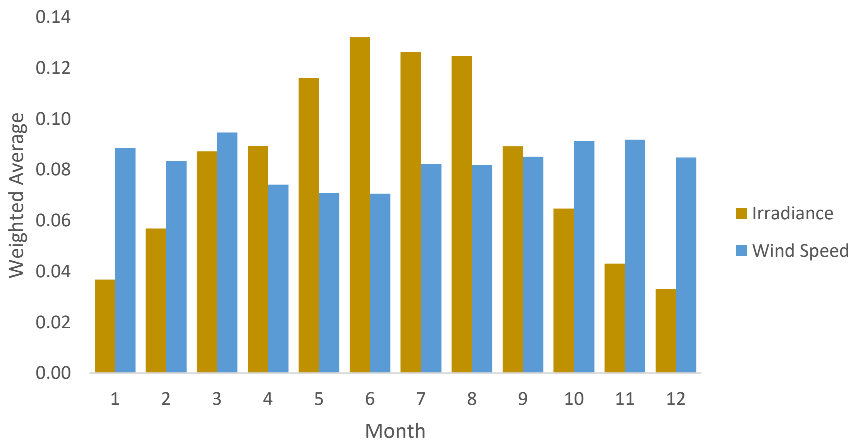

Fig 3.18. Wind speed, Irradiance weighted average by months; Northern Hemisphere area case

3.3.2.3 Tropic area case

The mean diurnal profile of the wind speed in each month of the measured period has been represented in *Figure 3.19* for the last global study case in the Tropic area. The available measured long-term representative period is from 03/15 to 03/17. In each graph, the y-axis corresponds to the mean wind speed [m/s] and it has been bounded on a scale of 3 to 19 m/s for a better representation. The local hour of the day is delimited from 0 to 23 and it is adjusted to the x-axis.

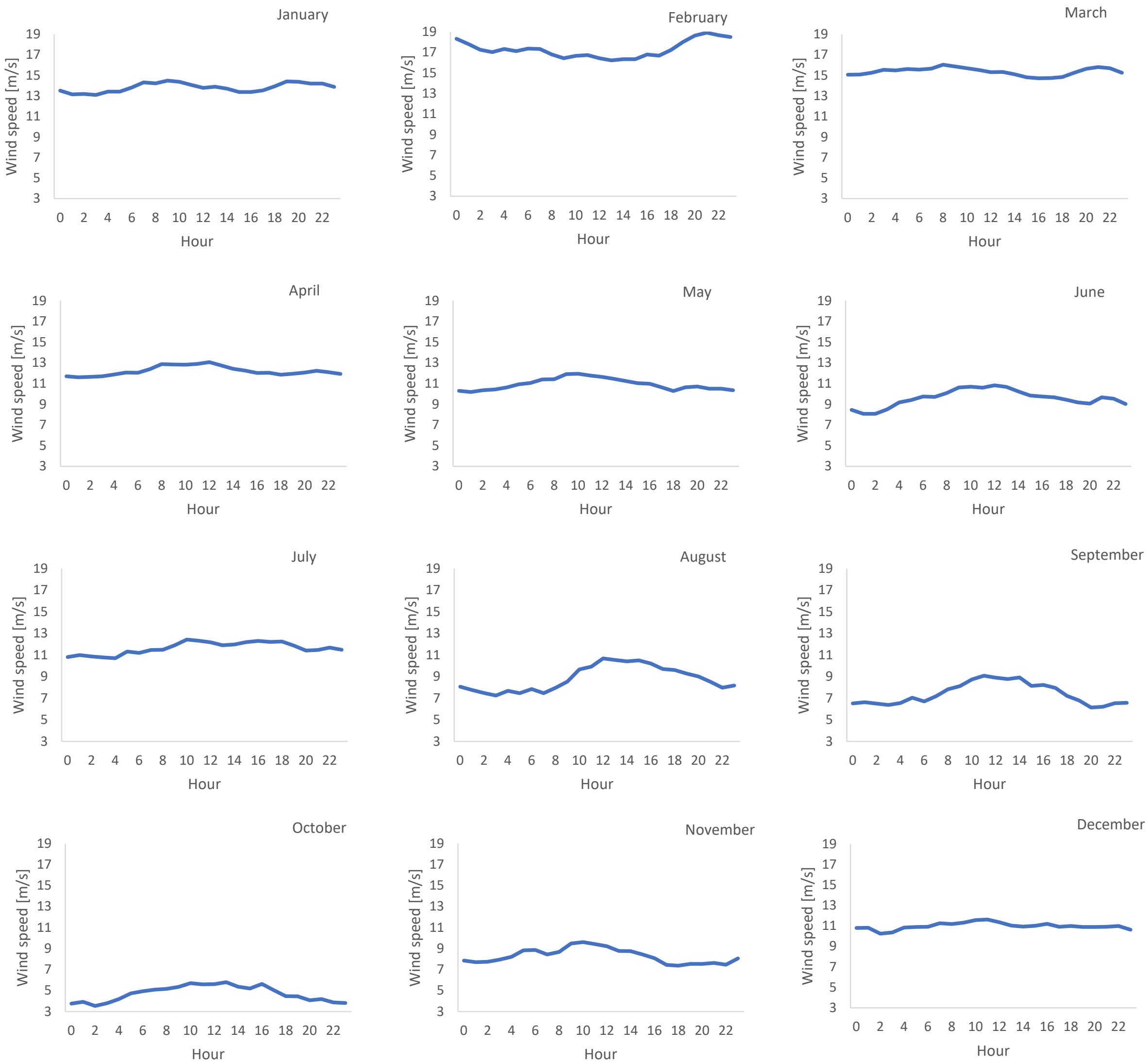

Fig 3.19. Wind speed mean diurnal profile for each month of the period; Tropic area case

From *Figure 3.19* a general ascending trend in the middle of the day can be noted. This tendency is greater from May to November, corresponding locally to the rainy season of the region. In addition, the mean wind speed tends to be higher from January to April, matching the dry season of the year.

Again, the overall wind speed mean diurnal profile for the whole period is displayed in *Figure 3.20*, which as previously seen in most months follows a mid-day upward trend. In addition, the mean wind speed values by month and its variation respect to the average are available in *Table 3.5*.

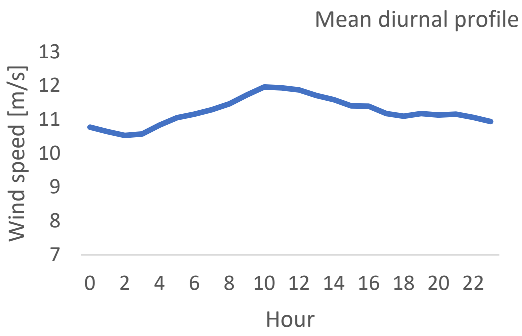

Fig 3.20. Wind speed mean diurnal profile for the whole period; Tropic area case

Table 3.5. Mean wind speed values; Tropic area case

Month	Mean Wind Speed [m/s]	Variation %
January	13.8	21.0%
February	17.3	36.8%
March	15.4	29.1%
April	12.2	10.6%
May	10.9	0.1%
June	9.6	-13.9%
July	11.6	6.1%
August	8.8	-23.9%
September	7.4	-47.6%
October	4.7	-131.5%
November	8.3	-31.7%
December	11.0	0.5%
Average	10.92	

Related to solar radiation, in this case with a latitude around 10º North far from the Equator and following the previous procedure, months have been grouped by seasons for their representation in *Figure 3.21*, where sum of the beam and diffuse irradiance on the horizontal plane have been displayed for each month of the TMY in the Tropic area case.

The period covered by TMY is 2006 to 2015. In each graph, the y-axis corresponds to the total irradiance on the horizontal plane [W/m²] while the x-axis relates to the local hour of the day.

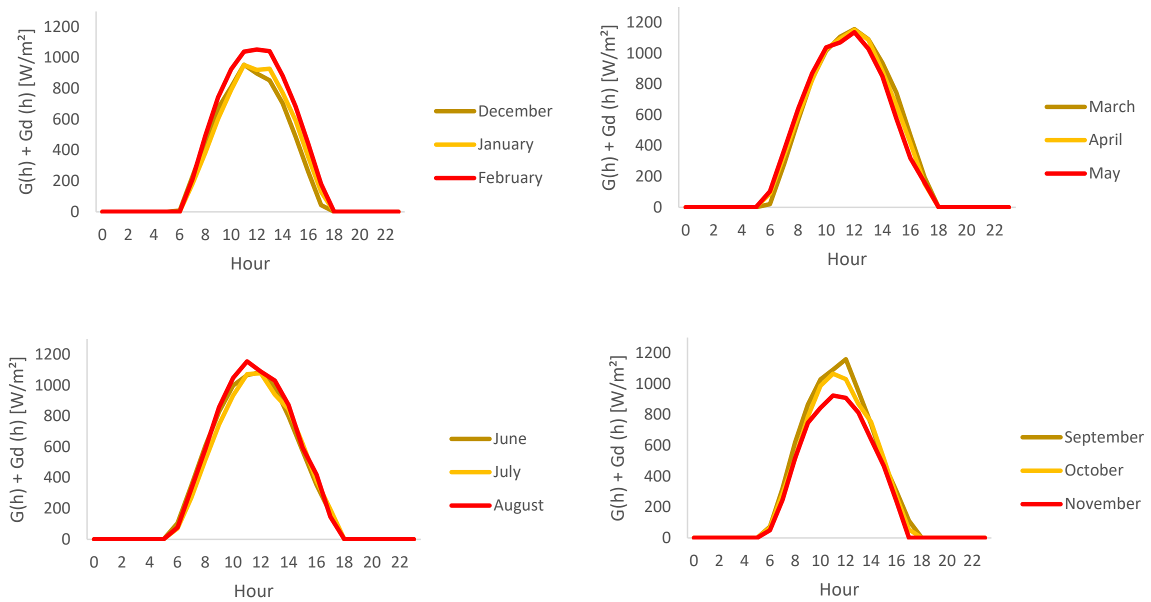

Fig 3.21. Irradiance mean diurnal profile for each month of the period; Tropic area case

In *Figure 3.21*, again it is appreciated the sun path along the day. It can be noted that due to the proximity of the location to the Equator, the day roughly lasts the same as the night throughout all the year.

Regarding seasonality, in this location there are higher and constant irradiance rates from February until September, however the variation with the remaining months is not very pronounce in comparison with the other latitudes studied, therefore solar radiation will be more or less constant throughout all the year.

The overall irradiance mean diurnal profile of the whole period is then displayed in *Figure 3.22*, as well as the mean total irradiance values by month and its variation respect to the average in *Table 3.6*, where we can see that the average values are the highest from the three studied cases due to the direct impact of the sun on the surface of the earth.

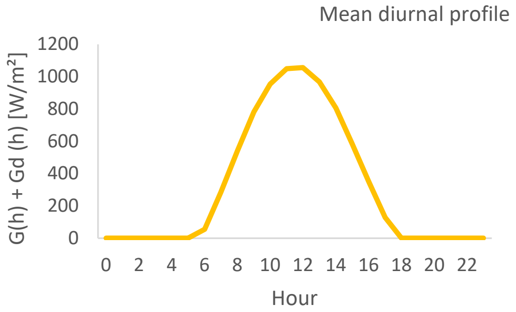

Fig 3.22. Irradiance mean diurnal profile for the whole period; Tropic area case

Table 3.6. Mean irradiance values; Tropic area case

Month	Mean Irradiance [W/m²]	Variation %
January	275.5	-14.4%
February	320.8	1.8%
March	382.6	17.7%
April	346.9	9.2%
May	340.2	7.4%
June	330.1	4.6%
July	319.5	1.4%
August	341.9	7.8%
September	322.9	2.4%
October	299.8	-5.1%
November	266.6	-18.2%
December	265.7	-18.6%
Average	315.05	

In the case of this particular location, it may be concluded that both resources would not complement each other really well in the space time.

In regard to the daily frame, it has been seen that in general terms both resources tend to have their greater incidence in the middle of the day, which would result in an excess of production in the hybrid scenario of interest. It is worth stressing that this also implies that when there is zero irradiance at nighttime the wind speed tends to stay lower.

With respect to seasonality, it has been seen that irradiance stays roughly constant throughout all the year being lower from October to January, while wind speed varies along the period with lower mean values from August to November, finding almost no complementarity.

To cover the abovementioned, the weighted average of both resources has been displayed for each month of the overall measured period in *Figure 3.23*.

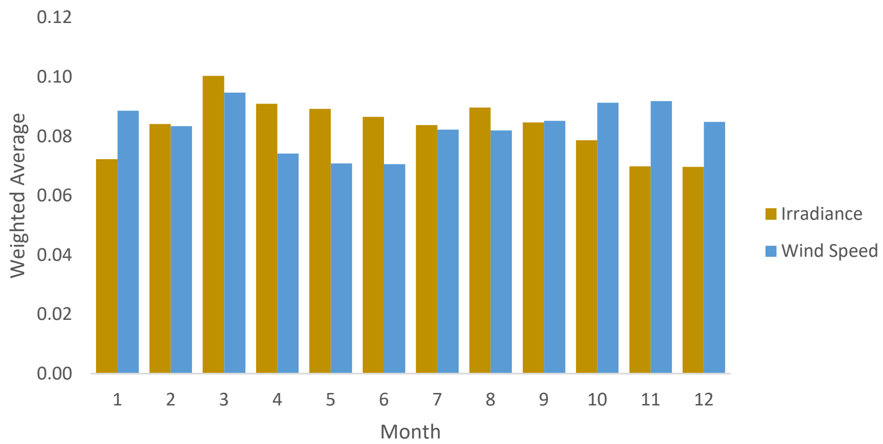

Fig 3.23. Wind speed, Irradiance weighted average by months; Tropic area case

3.3.2.4 Global study conclusions

Once the three cases have been subject of study, the following figures show globally the mean results obtained in this first study:

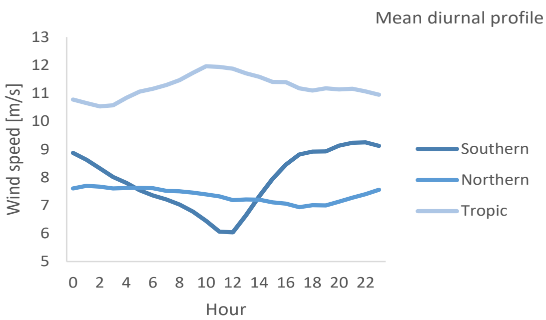

Fig 3.24. Wind speed mean diurnal profile; 3- case

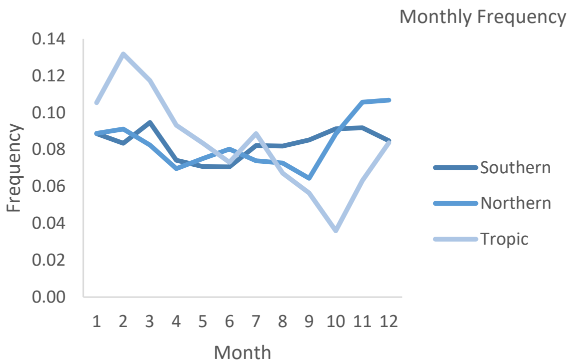

Fig 3.25. Wind speed monthly frequency; 3- case

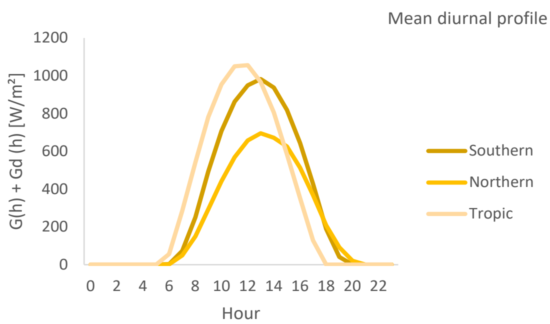

Fig 3.26. Irradiance mean diurnal profile; 3- case

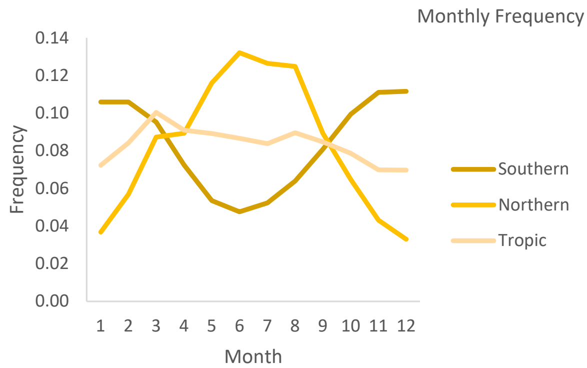

Fig 3.27. Irradiance monthly frequency; 3- case

As summary, different conclusions have been achieved:

- There can be a good complementarity of wind and sun in the Southern Hemisphere area case regarding the daily behavior.
- In regard to a seasonal time frame both resources could complement each other very good in the Northern Hemisphere area case.
- For the Tropic area case, there is not an apparent complementarity apart from night hours.
- The expected sun motion due to differences in latitude and seasonality corresponds very well to the illustrated irradiance behavior, having in consideration that for a local study it is advisable to carry out more precise measurements to take into account the atmospheric and orographic conditions of each specific site.
- When it comes to the wind, there is not a behavior as predictive as that of the sun, therefore the need for a local and accurate study is noticeable. Nevertheless, although not precisely it has been noticed that the mean diurnal profile of a complete period could reflect the daily trend of the wind speed.

3.3.3 Regional study

This second study focuses on the regional wind behavior of Spain (Iberian Peninsula) and Aragon (Autonomous Community of Spain), where different locations with high wind potential will be the subject of the study. As mentioned before, the GWA application (Annex B) has been used for the wind data download at 100 m height.

The selected sites correspond to locations where there are wind farms in operation, and their identification has been possible thanks to the Google Earth Pro tool [48], a free software that shows the earth as a virtual globe and allows the view of its multiple cartography, based on satellite photography. From the point of view of a project development, it allows GIS data treatment, the search for electrical network substations, neighboring projects, delimitation of land, access points ...

The objective of this second study is to analyze the mean variability of the wind for a further delimited region since the mean behavior of the sun can be quite predictive for a specific latitude as seen above.

It should be remembered that Spain is located around 40 degrees north of the Equator, so it will have great variability in radiation depending on seasonality due to the inclination of the earth. In addition, the southern regions of the country will count with a higher solar incidence due to their greater proximity to the Equator, which is well represented in *Figure 3.28*, the horizontal irradiation map of Spain.

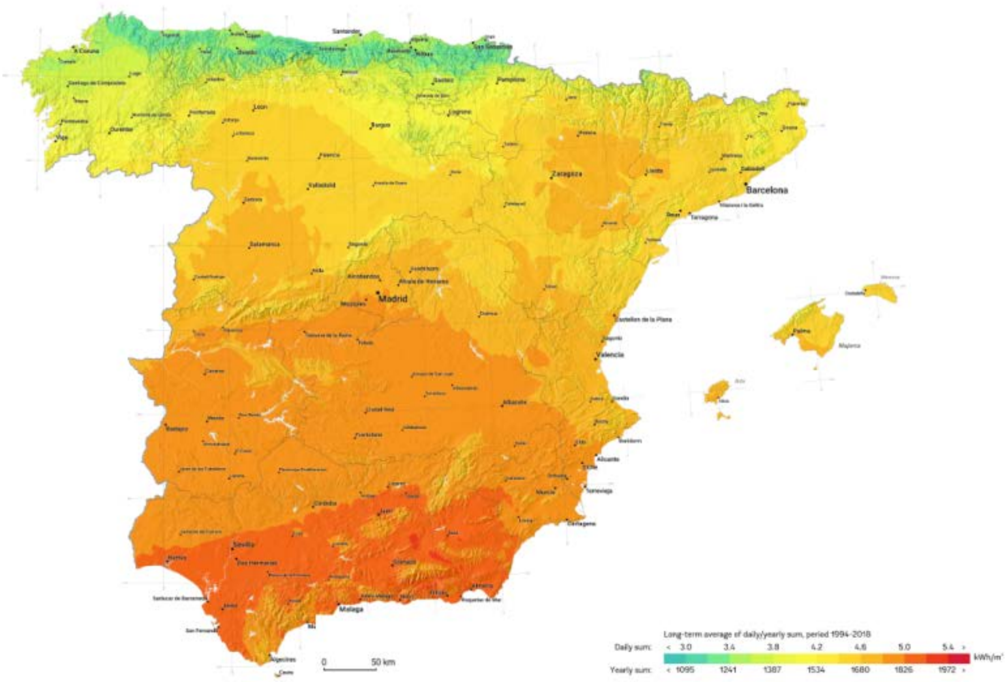

Fig 3.28. Global horizontal irradiation in Spain [35]

The selected sites for the wind study are shown in *Figure 3.29*, with yellow markers for different wind farms of Spain. Blue markers correspond to the selected locations in Aragon, with the aim of delimit the scope of analysis.

Fig 3.29. Selected wind farm locations[2]

[2] Image obtained from Google Earth Pro software

To get an overview of the different wind farms selected in Spain, the mean diurnal profile of the wind speed in each yellow marked location has been represented in *Figure 3.30*. In each graph, the y-axis corresponds to the mean wind speed [m/s] and it has been bounded for a better representation on the same scale but in different ranges depending on the mean wind speed values of each site. The local hour of the day is delimited from 0 to 23 and it is adjusted to the x-axis.

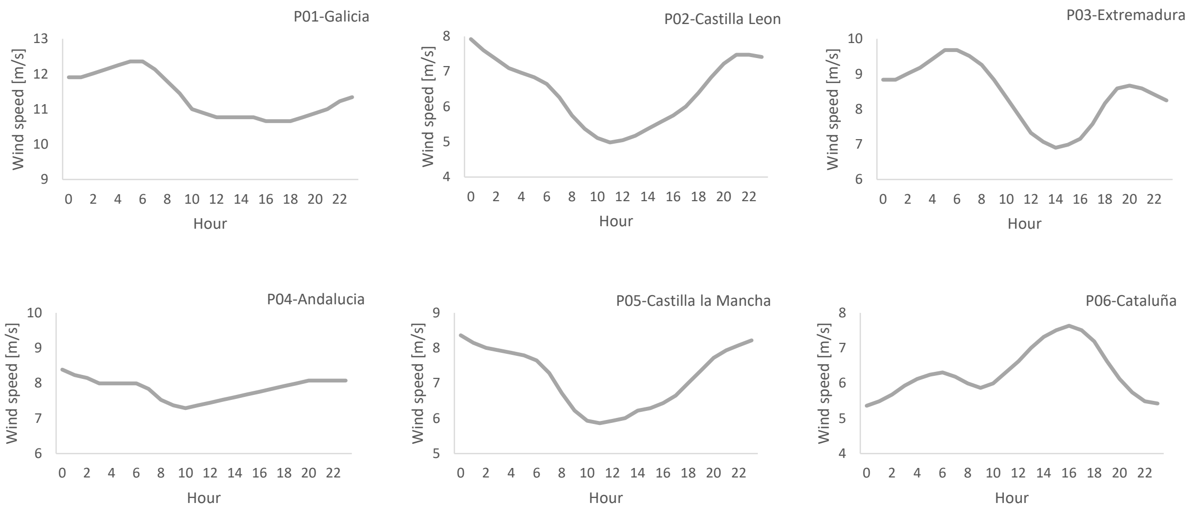

Fig 3.30. Wind speed mean diurnal profile for different sites in Spain

In *Figure 3.30* it can be observed that to a greater or lesser extent, all studied sites have a wind speed with a downward trend in the middle hours of the day, which as previously seen is a very positive aspect when looking for sun radiation complementarity. Although the location corresponding to P06 also experience a wind speed decrease in the morning, it reaches its maximum values in the same hours that irradiance is still high, which could not be an advantage from a hybrid generation point of view.

To see how the wind speed behaves in regard to seasonality, its weighted average values along the year have been displayed *Figure 3.31*, where it can be noted for all the selected sites that the mean wind speed is highest in winter and lowest in summer, the opposite of irradiance.

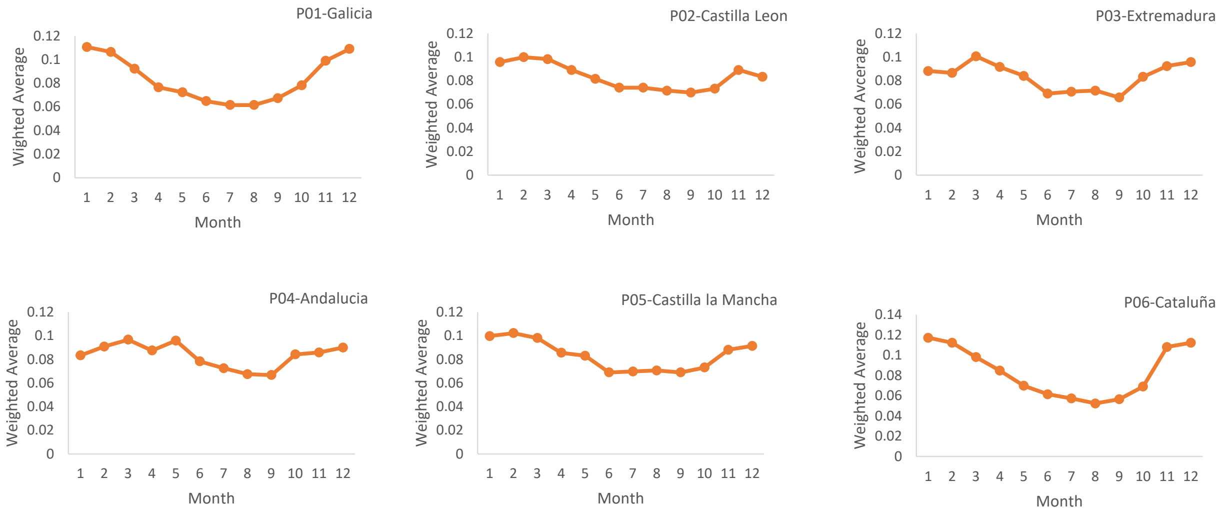

Fig 3.31. Wind speed monthly frequency for different sites in Spain

Now, in order to see how the wind can variate within a smaller region, the same procedure is repeated for the three selected wind farms in Aragon. Therefore, the mean diurnal profile of the wind speed in each blue marked location has been represented in *Figure 3.32*.

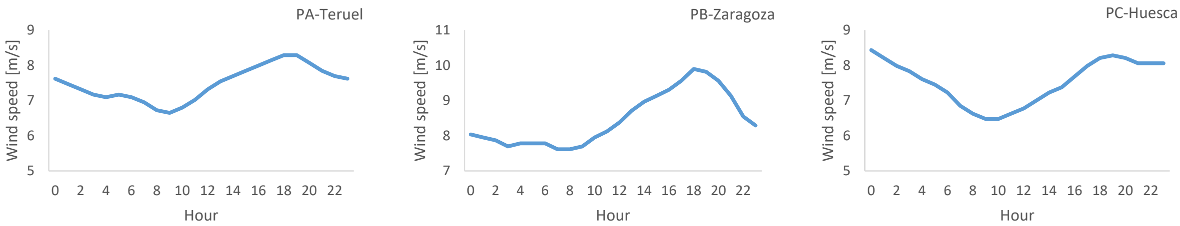

Fig 3.32. Wind speed mean diurnal profile for different sites in Aragon

From *Figure 3.32*, again it can be appreciated a mid-day descending tendency of the wind speed. Although the mean profile seems apparently more similar for the three cases, it is less favorable for instance in the case of *PB*, where wind speed counts with a pronounced increase in the hours of sunshine.

Regarding seasons, the wind speed monthly frequency of the three sites is represented in *Figure 3.33*, where again is highest in winter and lowest in summer although less pronounced in *PC* location.

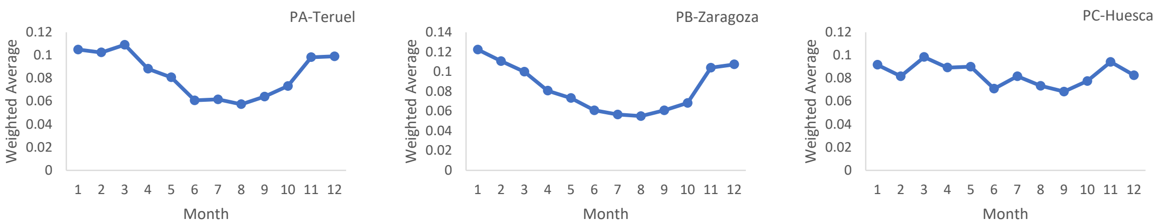

Fig 3.33. Wind speed monthly frequency for different sites in Aragon

3.3.3.1 Regional study conclusions

All in all, different conclusions are exposed:

- There can be a good complementarity of wind and sun in the Iberian Peninsula since the mean diurnal profile tends to descend in the hours that irradiance is high and vice-versa.
- In addition, regarding seasons wind tends to be highest in winter and lowest in summer while irradiance does it on the opposite way, therefore the seasonal inverse correlation could be very adequate.
- Although trends and favorable complementarities are being discussed, the need for a local study with precision data is apparent, since the behavior of the wind is highly variable and is strongly affected by the specific orographic and climatological conditions of each specific site.

4. INTEGRATION OF WIND AND SOLAR TECHNOLOGIES: TECHNO-ECONOMIC VIABILITY OF A HYBRID POWER PLANT

The main goal of this second chapter is the analysis of the time-space complementarity of wind and photovoltaic power generation over a common grid access point, according to the recent established regulatory framework and under two different scenarios.

Once wind and solar radiation behaviors have been studied in the previous chapter, the wind power potential and the photovoltaic power potential will be exposed with the intention of working with both resources in terms of power.

Moreover, two different studies will be carried out for the same area of operation, in which the adhesion of a hybrid solar plant will be studied for both an old wind farm (brownfield project) and a new projected wind farm (greenfield project). To do so, the legal framework of the decree law in which the subsequent studies rely on will be contextualized.

4.1 Wind power potential

A wind turbine converts the wind force into mechanical energy through the lift of the rotor blades, and this rotating mechanical energy is transformed into electrical energy through a generator located in the hub.

The amount of kinetic energy transferred to the rotor depends mainly on three factors: the size of the turbine rotor, the air density and the incident wind speed.

The air that passes through the rotor swept area determines the amount of energy that the wind turbine is able to capture. The larger the rotor blades, the greater the capacity to collect energy. Since the rotor area increases with the square of the rotor diameter, a turbine that is twice as large will receive four times as much power.

The air density directly influences the wind kinetic energy. The denser the air, the more energy the wind turbine will receive. The air is less dense at higher temperatures and decreases slightly with increasing humidity. In addition, at higher altitude the air pressure is lower, and therefore the air is less dense.

Finally, wind speed is very important for determining the total amount of energy that a wind turbine can transform into electrical energy. The power generated by the wind varies with the cube of its average speed, therefore if the wind speed doubles, the amount of energy it contains will be eight times greater.

Thus, the formula equivalent to the wind power that passes perpendicularly through a circular area is:

$$P = \frac{1}{2}\rho v^3 \pi r^2 \qquad (4.1)$$

Where:

P = wind power measured in W

ρ = air density = 1,225 measured in kg/m^3 (at average atmospheric pressure at sea level and at 15 °C)

v = wind speed measured in m/s.

π = 3.1415926535 ...

r = radius (half a diameter) of the rotor measured in m

The power curve of a wind turbine is a graph that displays how much electrical power will be available in the wind turbine for different wind speeds.

Wind turbines are designed to start rotating at speeds around 3-5 m/s, the cut-in wind speed. At an intermediate speed around 11-14 m/s, the rated or nominal wind speed, the wind turbine reaches the maximum power, rated or nominal power. In addition, the wind turbine will be programmed to stop at high speeds, around 25 m/s, to avoid possible damage to the operation of the turbine, and it is called the cut-out speed.

As an example, the power curve corresponding to the AW 70-1500 Class I turbine model has been represented in *Figure 4.1*. The data of the different powers for each speed bin can be found in *Table 4.1,* as well as some of the model specifications in *Table 4.2*.

Table 4.1. Bin speed and power output of the AW 70-1500 Class I power curve

Wind Speed [m/s]	Power Output[kW]
0	0.0
0.5	0.0
1	0.0
1.5	0.0
2	0.0
2.5	0.0
3	0.0
3.5	10.0
4	45.0
4.5	78.0
5	119.0
5.5	167.0
6	220.0
6.5	284.0
7	358.0
7.5	442.0
8	538.0
8.5	633.0
9	737.0
9.5	836.0
10	942.0
10.5	1061.0
11	1163.0
11.5	1272.0
12	1358.0
12.5	1419.0

Wind Speed [m/s]	Power Output[kW]
13	1461.0
13.5	1489.0
14	1500.0
14.5	1500.0
15	1500.0
15.5	1500.0
16	1500.0
16.5	1500.0
17	1500.0
17.5	1500.0
18	1500.0
18.5	1500.0
19	1500.0
19.5	1500.0
20	1500.0
20.5	1500.0
21	1500.0
21.5	1500.0
22	1500.0
22.5	1500.0
23	1500.0
23.5	1500.0
24	1500.0
24.5	1500.0
24.99	1500.0

Table 4.2. AW 70-1500 Class I specifications

Acciona AW 70-1500 Class I	
Rotor Diameter [m]	70
Rated Power [kW]	1500
Hub Heights [m]	80
Air Density [kg/m³]	1.225
Cut-in speed [m/s]	3.5
Cut-out speed [m/s]	25
Rated speed [m/s]	14

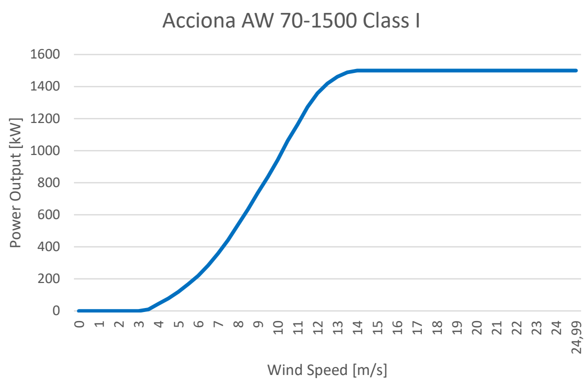

Fig 4.1. Power curve AW 70-1500 Class I.

The nominal power is only reached for wind speed values that are quite high and unlikely depending on the location. The wind turbine is never going to be constantly working at its nominal power, which makes a large part of the capacity of the evacuation power line available. Therefore, it will be necessary to know the speed probability distribution in order to know in which part of the power curve the wind turbines are most of the time. [36][37]

4.2 Photovoltaic power potential

Solar energy by photovoltaic effect is produced by direct transformation of solar radiation into electricity thanks to the properties of the semiconductor materials that make up the cells of the photovoltaic modules, capable of absorbing photons and releasing electrons, generating a potential difference that gives rise to an electric current.

The operating conditions of a photovoltaic cell such as irradiation and temperature directly affect the voltage, intensity and power generated by the modules and it is convenient to know how these conditions affect the energy generation.

Depending on the type of material used, each photovoltaic module will have different efficiency and electrical characteristics. Normally, these characteristics are given by the manufacturer through the I-V curves, where it is important to define the following parameters:

Depending on the type of material used, each photovoltaic module will have different efficiency and electrical characteristics. Normally, these characteristics are given by the manufacturer through the I-V curves, where it is important to define the following parameters:

- Open-Circuit Voltage, V_{OC} : potential difference that is reached when a photovoltaic module has no load connected; maximum voltage generated at zero current.
- Short-Circuit Current, I_{SC} : it occurs when the resistance is null and is proportional to the received irradiance; maximum current that may be drawn a photovoltaic module at zero voltage.
- Maximum Power Point, MPP : defined by the current at the maximum power point (I_{MPP}) and by the voltage at the maximum power point (V_{MPP}).

The PV module can work at any point on the I−V curve, and depending on the working point of the curve, a power that is determined by the electric power equation will be reached:

$$P = V\,I \tag{4.2}$$

Where:

P = photovoltaic power measured in W

V = voltage measured in V

I = photovoltaic current measured in A

The power curve has a maximum power point, called MPP. Most inverters include algorithms that make the modules work at points close to the MPP, where current and voltage have nearly the same relation to irradiance and temperature as the short circuit current and open circuit voltage.

The I_{SC} is nearly proportional to irradiance on the photovoltaic module, and it rises slightly with increasing temperature, which results in an increase in the module power and efficiency.

The dependence of the V_{OC} on the irradiance is logarithmic. At the same time the V_{OC} decreases at a faster rate with rising temperature, which will result in a maximum power and module efficiency decrease.

To illustrate all this, the I-V curves corresponding to the BISTAR TP6H72M monocrystalline solar module have been represented in *Figure 4.2* and *Figure 4.3*. Besides, some of the specifications of this module are displayed in *Table 4.3*.

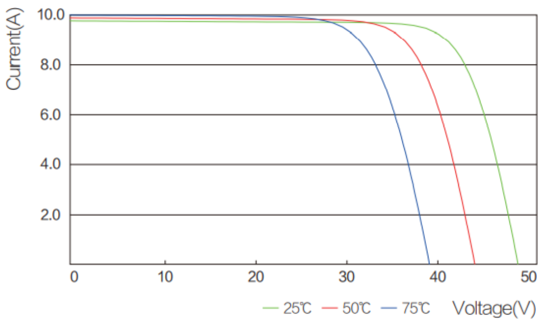

Fig 4.2. I-V curve BISTAR TP6H72M for different temperatures

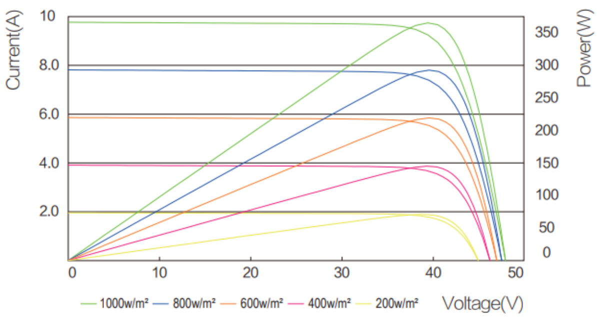

Fig 4.3. I-V curve and power curve BISTAR TP6H72M for different levels of irradiance

Table 4.3. BISTAR TP6H72M specifications

BISTAR TP6H72M	
Maximum Power, P_{MPP} [W]	360
Operating Voltage, V_{MPP} [V]	39.1
Operating Current, I_{MPP} [A]	9.21
Open-Circuit Voltage, V_{OC} [V]	47.8
Short-Circuit Current, I_{SC} [A]	9.70
Module Efficiency, η [%]	18.5

In order to make solar cells and modules comparable, MPP power is measured under Standard Test Conditions (STC) which are: irradiance 1000 W/m^2, module temperature 25ºC, and AM (air mass) 1.5, is also called peak power of the photovoltaic module.

However, the power generated by the solar modules in real weather conditions is usually lower and highly variable, being able to vary in a range of 0 - 1000 W/m^2, in the case of irradiance and cell temperature up to 50ºC higher than the ambient temperature. [38][39]

4.3 Hybrid power plant study

4.3.1 Regulatory framework

The *Royal Decree-Law 23/2020, of June 23*, establishes the possibility of carrying out HPP projects for existing and new power generation facilities with a common grid connection point and access capacity. The objective of this measure is the organized deployment of renewable energies and the achieving of a more stable and efficient supply optimizing existing networks.

On the other hand, the *Royal Decree 1183/2020, of December 29 of access and connection to transport networks and electrical power distribution [40]*, regulates the procedure for requesting and processing the conditions of access and connection for HPPs, and for updating, where appropriate, the permits already granted.

As defined in the decrees, the main requirements for the hybrid project development are the following:

- A power greater than the capacity of the grid access point can be installed as long as the power of the original source conforms to at least the 40% of the total HPP, that is, the new technology cannot occupy more than 60% of total final installed power.
- Power injection to the grid can never exceed what was allocated to the original installation. If wishing to exceed the access capacity already granted, a new access and connection permission would have to be requested.
- The holders of the access and connection permits already granted must request the relevant network manager to update said permits (abbreviated procedure with a 50% reduction in economic guarantees).
- The geometric project center does not differ by more than 10.000 m.
- The minimum bid value to participate in adjustment services stands at 10MW.
- Hybrid installations must have systems that always assure the control of the discharge into the network, as well as measurement equipment able to monitor the energy discharged by each technology.
- The access capacity of the line is not exceeded by 5%.
- All the above points provided that the new installation complies with the technical requirements that apply to it.

With these premises, two scenarios are going to be analyzed in the present study, the hybridization of an existing wind farm in operation for years, and the hybridization of a new projected wind farm, both with the addition of PV solar power generation.

4.3.2 Brownfield project

The first case study consists of a brownfield project, which means that a certain solar power will be added to an existing wind farm to optimize the evacuation power line and increase the load factor of the new HPP, compensating the losses due to reduction of generation (curtailment) with the economic savings resulting from installing the solar plant in hybridization mode.

For the project development, it will be necessary to know the characteristics of the wind farm studied, as well as its energy production, and on the other hand a solar production database will be required in order to evaluate the potential of the HPP. Therefore, the generation profiles of the two technologies will be analyzed in the first place, and then an energy analysis of the hybrid plant will be carried out based on the different percentages of solar power to be installed versus the installed wind power.

To perform the energy analysis, it will be necessary to carry out a curtailment analysis, in which the losses of the hybrid project will be considered as the excess generation that cannot be injected into the grid due to the capacity of the evacuation line and the high availability of resources.

Once the production data and energy losses are available according to the different percentages of installed PV power, an analysis of the LCOE will be carried out to study the economic viability of the plant and the optimal solar power to install.

4.3.2.1 Project features

The existing wind farm is composed of 25 Nordex N43/600 wind turbines of 600 kW of unit power, for a total of 15 MW.

To carry out the energy calculations of the PV plant, initially a power equivalent to the installed wind power will be considered, that is, 15 MW. In addition, as the ideal solar power to install is unknown for the project to be optimal, different solar power ratios will be calculated based on the installed wind power ($\frac{P_S}{P_W}$) with 0 being the absence of the PV plant, 1 a plant equivalent in size to the wind farm, and 1.5 the multiplying factor that would make the PV plant account for 60% of the total hybrid plant, in order to contemplate the maximum scenario allowed by the decree, which would be equivalent to a maximum PV power of 22.5 MW.

The hybrid project will therefore have a total maximum installed power of 37.5 MW with a maximum evacuation line capacity of 15 MW. All figures are summarized in *Table 4.4.*

Table 4.4. Brownfield project features

Brownfield project features	[MW]
Total wind installed power	15
Access line capacity	15
Max. solar power allowed	22.5
Total Max. hybrid project power	37.5

The analysis has been carried out considering 4 years of wind data and injected power, measured in a meteorological station located in the existing wind farm. For solar power, a reference year of injected solar power has been obtained from an existing solar farm close to the studied site.

In this study, the wind and solar resource data have been analyzed separately, and the energy capacity associated with each of them has been evaluated. Subsequently, the losses and complementarities of their hybridization have been analyzed over a period of 4 representative years, discretizing the capacity of each of the project in units of 10%.

In addition, to complete the study a basic economic analysis intended to find the optimum solar power to be installed has been included.

4.3.2.2 Available information

The information to carry out this study is described below:

- Hourly wind speed records and hourly power injected to the grid from a data logger of the wind farm weather station are available for a representative period between 2009 to 2012. The data from this station is real operational power data and does not require any analysis since wake losses, unavailability… are already considered.
- Information on solar injected power to the grid has been obtained from an existing solar farm of 4 MW, extracting a typical year of hourly time basis data from the 2015-2019 period.

In addition, different timeseries of the available data have been displayed in *Figure 4.4* and *Figure 4.5* for a better understanding of the nature of this data.

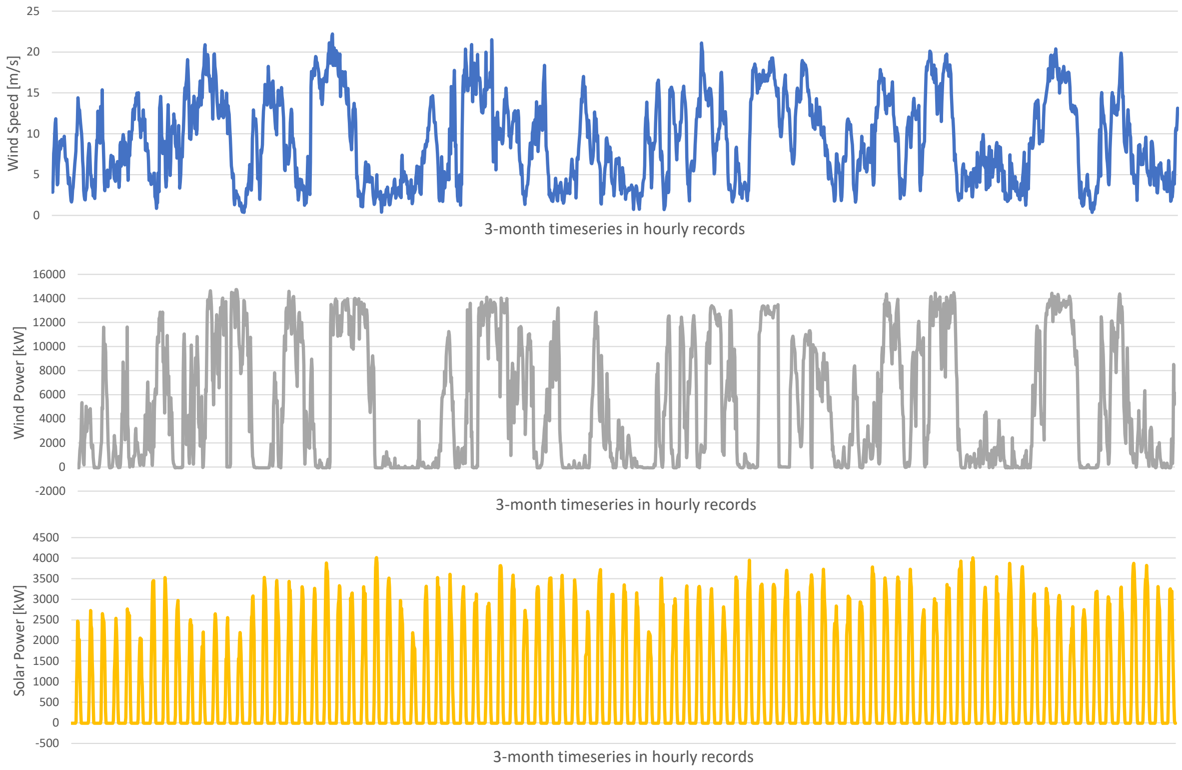

Fig 4.4. Wind speed, Wind power and Solar power hourly records 3-month timeseries

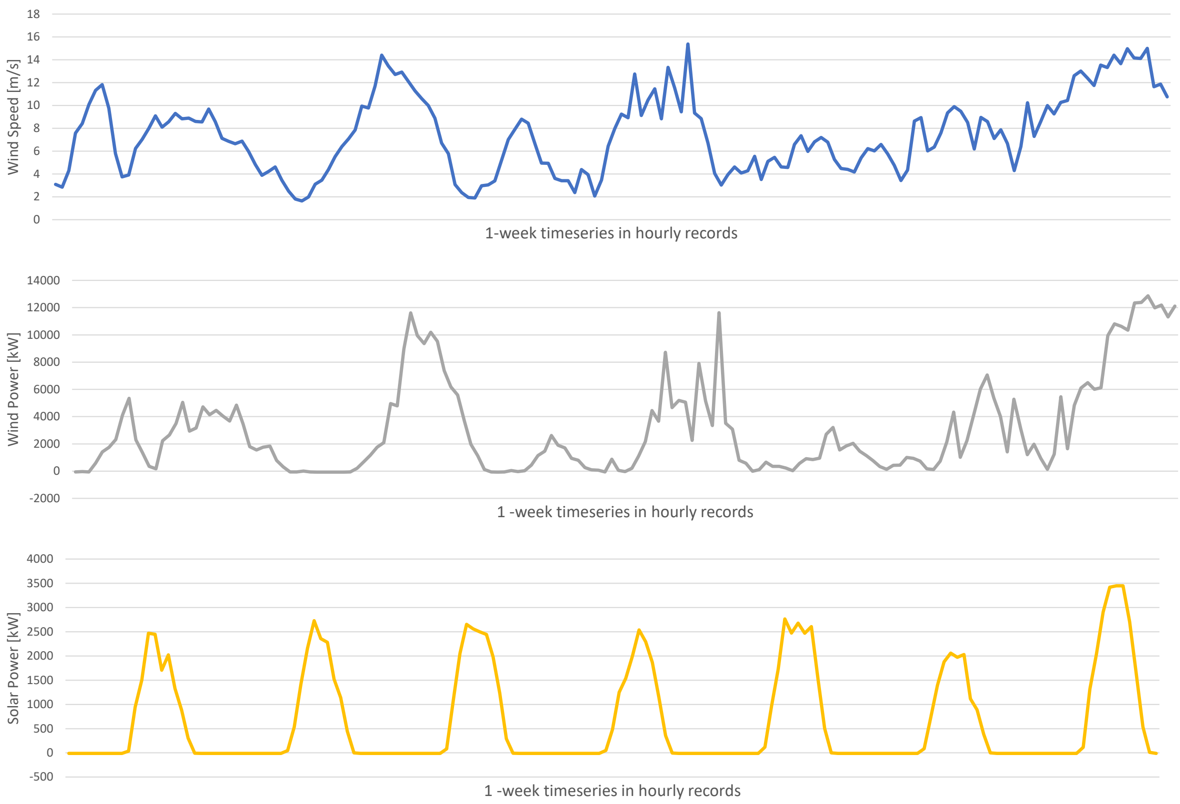

Fig 4.5. Wind speed, Wind power and Solar power hourly records 1-week timeseries

4.3.2.3 Wind farm generated energy

In the case of wind energy, it is not possible to define a typical year of resource, since the variability of the wind prevents determining a specific average speed of one hour, day, month and year, hence it is necessary to base the study on more than one year, in this case four years.

The speed frequency analysis of the studied period is represented in *Figure 4.6*, where it can be seen that the highest frequency (number of hours) of speed occurs between 2 m/s and 6 m/s, with most of the time the park below its nominal power and therefore leaving free evacuation capacity.

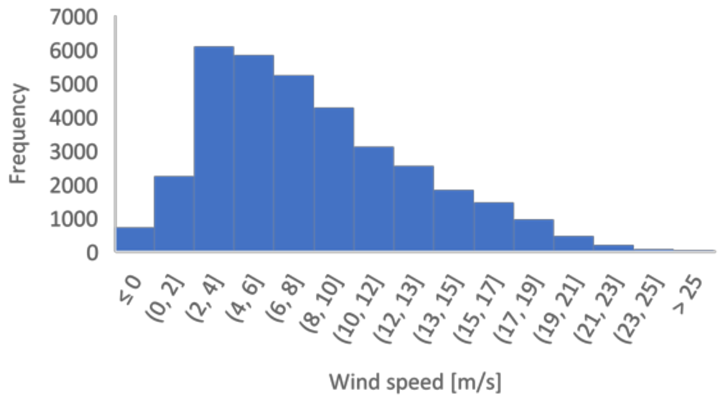

Fig 4.6. Frequency analysis of the wind speed that characterizes the site (number of hours); Brownfield project

The wind farm has twenty-five operative wind turbines with a machine model Nordex N43/600 and a unit power of 600 kW, making a total of 15 MW that have been in operation more than ten years. In *Figure 4.7*, the frequency distribution of the power injected into the network is presented for the wind technology. A dominant peak is observed in the graph, corresponding to the wind farm in standby, when the speeds are less than 3 m/s or is not possible to inject power into the grid. It can be also noticed that full power, corresponding to speeds greater than 13 m/s (nominal speed), is less frequently reached, also due to the maturity stage of the wind turbines.

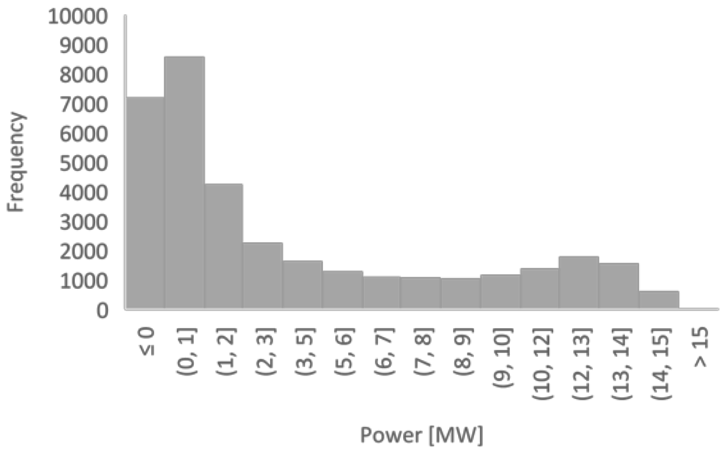

Fig 4.7. Frequency analysis of the power injected to the grid (number of hours); Brownfield project

The viability of the hybrid project will depend on the coincidence of this frequency at full capacity with the hours of solar generation, which as seen in *Figure 4.8* where the hourly distribution of the N43/600 has been displayed, is usually lowest at the beginning of morning and higher at night hours. This means that in this location there could be a good integration between the wind energy and the photovoltaic energy, that produces its maximums in the middle of the day.

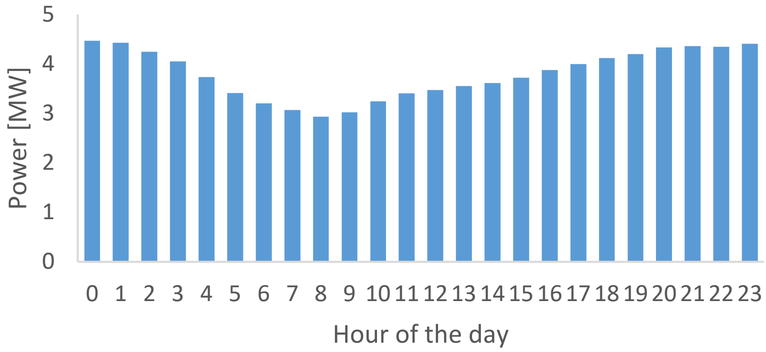

Fig 4.8. Hourly analysis of the wind power distribution (N43/600); Brownfield project.

The energy estimation of the wind farm has been recorded from the curve register of the operating wind farm, therefore wakes between machines and other losses due to unavailability or external factors are already considered. The energy generated then is 30.7 GWh/year for the 25 N43/600.

4.3.2.4 Solar plant generated energy

For solar power, the calculation is based on recorded data from a real photovoltaic power plant located close to the studied wind farm, where it has been obtained an average year of solar power representative of the site with a nominal installed power of 15 MW, which corresponds to a plant size equivalent to existing wind farm. The average power frequency and hourly distribution of the solar power are then shown in *Figure 4.9* and *Figure 4.10* respectively.

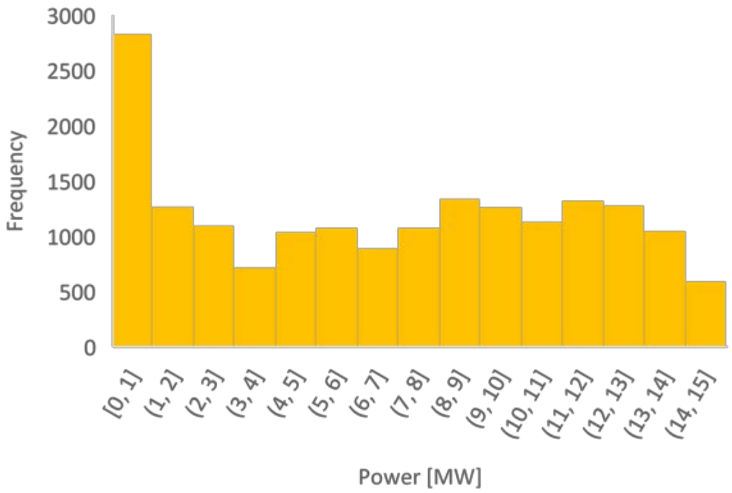

Fig 4.9. Frequency analysis of the power injected to the grid (number of hours); Brownfield project

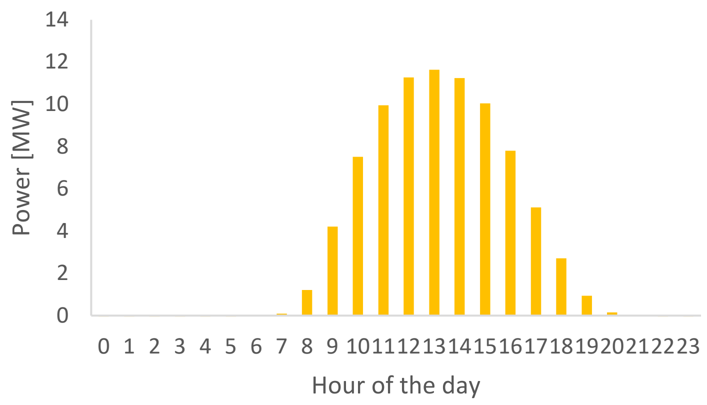

Fig 4.10. Hourly analysis of the solar power distribution; Brownfield project

From this analysis it is observed that solar energy is much more constant in generation than wind energy in its hours of operation, and that there is a complementarity between both resources.

The energy estimation of the solar plant has been recorded from the curve register of the operating solar plant, therefore all losses are already considered. The expected energy for the 15 MW photovoltaic power plant without considering losses due to power limitation of the hybrid project conditions will be 28.1 GWh/year for the first year of production. For the following years, due to the inherent degradation of photovoltaic cells, a decrease of up to 0.7% per year should be taken into account.

4.3.2.5 Energy analysis of the hybrid plant

The hybridization analysis consists of combining the typical production year of solar energy with the 4 years of wind energy production. To do this, the data is processed on an hourly basis, generating a 4-year database in which wind energy and solar production are available for each hour.

To estimate the HPP production, it will be necessary to first perform a loss analysis. It should be noted that generation losses related to each technology have already been considered, since gross generation injected into the grid data is being used, so this curtailment analysis will only refer to losses associated with the restrictions of the capacity of the grid evacuation line and the simultaneous excess generation.

In this study, losses in the generation of photovoltaic energy are always about to be discussed in order to take into account the use of the new added technology in the economic viability of the project, nevertheless in practice it does not have to be solar energy the one that is not injected into the grid in the event that the capacity of the line is exceeded, but it may also be the case that the wind power is limited by stopping some wind turbines, something that would contribute to the lengthening of the useful life of the machines. However, as it was discussed before, due to technical reasons cutting the solar production is being the preferred option by current brownfield projects owners.

To carry out the curtailment analysis, the calculation has been made looking for each hour throughout the studied period (35064 hourly records) the contribution of the different proportions of photovoltaic power to the free evacuation capacity of the wind farm power line, obtaining for each hour the losses that could arise due to the simultaneous generation of both technologies and the exceeding of the power line limits, displayed in *Formula 4.3*. The computation of the hybrid project losses has been carried out by means of a conditional sentence executed in the code of an Excel programming sheet. In addition, *Formula 4.4* shows the necessary parameters for estimating the hourly production of the HPP, being this the sum of the wind energy generation and the PV energy generation, and the subtraction of the power loss previously analyzed in case of exceeding the network access capacity.

$$P_{LOSS} = \begin{cases} 0, & (P_W + P_S) \leq P_{LINE} \\ P_W + P_S - P_{LINE}, & (P_W + P_S) > P_{LINE} \end{cases} \qquad (4.3)$$

$$P_{HYBRID} = P_W + (P_S - P_{LOSS}) \qquad (4.4)$$

Where:

P_W = Wind power

P_S = Solar Photovoltaic power

P_{LINE} = Access Line power limit

P_{LOSS} = Power loss due to the power limitation

P_{HYBRID} = Total Hybrid Power Generation

(All measured in MW)

To be able to perform fractional analysis and take into account the possibility of evaluating installing more or less solar power than that equivalent to the wind installed power, the work is performed in a standardized way with respect to the total capacity of the line, and all the calculations of losses and solar contribution are performed taking into account increments of 10% of installed solar power with respect to the total installed wind power.

In addition, since the subsequent decree, *RD 1183/2020*, allows a higher percentage of new technology to be installed in a hybrid project than the existing one (60/40), the analysis has been extrapolated to have an estimated scenario of up to 50% more of installed photovoltaic power.

Furthermore, the decree establishes the maximum limit of power injected into the network to be exceeded by 5%, therefore and with the aim of minimizing losses as much as possible, a line access capacity of 15.7 MW has been considered for calculations, being the additional 0.7 MW equivalent to around 4.5% of the evacuation line.

To see in practice the contribution of the PV power generation for different weather conditions and the losses that could arise when both technologies are at high levels of production, the diurnal profile power generation of a HPP with an installed photovoltaic power equivalent to the wind farm capacity, 15 MW, has been displayed for some selected days in *Figure 4.11*.

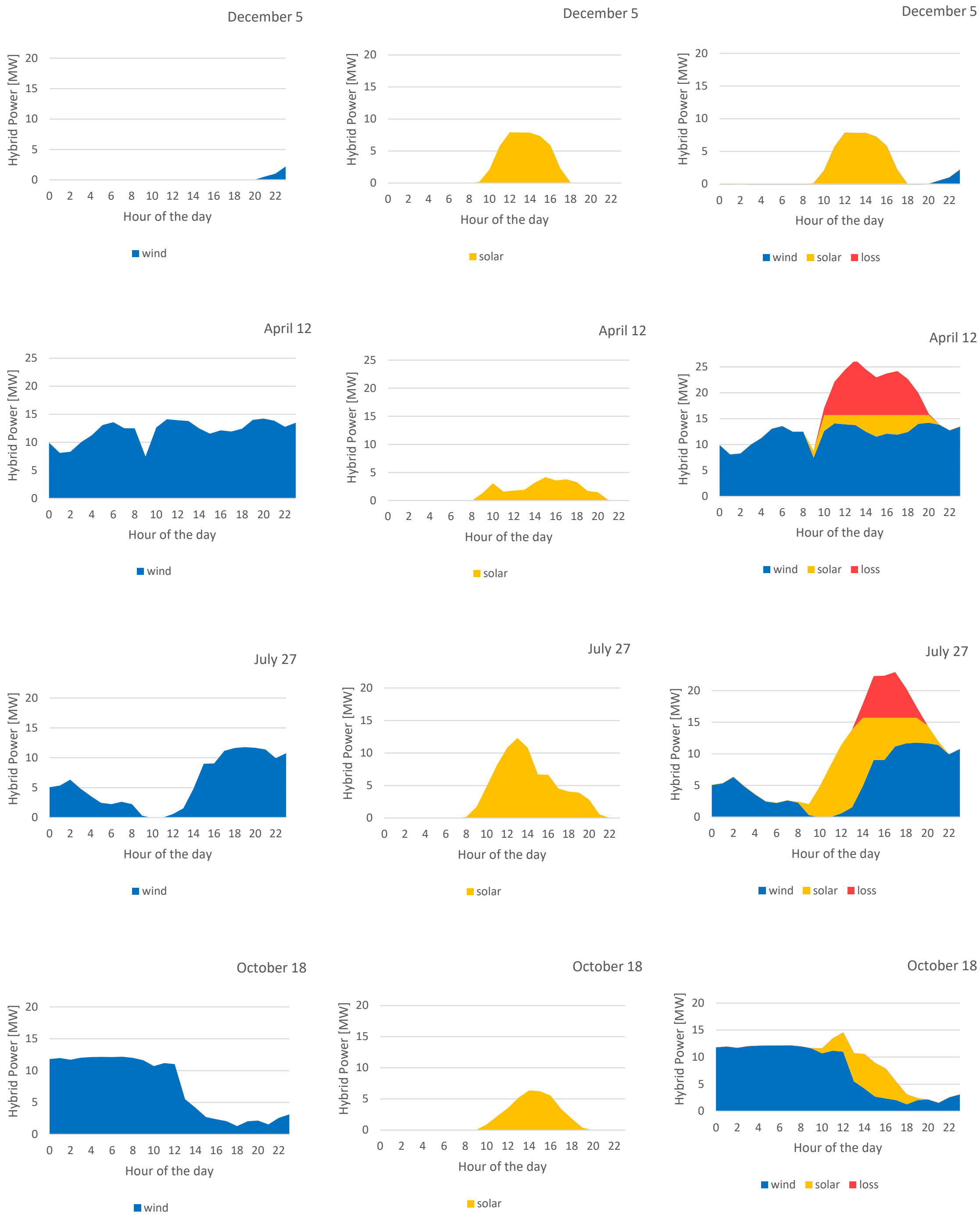

Fig 4.11. *Power generation diurnal profile of the hybrid project for selected days*

The average annual result, based on the different proportions of installed photovoltaics, is shown in *Figure 4.12*. On the x-axis of the figure, the percentage of photovoltaic installed is indicated, where the unit corresponds to 15 MW, and zero to the absence of a photovoltaic plant. On the y-axis, the percentage of the evacuation capacity is indicated, being the unit 15 MW, complete use of the access capacity, and zero the non-discharge into the network.

The wind farm has a line capacity factor close to 25%, and the capacity factor of the hybrid plant will increase as the size of the photovoltaic installation expands, in the same way that losses due to excess generation of the hybrid project increase.

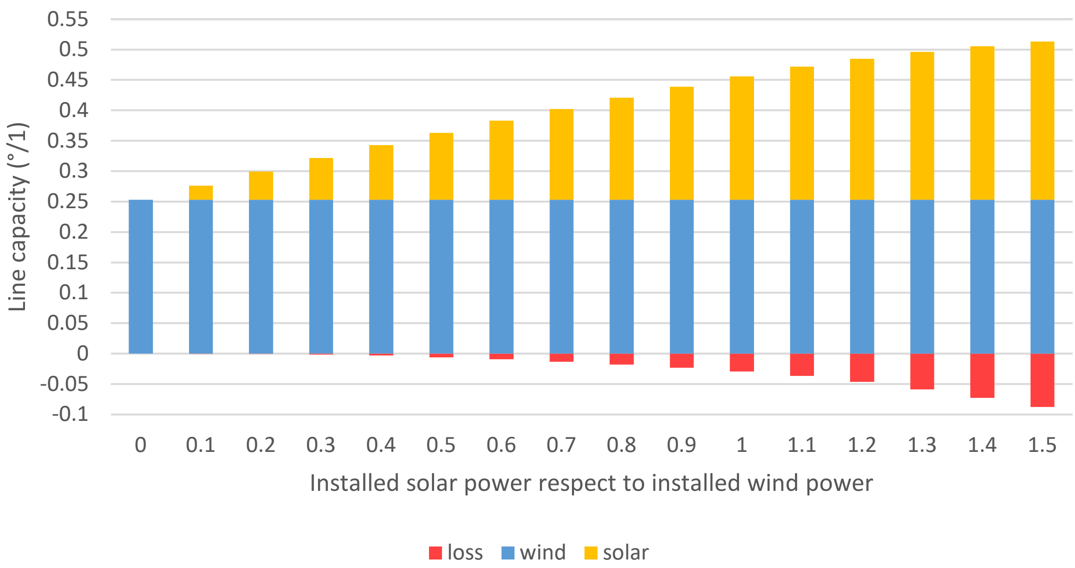

Fig 4.12. *Line capacity factor of the hybrid power plant proportional to the percentage of photovoltaic installed power; Brownfield project*

Figure 4.13 shows the evolution of the percentage of photovoltaic energy generated that can be delivered, as well as the solar energy generated that cannot be injected into the grid and is converted into losses, all based on the installed solar power. The project is feasible when the percentage of lost solar energy is compensated or exceeded by the cost reduction of the new photovoltaic plant project as it is a hybrid project.

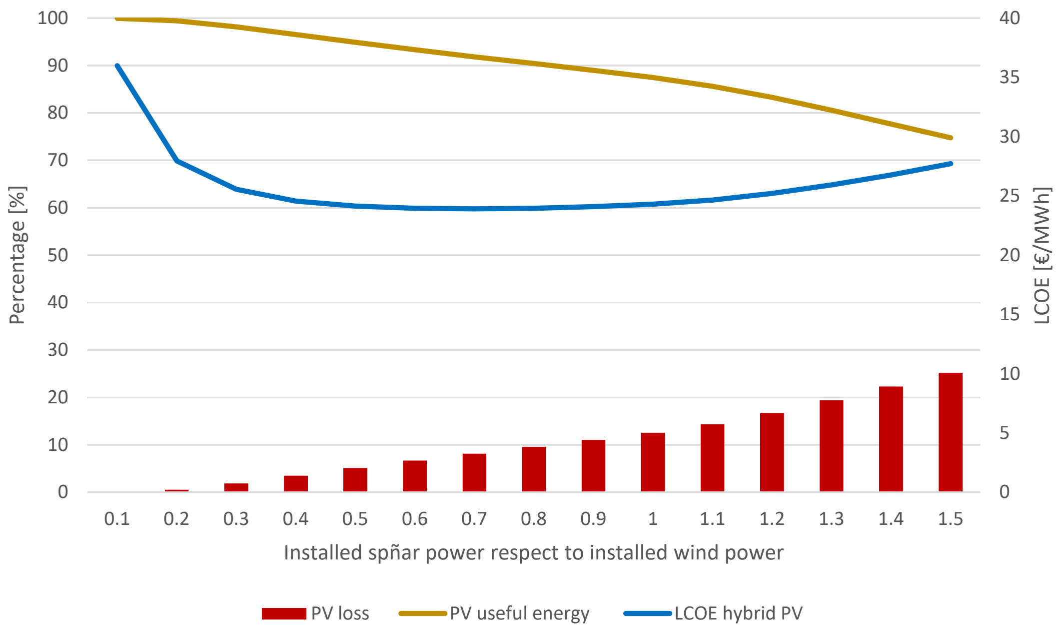

Fig 4.13. *Percentage of the useful energy production and losses on the photovoltaic project; Brownfield project*

The previous figure also displays the Levelized Cost of Electricity (LCOE), the cost of energy throughout the life of the project, a result of the economic analysis. This concept, its calculation and the results will be later explained in detail.

Figure 4.14 shows in detail the result of integrating a solar power equivalent to the installed wind power, where it can be seen how the wind power of the 25 N43/600 machines have a capacity factor close to 25%, photovoltaics would contribute on 20%, rising the overall hybrid project capacity factor close to 45%, and having lost around 3% of production on the project as a whole due to the limiting power of the evacuation line.

In the assumption of having a photovoltaic power plant of the same power as the existing wind farm, there would be an 87.5% use of the new added technology, which is equivalent to 24.6 GWh/year and losses on the solar project of 12.5%, as it is displayed in *Figure 4.15.*

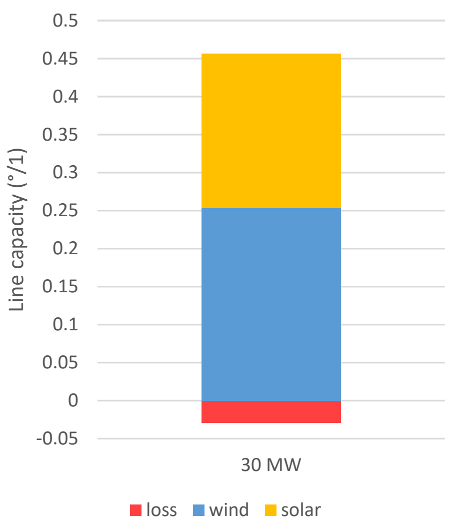

Fig 4.14. Line capacity factor of a 30 MW hybrid power plant; Brownfield project

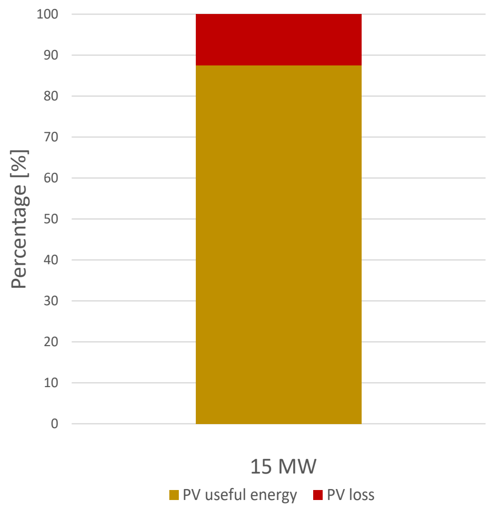

Fig 4.15. Percentage of the useful energy production and losses on a 15MW photovoltaic plant; Brownfield project

4.3.2.6 Economic study

One of the key aspects of the hybridization of an existing plant is the determination of the optimal power of the new technology to be installed, in this case photovoltaics, with respect to the existing one, in this occasion wind power. In some projects there may be restrictions such as the availability of land, investment capacity or previous energy sales agreements that limit the decision-making capacity, but in cases that do not exist, the power that minimizes the cost of energy is considered optimal.

The economic analysis of this project is not intended to be an analysis of the economic performance and financial expenses, but an approximation of the current total cost of the energy value (LCOE) based on the hybridization factor of the photovoltaic power plant.

The LCOE is a common economic assessment that allows the cost comparison between different power generation systems, considering the estimated production throughout the useful life of a project as well as all the expenses for that period, including the initial investment for the plant set-up, operation and maintenance, cost of capital, end-of-life management… [41][42][43][44]

According to its definition, the LCOE would be the current average price at which the generated energy should be sold to cover all expenses associated with the project during its useful life, which would be equivalent to obtaining a zero Net Present Value (NPV). Its expression is shown in *Formula 4.5*:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (4.5)$$

Where:

I_t = Investment expenditures in year t

M_t = Operational and maintenance expenditures in year t

F_t = Fuel expenditures in year t (zero for photovoltaic power generation)

E_t = Energy generation in year t

r = Discount Rate

n = Financial lifetime of the calculation

The increase in the photovoltaic installed power and the energy generated will reduce the cost of energy due to the decrease of the fixed costs impact of purchase, construction and operation. However, the reduction of the utilization factor as the hybridization factor and the losses increase, results in an increase in the cost of energy and counteracts to some extent the profits of installing more photovoltaic power.

The optimal sizing factor of the photovoltaic hybrid power plant considering that it corresponds with the hybridization factor with the lowest possible LCOE will be mainly affected by:

- The size of the plant.
- The capacity factor of the existing wind farm, which directly affects the reduction of solar use.
- Wind and solar resource conditions specific to the location and modeling of the plant.
- The relationship between fixed and variable costs (per MWp) in Capital Expenditure (CAPEX) and Operating Expense (OPEX).
- To a lesser extent due to the useful life of the photovoltaic power plant, the average annual degradation of the plant and its residual value.

In order to estimate the LCOE comparison of the hybrid solar project with a commercial solar plant, the following points have been taken into account:

- The nominal power of the photovoltaic power plant is expressed in terms of that of the wind installed power.
- An operating period of 20 years, on which operating costs will be calculated.
- An estimated annual average degradation for the whole plant of 0.8%, which would correspond to the degradation of the modules and a reduction in the availability of other related equipment.
- A discount rate of 7%.
- The initial solar yield and the estimated global yield, that have been calculated according to the solar resource study and plant modeling.
- A breakdown of CAPEX costs (fixed and variable) according to different concepts, to help analyze the main cost differences between a commercial solar plant with an individual connection to the grid and a hybrid photovoltaic power plant connected to the wind farm common access point.
- Estimated OPEX costs (fixed and variable).
- An estimated residual value of the plant at the end of the exploitation period.

The following tables show the estimation and arrangement of the values described above:

Table 4.5. Plant parameters considered from the energy study; Brownfield project

Plant parameters	
Nominal Power [MWn]	15.0
Operating period [years]	20.0
Initial solar production [kWh/kWp]	1637.61
Mean annual degradation [%]	0.8
Estimated global production [MWh/kWp]	27511.85

Table 4.6. Photovoltaic power plant cost breakdown difference between commercial and hybrid PV

Plant costs	**Commercial PV**		**Hybrid PV**	
	Fixed	1/MWp	Fixed	1/MWp
CAPEX - Civil work		20000		20000
CAPEX - Metallic structure		40000		40000
CAPEX - PV Modules		300000		300000
CAPEX - Electric infrastructure (until inverter and TC)		40000		40000
CAPEX - Electric infrastructure (power line evacuation and ES)		60000		20000
CAPEX - Communication systems, monitoring, security…		20000		10000
CAPEX - EPC, supervision, quality and control, HSE…	300000	10000	150000	10000
CAPEX - Development, permits, guarantees…	600000	10000	300000	10000
CAPEX [€]	900000	500000	450000	450000
OPEX [€/year]	10000	8000	10000	7000
Residual Value [€]	-25000	50000	-25000	50000

As a result of the defined parameters, the following LCOE estimations will be obtained in relation to the hybridization factor in discrete fractions of 10%, which allows estimating the optimal sizing factor and analyzing which variables and to what extent they influence:

- Estimated energy cost for a commercial PV plant.
- Estimated energy cost for a hybrid PV plant with adjusted energy losses due to curtailment.

The results according to the previous cost breakdown are presented in *Table 4.7*, where it can be seen that with these parameters the hybrid plant optimal proportion that achieves the minimum energy sales price would be around 70% of the current wind installed power, which means around 10.5 MW of solar power. As mentioned before, the results depend on many parameters, and their variation could change the optimal power to install.

Table 4.7. Commercial and Hybrid PV LCOE for different installed power; Brownfield project

	Ratio PV/WIND	0.1	0.2	0.3	0.4	0.5	0.6	**0.7**	0.8	0.9	1
	Installed PV power [MW]	1.5	3	4.5	6	7.5	9	**10.5**	12	13.5	15
	Hybridization utilization	1.00	0.99	0.98	0.97	0.95	0.93	**0.92**	0.90	0.89	0.87
Commercial PV	LCOE - CAPEX [€]	1,650,000	2,400,000	3,150,000	3,900,000	4,650,000	5,400,000	6,150,000	6,900,000	7,650,000	8,400,000
	LCOE - OPEX [€]	440,000	680,000	920,000	1,160,000	1,400,000	1,640,000	1,880,000	2,120,000	2,360,000	2,600,000
	LCOE - Residual value [€]	50,000	125,000	200,000	275,000	350,000	425,000	500,000	575,000	650,000	725,000
	LCOE - Estimated production [MWh]	41,268	82,536	123,803	165,071	206,339	247,607	288,874	330,142	371,410	412,678
	LCOE commercial PV [€/MWh]	49.43	35.80	31.26	28.99	27.62	26.72	**26.07**	25.58	25.20	24.90
Hybrid PV	LCOE - CAPEX [€]	1,125,000	1,800,000	2,475,000	3,150,000	3,825,000	4,500,000	5,175,000	5,850,000	6,525,000	7,200,000
	LCOE - OPEX [€]	410,000	620,000	830,000	1,040,000	1,250,000	1,460,000	1,670,000	1,880,000	2,090,000	2,300,000
	LCOE - Residual value [€]	50,000	125,000	200,000	275,000	350,000	425,000	500,000	575,000	650,000	725,000
	LCOE - Estimated production [MWh]	41,258	82,078	121,500	159,326	195,770	231,079	265,313	298,496	330,475	360,884
	LCOE hybrid PV [€/MWh]	35.99	27.96	25.56	24.57	24.14	23.95	**23.92**	23.97	24.10	24.32

As it has been seen in the above defined cost breakdown, due to the existence of fixed and variable CAPEX and OPEX, the percentage of reduction of the same in the hybrid plant compared to the commercial plant will vary depending on the installed solar power, as shown in *Figure 4.16*.

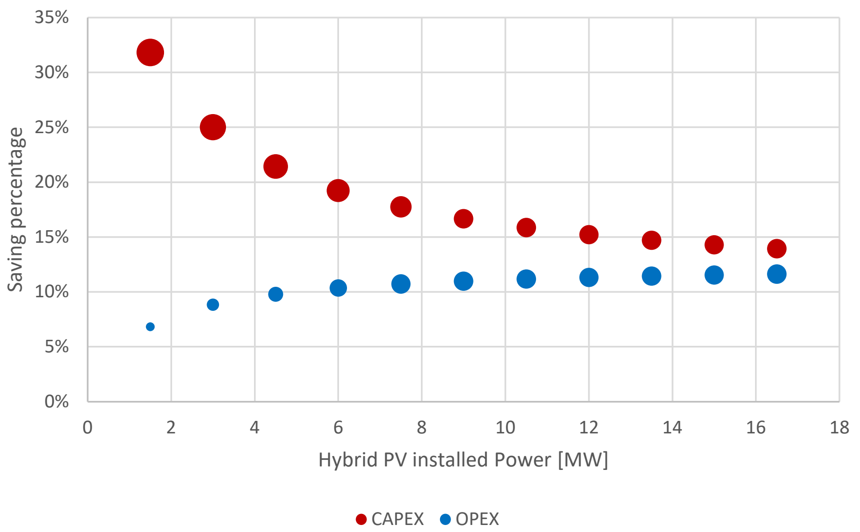

Fig 4.16. CAPEX and OPEX reduction percentage of the Hybrid PV project; Brownfield project

Another option to consider in order to calculate the solar power to install could be taking as a reference the savings of setting up a plant in hybridization mode compared to building a commercial PV plant from zero. In this way and as shown in *Figure 4.17*, a power equivalent to that of the installed wind power equivalent to 15 MW could be installed in a hybrid PV power plant with the same budget as for a commercial PV plant, being the difference between both LCOE null. However, as it has been commented previously, it would not be the most optimal nor profitable option since more energy would be lost due to the evacuation power line restrictions.

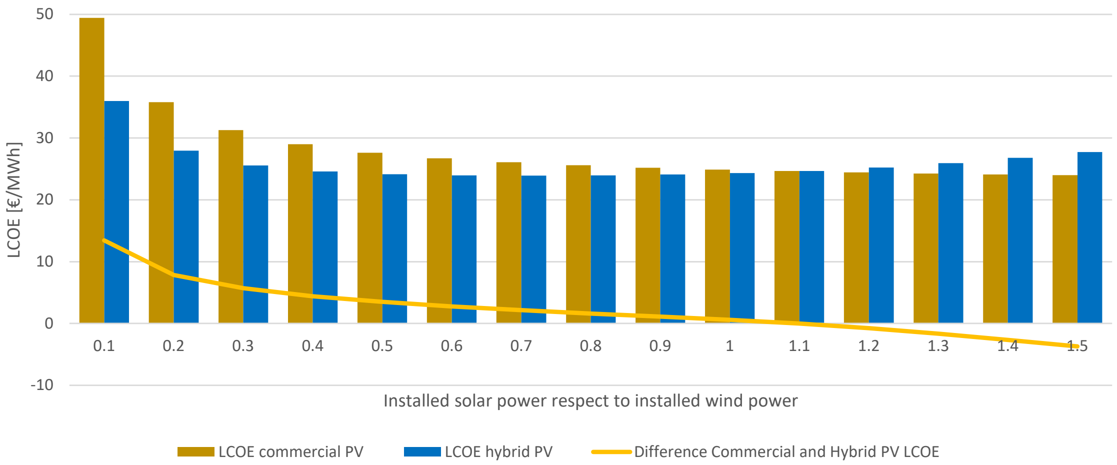

Fig 4.17. Difference between Commercial and Hybrid PV LCOE; Brownfield project

As previously described, the value of the LCOE marks the minimum price at which the energy should be marketed to amortize the plant investments, so once the optimal plant size according to the curtailment analysis and the hybridization utilization that would reach the minimum of this value has been obtained, the economic viability of the study will depend on the range in which it is found.

The utility-scale photovoltaic energy LCOE has plummeted last years, and nowadays it is still cheaper than spot prices in Spain and many other countries. This is reported by a 2019 study carried out by the LUT University in Finland [49], in which it is estimated that in 2019 the LCOE in Europe with a nominal weighted average cost of capital (WACC) of 7% would range between 24 €/MWh in Malaga and 42 €/MWh in Helsinki, an outstanding fact since the average day-ahead market price in Finland was 47 €/MWh and in Spain 57 €/MWh in 2018. In addition, it is worth highlighting the predictions for 2030, where the value of the LCOE is estimated to fluctuate between 14 €/MWh in Malaga and 24 €/MWh in Helsinki.

Therefore, although the values entered in the formula are estimates and the future spot price carries a great level of uncertainty, it would be considered that for the optimal power chosen with which an LCOE of approximately 24 €/MWh is obtained for hybrid PV compared to 26 €/MWh for commercial PV, the project would be viable and more profitable than an individual PV plant.

4.3.2.7 Brownfield project conclusions

Table 4.8 shows in detail the hybrid power plant results after integrating a solar power equivalent to the 70% of the wind installed power. The capacity factor of the overall hybrid project capacity will be close to 40% as it is displayed in *Figure 4.18*, with losses due to power restrictions of slightly more than 1% of the whole production capacity.

In terms of the PV project there would be a 92.3% use of the new added technology with equivalent losses of 12.5%, as it can be seen in *Figure 4.19*. In addition, the saving percentages of the hybrid PV power plant respect to a commercial PV facility is also showed in *Table 4.8*.

Table 4.8. Hybrid Power Plant Results and savings in the LCOE cost breakdown; Brownfield project

Hybrid Plant Results	Wind	Solar	Hybrid project
Installed Power [MW]	15.0	10.5	25.5
Capacity Factor [%]	25.3	14.9	40.2
Hybridation Utilization [%]	100.0	92.2	98.7
Loss Percentage [%]	0.0	7.8	1.3
Estimated energy producion [GWh/year]	30.68	18.06	48.74

Hybrid PV savings	
CAPEX	15.9%
OPEX	11.2%
LCOE	8.3%

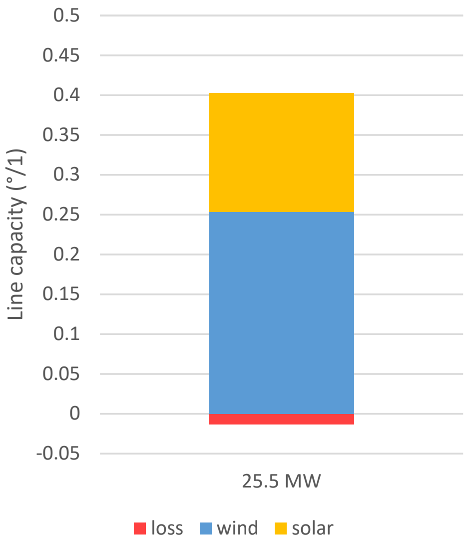

Fig 4.18. Line capacity factor of the optimal hybrid power plant; Brownfield project

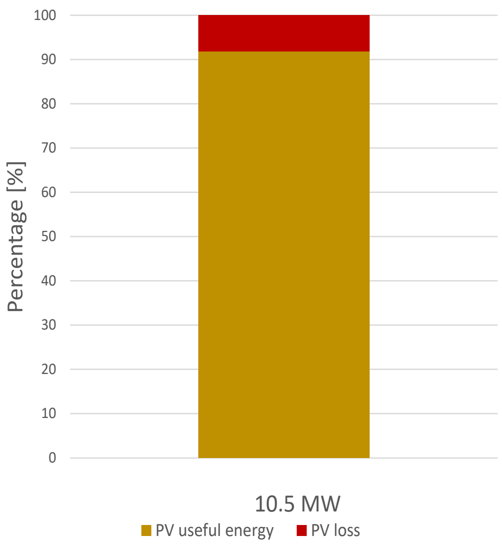

Fig 4.19. Percentage of the useful energy production and losses on the optimal photovoltaic project; Brownfield project

Finally, with the aim of showing the synergy of the technologies once the optimal solar power of the studied hybrid project has been selected, the mean power generation diurnal profiles of the HPP technologies has been represented in *Figure 4.20*.

In addition, to see in practice the contribution of the photovoltaic power generation for different weather conditions and the losses that could arise when both technologies are at high levels of production, four selected days of power generation diurnal profiles for the 25.5MW hybrid project have been displayed in Figure *4.21*.

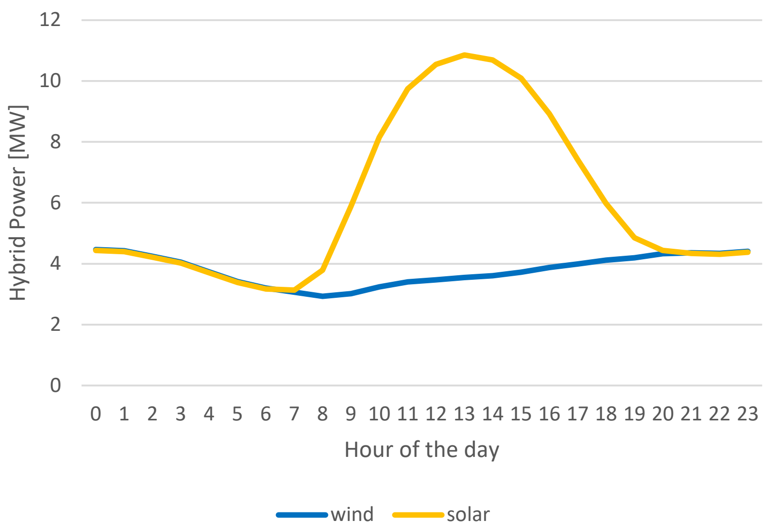

Fig 4.20. Mean power generation diurnal profile of the hybrid project; Brownfield project

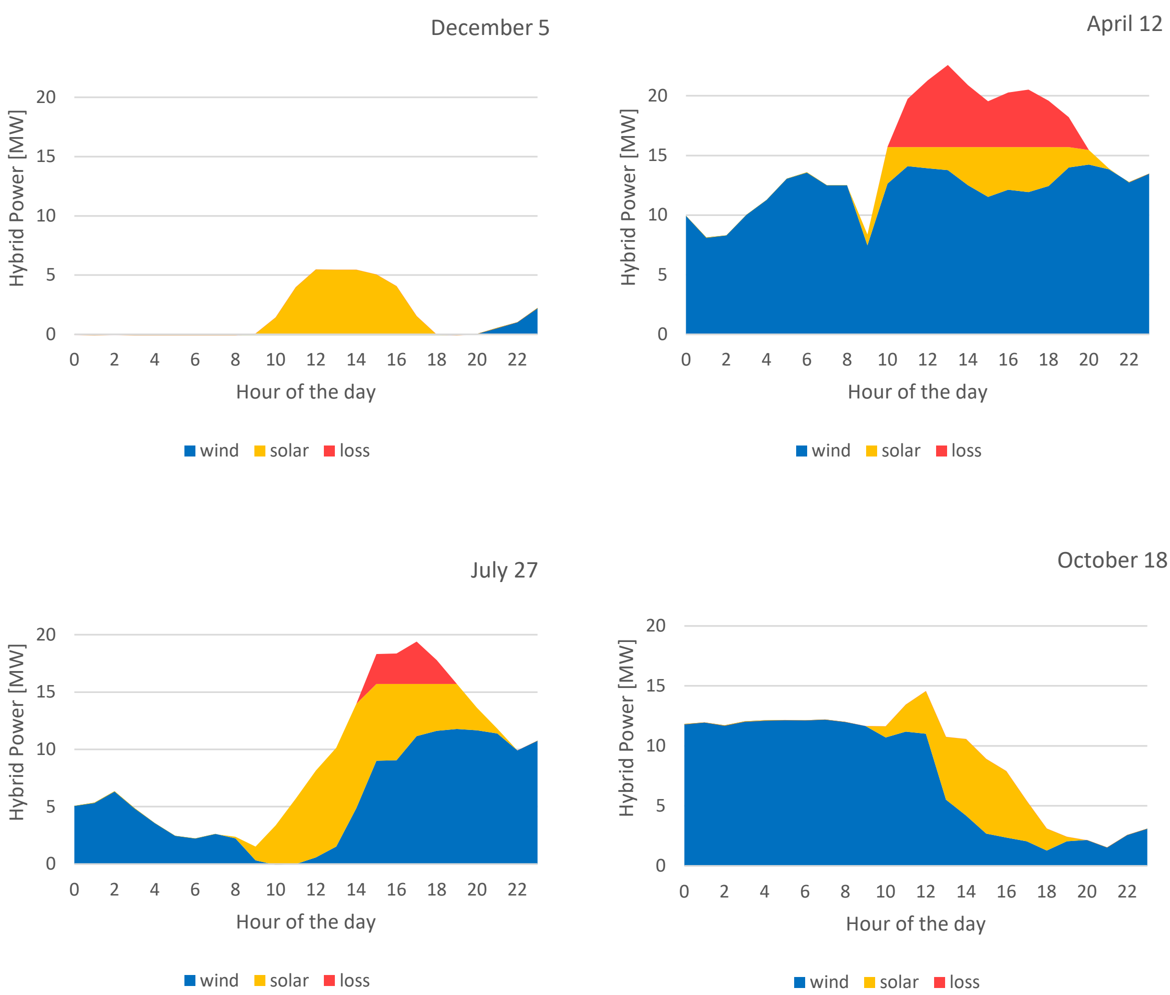

Fig 4.21. Power generation diurnal profile of the hybrid project for selected days

4.3.3 Greenfield project

The second case study consists of a greenfield project, which means that a certain solar power will be combined with a newly wind farm construction to optimize the evacuation power line of the HPP achieving a higher load factor, again compensating the curtailment losses with the economic savings resulting from the common use of some infrastructures and services.

The project development will follow the same procedure than in the brownfield project, however the databases used as well as the wind farm characteristics will be different. Unlike the other project, this time the hybrid set will admit a lower solar power, since being the newly designed wind farm, it will have a higher load factor due to the advanced technology of the wind turbines.

In this line, the analysis will include the generation profiles of the two technologies, an energy analysis of the hybrid plant for different percentages of solar power to be installed versus the wind power considered, and the LCOE estimation to determine the optimal solar power to install achieving a viable project.

4.3.3.1 Project features

The projected wind farm is made up of 10 SG-132 wind turbines of 3.55 MW of unit power, making a total of 35.5 MW.

The photovoltaic power calculated is equivalent to the same installed wind power, and an evacuation power of the totality of 35.5 MW is considered. Discrete fractions of 10% have also been calculated, as well as an additional extrapolation so that the installed solar power achieves the 60 percent of the total installed power of the hybridized plant, to compare the values of the maximum solar power allowed by the decree, that in this scenario would be 53.25 MW.

The hybrid project in this case can have a total maximum installed power of 88.75 MW with a maximum evacuation capacity of 35.5 MW. All figures are summarized in *Table 4.9*.

Table 4.9. Greenfield project features

Greenfield project features	[MW]
Total wind installed power	35.5
Access line capacity	35.5
Max. solar power allowed	53.25
Total Max. hybrid project power	88.75

The study has been performed with 4 years of data from a long-term representative period in wind, measured in a meteorological station located in the studied site. For solar power, a reference year of solar radiation and power simulation of the site has been obtained from reanalysis sources.

All the calculation has been made in the same line that on the previous scenario, analyzing both wind and solar power resources, and evaluating their hybridization potential.

4.3.3.2 Available information

The information to accomplish this study is the following:

- Ten-minute wind speed records from a meteorological station from 2009 to 2012. The data from this station has been previously used for a resource study and therefore it has not been necessary to analyze it again. The selected period coincides with a period considered representative of the wind resource.
- The information on solar radiation has been obtained from the Meteonorm 7.2 reanalysis databases, extracting a typical year of hourly mean data from the 1999-2010 period, with a Sat = 96% cloudiness.

4.3.3.3 Wind farm generated energy

Like in the previous scenario, the wind data for the studied case is based on four years, corresponding to a reference period of the site previously determined according to the resource study for a long-term characterization of the site.

The frequency analysis of the speeds of the studied period is displayed in *Figure 4.22*, where it can be observed that the highest frequency (number of hours) of speed happens between 2 m/s and 8 m/s, which again means that much of the time the park will be operating below its nominal power and will leave free evacuation capacity.

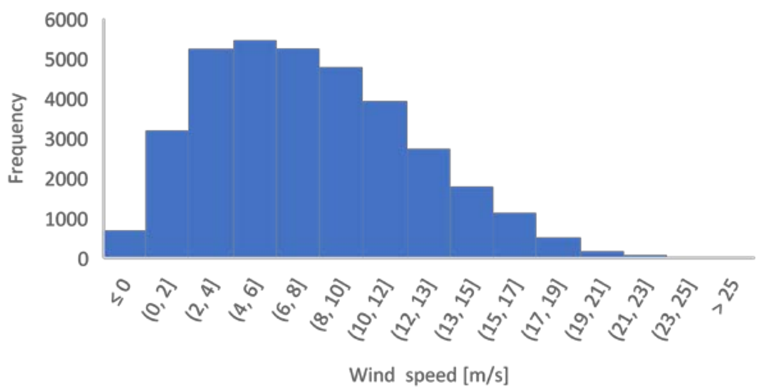

Fig 4.22. Frequency analysis of the wind speed that characterizes the site (number of hours); Greenfield project

The wind project has ten wind turbines with a machine model Siemens Gamesa SG-132 and a unit power of 3.55 MW, which makes a total of 35.5 MW that will be installed in a coming future. In *Figure 4.23*, the frequency distribution of the power injected into the network is presented for the wind technology. In the graph can be observed that there are two peaks, one corresponding to the wind farm in standby, when the speeds are less than 3 m/s (cut-in speed), and another at full power when the speeds are greater than 11 m/s (nominal speed).

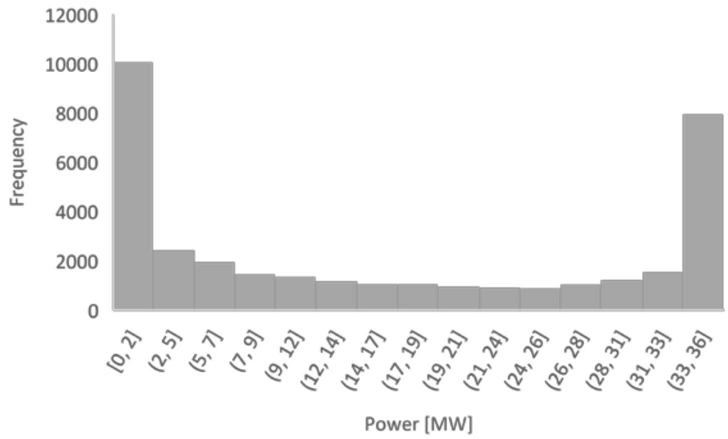

Fig 4.23. Frequency analysis of the power injected to the grid (number of hours); Greenfield project

As it was explained before, the viability of the hybridized project will strongly depend on the coincidence the hourly frequency at full capacity with the hours of solar generation. As seen in *Figure 4.24*, the SG-132 estimated hourly distribution is usually lowest in the middle of the day, meaning that there can be a good integration between wind and solar energy in this particular location.

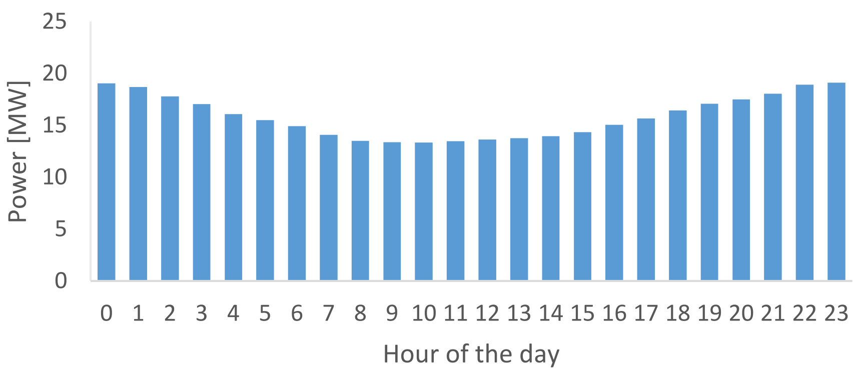

Fig 4.24. Hourly analysis of the wind power distribution (SG_132); Greenfield project

The energy estimation of the wind farm has been done in a discrete way associating to each one of the ten-minute speeds the corresponding power according to the specific power curve for the density and type of wind turbine.

This calculation has the advantage that it allows estimating for every ten-minute step the power that is free in the evacuation, but it has the disadvantage that it is not possible to take into account the wakes between the machines, the differences in incident wind on the rotor in each one of the positions and losses due to unavailability or external factors as considered in a resource study.

To emulate the real operating conditions estimated in the resource studies, approximately 10% losses have been considered. The estimated energy generation with this condition is 115.2 GWh/year for the 10 SG-132.

4.3.3.4 Solar plant generated energy

The energy generated in a photovoltaic plant is directly proportional to the radiation received. In this case, the work is performed with reanalysis data where it is possible to obtain an average year of solar radiation representative of a site.

The yearly average power frequency and hourly distribution of a PV plant with a nominal power of 35.5 MW, equivalent in size to the wind farm power considered, are shown in *Figures 4.25* and *Figure 4.26* respectively:

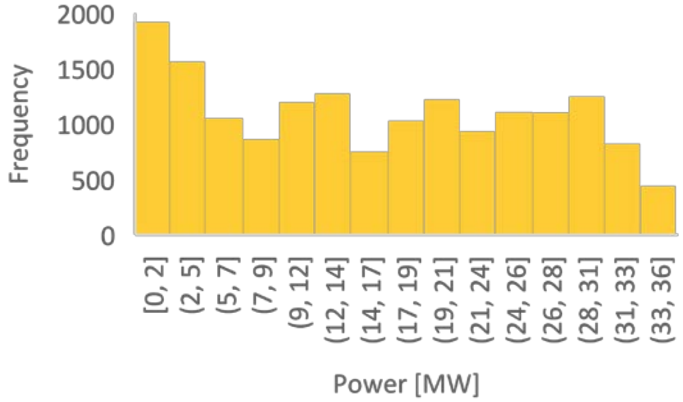

Fig 4.25. Frequency analysis of the power injected to the grid (number of hours); Greenfield project

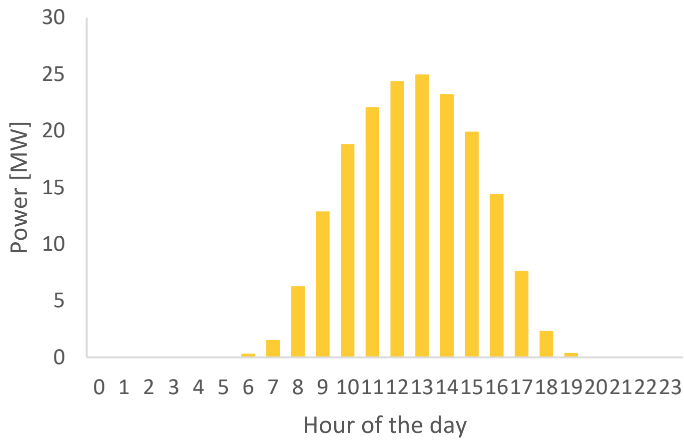

Fig 4.26. Hourly analysis of the solar power distribution; Greenfield project

As it was seen in the previous scenario, solar energy is more constant and predictable than wind energy in its hours of operation, and both resources can be complementary.

To estimate the energy from the solar plant, the PVSyst tool has been used, in which, based on the series of reanalysis data of radiation, and considering the position of the site and the temperature, an hourly power has been obtained over a typical year. Further information in Annex B.

For the power simulation, 97440 silicon CHSM72M-HC monocrystalline modules with a unit power of 410W, and 203 three-phase 50 Hz ABB PVI-175 TL inverters were considered. The connections made were 24 modules in series, 4060 in parallel and 20 strings per inverter.

The expected energy from the photovoltaic plant, having discounted all photovoltaic losses (thermal, wiring, soiling, unavailability…) and without considering losses due to hybrid power capacity limits will be 60.3 GWh/year for the first year of production. From the second year, due to the inherent degradation of photovoltaic cells, a decrease of up to 0.7% per year is expected.

4.3.3.5 Energy analysis hybrid plant

Following the same line of calculations than in the previous scenario, the results will be shown in the following graphs. Again, considering that the maximum limit of power injected into the network can be exceeded by 5%, line access capacity of 37 MW has been taken into account for calculations, being the additional 1.5 MW equivalent to around 4.5% of the evacuation line.

The average annual result, based on the different proportions of installed photovoltaics, is shown in *Figure 4.27*. As represented before, the percentage of photovoltaic installed is indicated on the x-axis, where the unit corresponds to 35.5MW and the absence of a photovoltaic plant is equivalent to zero. The percentage of the evacuation capacity is indicated on the y-axis, being the unit 35.5 MW, complete use of the evacuation line, and zero the non-discharge into the utility grid.

The wind farm has a line capacity factor close to 40%, and in the same way than on the previous case, the capacity factor of the hybrid plant and project losses due to excess generation will increase as the size of the photovoltaic installation rises.

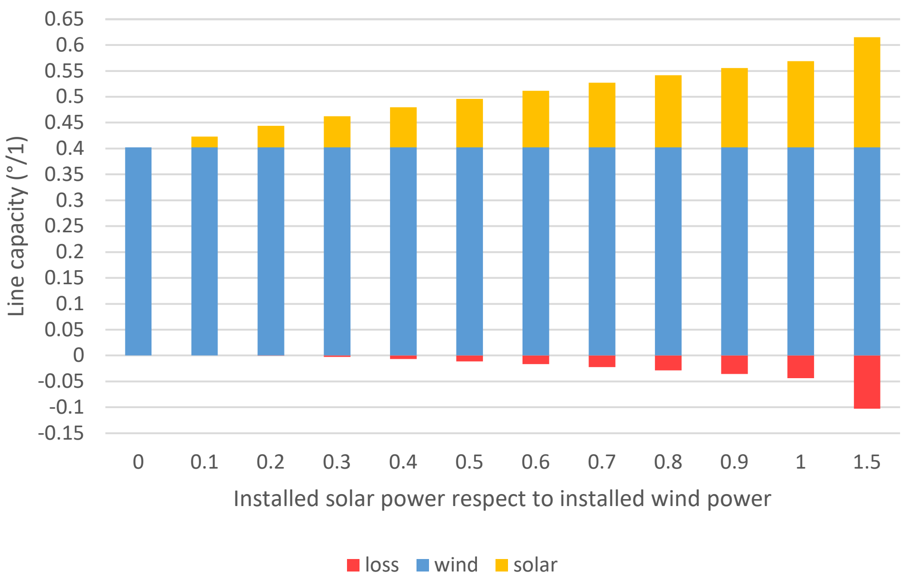

Fig 4.27. Hybridization results. Line capacity for the wind installed power and the fractional addition of photovoltaics; Greenfield project

Figure 4.28 shows the evolution of the percentage of solar energy generated that can be sold and the solar energy generated that cannot be sold and is converted into losses, all based on the installed solar power, and again it also displays the LCOE of the hybrid photovoltaic project.

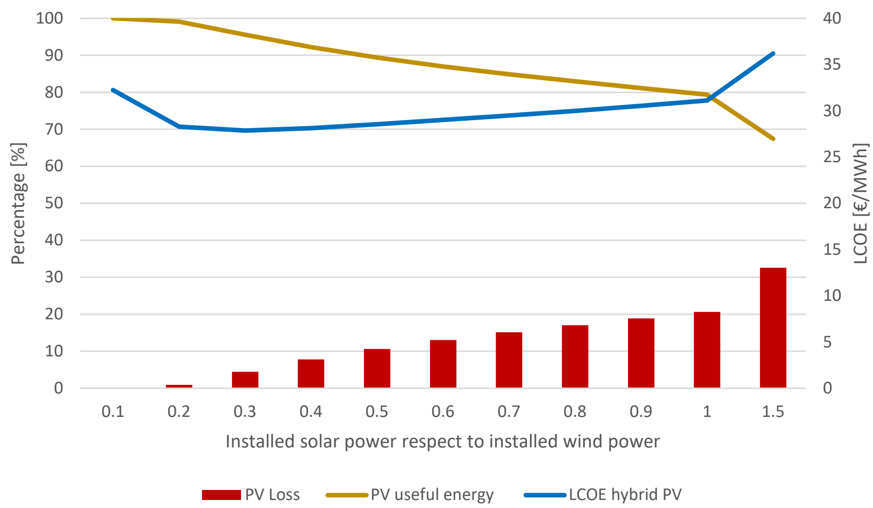

Fig 4.28. Percentage of the energy production and losses on the photovoltaic project; Greenfield project

The result of integrating a solar power equivalent to the installed wind power is shown in *Figure 4.29*. In the graph it can be seen how the wind power of the 10 SG -132 machines has a capacity factor close to 40%, photovoltaics would contribute on 17%, which means that in this case the total project would have a line capacity close to 60%, having lost around 5% of total production due to the limiting power of the evacuation line.

In the assumption of having the wind project working at 90% to take into account the losses of wakes and unavailability, and a photovoltaic plant of the same power as the wind farm, there would be a 79.3% use of the new photovoltaic plant, which is equivalent to 47.87 GWh / year and losses of 20.7%, as displayed in *Figure 4.23*.

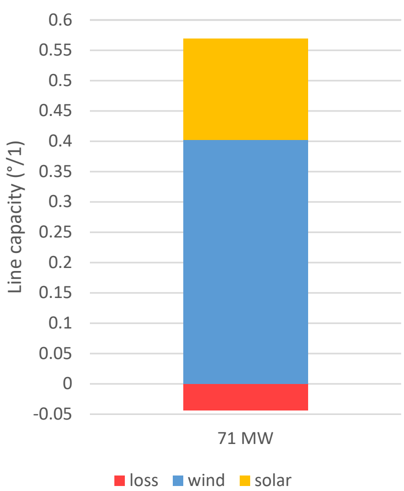

Fig 4.29. Line capacity factor of a 71 MW hybrid power plant; Greenfield project

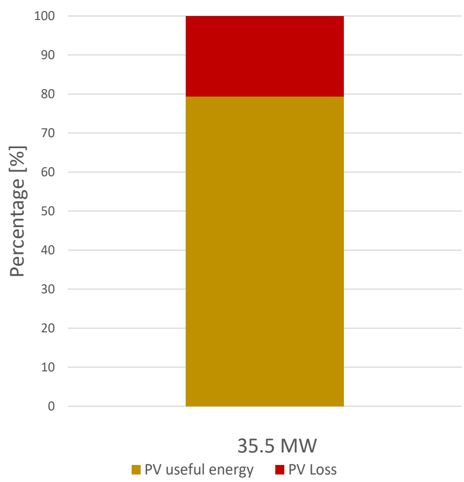

Fig 4.30. Percentage of the useful energy production and losses on a 35.5MW photovoltaic plant; Greenfield project

4.3.3.6 Economic study

The optimal photovoltaic size ratio depending on the characteristics of the wind project built, is the value that minimizes the LCOE of the hybridized project. For this reason, an estimation of this cost has been made in order to find the photovoltaic power that would minimize the cost of the energy produced.

In order to estimate the LCOE of the greenfield project, even though the cost savings will vary respect to a brownfield project due to design variables, as the values are estimates and for simplicity the same considerations and cost breakdown that were taken into account for the brownfield project are kept, summarizing in *Table 4.10* the specific plant parameter for this case study. It should be noted that the most weight added to the equation will be the energy estimation carried out, in which in this case and unlike the brownfield project, as the estimated global production is lower, a higher LCOE will be obtained. On the other hand, it will be the hybridization use obtained from the curtailment analysis that most will affect the plant size determination.

Table 4.10. Plant parameters considered from the energy study; Greenfield project

Plant parameters	
Nominal Power [MWn]	35.5
Operating period [years]	20.0
Initial solar production [kWh/kWp]	1348.56
Mean annual degradation [%]	0.8
Estimated global production [MWh/kWp]	22655.88

The result according to the previous proposals is presented in *Table 4.11*, where assuming that the wind farm is fully operational it can be seen that the benefit of the project would be maximized in the order 30%, the proportion that will minimize the LCOE and that is equivalent to 10.65 MW of installed solar power. As above mentioned, the results will depend on many parameters, and their variation could change the optimal power to install.

Table 4.11. Commercial and Hybrid PV LCOE for different installed power; Greenfield project

	Ratio PV/WIND	0.1	0.2	**0.3**	0.4	0.5	0.6	0.7	0.8	0.9	1
	Installed PV power [MW]	3.55	7.1	**10.65**	14.2	17.75	21.3	24.85	28.4	31.95	35.5
	Hybridization utilization	1.00	0.99	0.96	0.92	0.89	0.87	**0.85**	0.83	0.81	0.79
Commercial PV	LCOE - CAPEX [€]	2,675,000	4,450,000	6,225,000	8,000,000	9,775,000	11,550,000	13,325,000	15,100,000	16,875,000	18,650,000
	LCOE - OPEX [€]	768,000	1,336,000	1,904,000	2,472,000	3,040,000	3,608,000	4,176,000	4,744,000	5,312,000	5,880,000
	LCOE - Residual value [€]	152,500	330,000	507,500	685,000	862,500	1,040,000	1,217,500	1,395,000	1,572,500	1,750,000
	LCOE - Estimated production [MWh]	80,428	160,857	241,285	321,713	402,142	482,570	562,999	643,427	723,855	804,284
	LCOE commercial PV [€/MWh]	40.91	33.92	31.59	30.42	29.72	29.26	**28.92**	28.67	28.48	28.32
Hybrid PV	LCOE - CAPEX [€]	2,047,500	3,645,000	5,242,500	6,840,000	8,437,500	10,035,000	11,632,500	13,230,000	14,827,500	16,425,000
	LCOE - OPEX [€]	697,000	1,194,000	1,691,000	2,188,000	2,685,000	3,182,000	3,679,000	4,176,000	4,673,000	5,170,000
	LCOE - Residual value [€]	152,500	330,000	507,500	685,000	862,500	1,040,000	1,217,500	1,395,000	1,572,500	1,750,000
	LCOE - Estimated production [MWh]	80,428	159,376	230,573	296,595	359,340	419,654	477,810	533,774	587,315	638,057
	LCOE hybrid PV [€/MWh]	32.23	28.29	27.87	28.13	28.55	29.02	**29.50**	30.00	30.53	31.10

The CAPEX and OPEX reduction percentage in the hybrid photovoltaic power plant compared to the commercial plant will vary depending on the installed solar power, as shown in *Figure 4.31*.

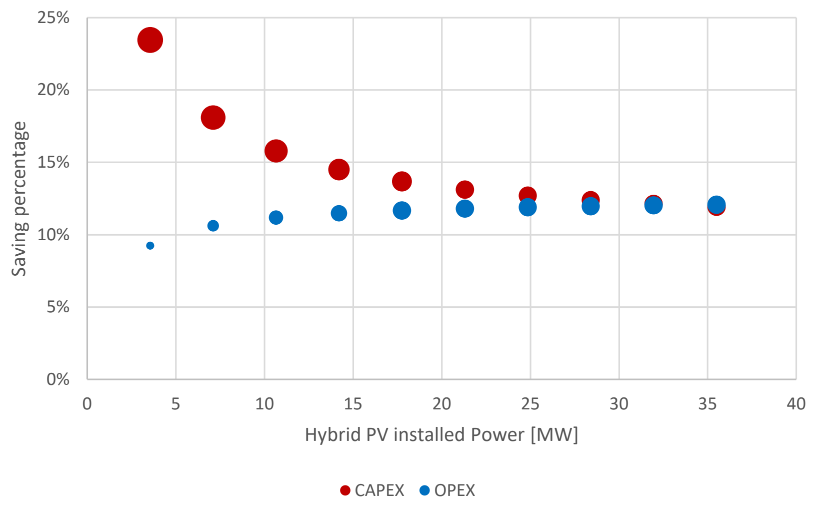

Fig 4.31. CAPEX and OPEX reduction percentage of the Hybrid PV project; Greenfield project

Taking as a reference the savings of setting up a plant in hybridization mode compared to building a commercial photovoltaic plant from zero, around 60% of photovoltaic power could be installed in a hybridization plant with the same budget as a commercial photovoltaic plant, as shown in *Figure 4.32*. However, again this would not be the most effective option since many energy would be lost because due to the power line limitations.

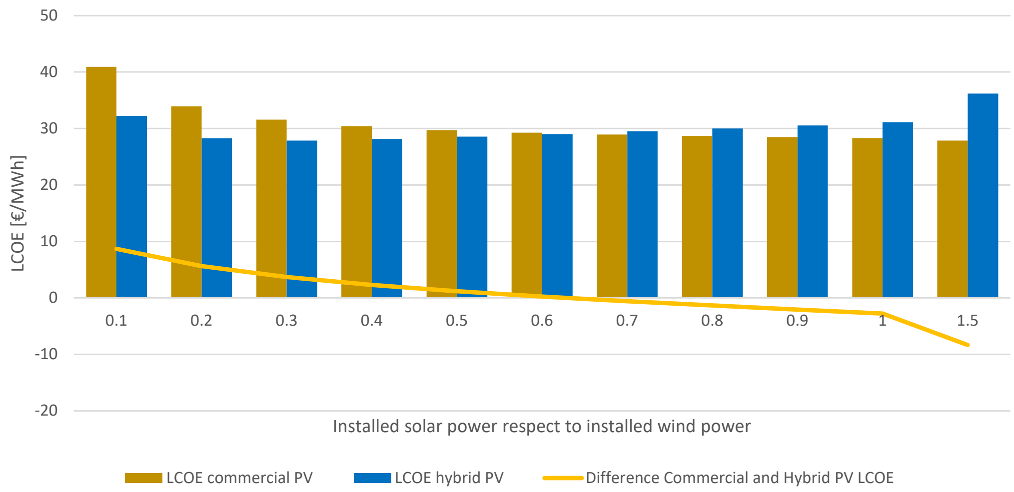

Fig 4.32. Difference between Commercial and Hybrid PV LCOE; Greenfield project

In this way, for the optimal power chosen in this case an LCOE of approximately 28 €/MWh is obtained for hybrid PV compared to 31.5 €/MWh for commercial PV, so it will be considered that the project would be viable and more profitable than an individual PV plant.

4.3.3.7 Greenfield project conclusions

Table 4.12 shows in detail the hybrid power plant results after integrating a solar power equivalent to the 30% of the wind installed power. The capacity factor of the overall hybrid project capacity will be close to 45% as it is displayed in *Figure 4.33*, with losses due to power restrictions of around 0.3% of the whole production capacity.

In terms of the PV project there would be a 95.6% use of the new added technology with equivalent losses of 4.4%, as it can be seen in *Figure 4.34*. In addition, the saving percentage of the hybrid PV power plant respect to a commercial PV facility is also showed in *Table 4.12*.

Table 4.12. Hybrid Power Plant Results and savings in the LCOE cost breakdown; Greenfield project

Hybrid Plant Results	Wind	Solar	Hybrid project
Installed Power [MW]	35.5	10.65	46.15
Capacity Factor [%]	40.2	6.0	46.2
Hybridation Utilization [%]	100.0	95.6	99.7
Loss Percentage [%]	0.0	4.4	0.3
Estimated energy producion [GWh/year]	115.25	17.30	132.55

Hybrid PV savings	
CAPEX	15.8%
OPEX	11.2%
LCOE	11.8%

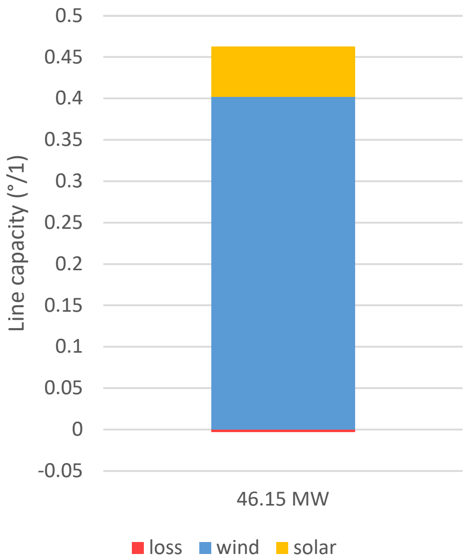

Fig 4.33. Line capacity factor of the optimal hybrid power plant; Greenfield project

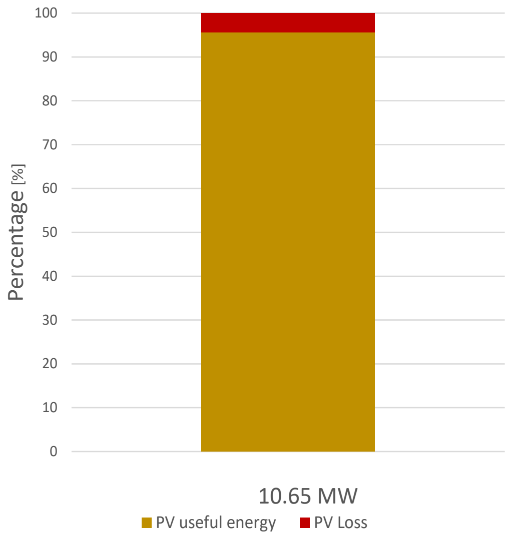

Fig 4.34. Percentage of the useful energy production and losses on the optimal photovoltaic project; Greenfield project

To conclude with the study, the overall mean power generation diurnal profile of the hybrid power plant is displayed in *Figure 4.35*.

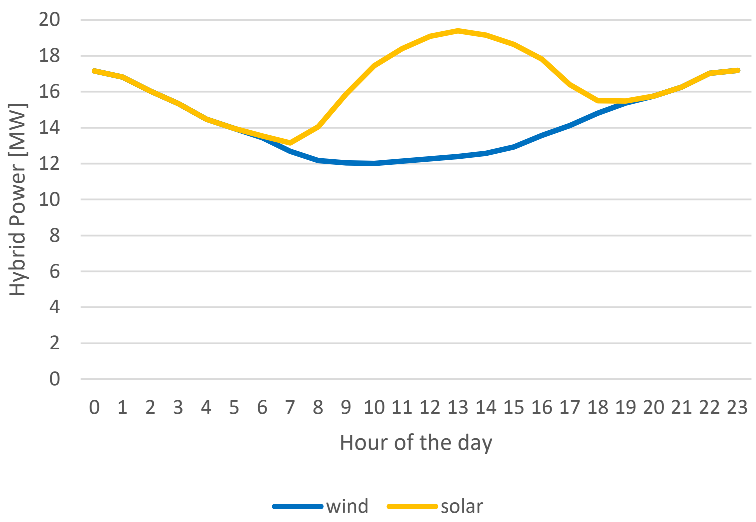

Fig 4.35. Mean power generation diurnal profile of the hybrid project; Greenfield project

4.3.4 Conclusions on the studied scenarios

Once the two studies have been carried out, the following ideas can be highlighted:

- The hourly distribution generation for wind power and photovoltaic power is complementary in both studies with almost irrelevant losses in the case of the adhesion of small percentages of solar installed capacity.
- The highest speed frequencies occur for both studies below the nominal speed values, meaning that even if the turbines are working at sun hours the wind farm will be most of the time operating below its nominal power and therefore leaving free evacuation capacity for solar power.
- The overall capacity factor of the hybrid project will rise as the size of the photovoltaic installation is increased, however the more solar power is installed the higher the project losses will be.
- The lower the capacity factor of the wind farm, the higher the optimal photovoltaic power to be installed. Thus, in general, brownfield projects will admit higher solar energy percentage than greenfield projects.
- For the specified values, the CAPEX percentage cost reduction will decrease as more photovoltaic megawatts are installed, while for the OPEX it will increase, due to the defined fixed and variable estimated values.
- It should be noted that the variation in the defined parameters that take part in the LCOE calculation could change the optimal power to install, although the hybridization utilization percentage is key and will strongly affect this parameter.

5. SUMMARY AND FUTURE LINES

5.1 Summary

In this Final Project the following activities have been carried out:

- The context in which it was to be developed has been studied, efforts have been made to introduce the receiver to all the aspects that would be useful for reading the rest of the chapters.
- A brief explanation of the relevant energy resources has been made, as well as a search and compilation of meteorological data for the resources analysis for different locations, on global and local scales, to understand their behavior and complementarity and to be able to put in context the potential of the technical study carried out later.
- A possible solution has been proposed for the existing problems related to the energy transition and the imminent deployment of renewable energies through two scenarios that study the viability of hybrid solar wind power plants. This has been easier thanks to the collaboration of CIRCE, more specifically Ana Patricia Talayero Navales who, with her knowledge and experience in diagnosing wind farms and solar plants, has guided the proposal.

The results obtained correspond to the achievement of the proposed objectives, so the evaluation of the work has been positive.

Regarding the objective related to the analysis of the resources, the evaluation of the spatial and temporal variability of the wind and solar resources as well as their degree of inverse correlation will be a key factor for the design of the HPPs. After an overview of the behavior of the same, the result of the regional analysis, of great interest due to the regulatory frame of the project, has been considered effective due to the generalized complementarity of the resources on the hourly and monthly scales.

In addition, the two scenarios in which the proposal has been developed have led to a positive result, fulfilling the objective of presenting a viable and beneficial idea for all parties involved.

In regard to the SDGs, as mentioned at the beginning of the project, an attempt has been made to work on the following goals [4]:

- Goal 7: "Ensure access to affordable, reliable, sustainable and modern energy for all". Carrying out the different hybrid projects, a clean and zero cost energy more stable in its generation would be promoted, leading to a decrease in the price of the wholesale market and thus savings in electricity bills.
- Goal 9: "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation". Work has been done to carry out a renewable innovative project that allows optimizing the network infrastructures, alleviating much of the problem of renewable generation.
- Goal 13: "Take urgent action to combat climate change and its impacts". It would be a small change in this area, as it would reduce CO_2 emissions and increasing the use of clean energy.

5.2 Socio-economic Impact

Hybrid generation projects count on numerous advantages that have already been described at the beginning of the project. For this reason, once the work is finished and as a summary, the socio-economic impact that the development of this type of projects may entail is presented in *Table 5.1*. [14]

Society	Power System
- Efficient land-use - Clean energy, lower CO2 emissions - Accelerate rural electrification - Lower electricity price	- Mitigation of RES variability - Less power and voltage peaks - Reduced network investment - Lower administration load
Developers	**Owners**
- Cost-effective grid use - Higher capacity factor - Synergies in permitting, development, O&M	- Reduced LCOE - Lower uncertainty due to higher reliability - Higher income from adjustment markets - Efficient land-use

Table 5.1. Socio-economic impact of hybrid power plants

5.3 Project Budget

This section aims to estimate the cost of this project in the case it would had been professionally developed. For this purpose, the following initial considerations will be considered:

- The project will be developed by a single person with a professional level equivalent to that of a junior engineer. Considering an average salary of 1700 euros per month and a working week of 37.5 hours, a price of 10 euros per hour of work will be considered.
- Only the estimated working hours for the performance of the techno-economic analysis of the solar wind HPPs will be taken into account, that is to say that although the project development period covers about four months in which information has been collected, a contextual analysis of the resources has been carried out, two different projects have been studied and a large part of the time has been devoted to the realization of the overall project report, these hours will not be part of the budget since they are considered hours of academic background and research.

The two projects studied will be considered separately, since the budget will vary significantly according to the data that the client provides for the analysis. For example, in the case of the brownfield project, solar power data is available; however, for the greenfield project, an energy estimation is required.

Therefore, the project budget displayed in *Table 5.2* and *Table 5.3* will include:

- Work hours required by a junior engineer for data processing and the elaboration of a report.
- Price of the licenses of the computer programs used (Windographer for wind data processing, PVSyst for downloading meteorological databases and estimation of photovoltaic production).

Table 5.2. Brownfield project budget

Brownfield project budget	Cost [€]
30 hours (4 days of work)	300
Windographer use	15
Total	315

Table 5.3. Greenfield project budget

Greenfield project budget	Cost [€]
37.5 hours (5 days of work)	375
Windographer and PVSyst use	30
Total	405

5.4 Future Lines of Work

Utility-scale HPPs are still in a development phase in Spain, and although there is still a long way of research in terms of their design for a greater optimization and greater impact achievement, they clearly present lower costs and greater performance. It should be noted that savings and efficiency will depend specifically on the site and the project in particular, having the level of complementarity of the resources and their incidence a great weight in the equation. Therefore, it will be essential for developers to consider the multiple factors related to each project that will impact their design.

As financing mechanisms and market rules continue to evolve, these projects are expected to start to take off. The possibility of making a project of these characteristics real lies largely in an effective policy resolution in the hands of the administrations, and it is expected that the new decree that regulates this type of facilities accelerates the projects development.

Finally, another challenge that is positioned as an effective tool in terms of supply guarantee is the incorporation of storage, thus increasing the flexibility and reliability of the plant and minimizing losses due to excess generation. In this way, by combining the two most competitive renewable technologies, hybrid power plants with storage could give even greater support to the grid.

To conclude, it has been a very interesting research in the field of engineering and renewable energies, as well as encouraging with the commitments for the planet decarbonization and the energy transition towards a green and sustainable future. In addition, being able to have used the knowledge learned in the degree to propose a solution to a current problem has been very gratifying on a personal level.

6. BIBILIOGRAPHY

[1] everis, "HIBRIDACIÓN EN LA GENERCIÓN RENOVABLE. Análisis sobre el panorama actual y futuro en España.," appa renovables, 2021.

[2] MITECO, "PLAN NACIONAL INTEGRADO DE ENERGÍA Y CLIMA 2021-2030," 2020.

[3] CIRCE, "Centro de investigación y recursos y consumos enegéticos," CIRCE, 2017. [Online]. Available: https://www.fcirce.es/. [Accessed 2021].

[4] UN, "TRANSFORMING OUR WORLD: THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT" 2015.

[5] IPCC, "Global Warming of 1.5°C. An IPCC Special Report," 2018.

[6] REE, "EL SISTEMA ELÉCTRICO ESPAÑOL. Previsión de cierre 2020," 2020.

[7] REE, "RED ELÉCTRICA DE ESPAÑA," 17 12 2020. [Online]. Available: https://www.ree.es/es/sala-de-prensa. [Accessed 2021].

[8] REE, "RED ELÉCTRICA DE ESPAÑA," Red Eléctrica de España, April 2021. [Online]. Available: https://www.ree.es/es/clientes/generador/acceso-conexion/conoce-el-estado-de-las-solicitudes. [Accessed May 2021].

[9] BOE, "Real Decreto-ley 23/2020, de 23 de junio, por el que se aprueban medidas en materia de energía y en otros ámbitos para la reactivación económica," Agencia Estatal Boletín Oficial del Estado, 2020.

[10] M. Milligan, H. Holttinen, J. Kiviluoma, A. Orths, M. Lynch and L. Söder, "Market Designs for High Levels of Variable Generation," National Renewable Renewable Energy Laboratory (NREL), Maryland, 2014.

[11] REE, "REData," May 2021. [Online]. Available: https://www.ree.es/es/datos/generacion/potencia-instalada. [Accessed May 2021].

[12] AEE, "FOMENTO DE LA HIBRIDACIÓN EÓLICA PROPUESTA REGULATORIA.," Asociación Empresarial Eólica, 2019.

[13] IBERDROLA, "ENERGÍA HÍBRIDA IBERDROLA," 2021. [Online]. Available: https://www.iberdrola.com/innovacion/energia-hibrida. [Accessed 2021].

[14] WindEurope, "Renewable Hybrid Power Plants. Exploring the benefits and market opportunities," windeurope.org, 2019.

[15] AECOM, "CO-LOCATION INVESTIGATION. A study into the potential for co-locating wind and solar farms in Australia," Australia Renewable Energy Agency, ARENA, Sydney, 2016.

[16] D. Pratt, "Updated: Vattenfall praises good performance of co-located wind and solar energy park," SOLAR POWER PORTAL, 2017.

[17] C. Bozonnat and C. A. Schlosser, "Characterization of the Solar Power Resource in Europe and Assesing Benefits of Co-Location with Wind Power Installations," Massachusetts Institute of Technology, MIT, Cambridge, 2014.

[18] L. Stoker, "Joined at the hip: A hybrid future for onshore renewables," SOLAR POWER PORTAL, 2020.

[19] P. S. Molina, "Iberdrola begins construction on 317 MW hybrid wind-solar plant in Australia," pv magazine, 2020.

[20] T. Kenning, "Hero launches India's first solar-wind hybrid project," SOLAR POWER PORTAL, 2018.

[21] P. Bartlett, "Solar projects VATTENFALL," [Online]. Available: https://group.vattenfall.com/uk/what-we-do/our-projects/solar-projects. [Accessed May 2021].

[22] M. Á. P. Ureña, "ANÁLISIS DE LA COMPLEMENTARIEDAD DEL RECURSO EÓLICO Y SOLAR EN ANDALUCÍA Y ESTUDIO PORMENORIZADO DE DIVERSAS ZONAS," 2008. [Online]. Available: https://matras.ujaen.es/info_proyecto.php?id=analcompl. [Accessed May 2021].

[23] K. Dykes, J. King and N. DiOrio, "Research Opportunities in the Physical Design Optimization of Hybrid Power Plants," National Renewable Energy Laboratory (NREL), 2019.

[24] M. Arthur, D. Saffer and P. Belmont, "Global Wind Explained, Penn State University," [Online]. Available: https://www.e-education.psu.edu/earth111/node/1013. [Accessed April 2021].

[25] NASA, "Global Wind Patterns, CLIMATE SCIENCE INVESTIGATION (CSI)", 11 August 2016. [En línea]. Available: http://www.ces.fau.edu/nasa/content/resources/global-wind-patterns.php. [Último acceso: April 2021].

[26] A. Talayero Navales and E. Telmo Martínez, Energía Eólica, Textos docentes, Serie Energías renovables, 2011.

[27] E. Houghton, N. Carruthers and E. Arnold, Wind Forces on Buildings and Structures, 1976.

[28] MiniPhysics, "The Electromagnetic Spectrum," 22 May 2016. [Online]. Available: https://www.miniphysics.com/electromagnetic-spectrum_25.html. [Accessed April 2021].

[29] C. Honsberg and S. Bowden, "Photovoltaics Education Website," 2019. [Online]. Available: www.pveducation.org.

[30] A. M. Abu Hanieh, "Automatic Orientation of Solar Photovoltaic Panels," Birzeit University, Palestine.

[31] Department of Energy Sources. Science, "Chapter 1: Solar Radiation," University of California, 2020. [Online]. Available: https://www.ess.uci.edu/. [Accessed April 2021].

[32] Universitat de Barcelona, "Efecto de la disminución de calor consiguiente de la inclinación de los rayos solares en invierno," [Online]. Available: http://www.ub.edu/geoimatge/es/content/efecto-de-la-disminuci%C3%B3n-de-calor-consiguiente-de-la-inclinaci%C3%B3n-de-los-rayos-solares-en. [Accessed April 2021].

[33] European Comission, "Photovoltaic Geographical Information System (PVGIS)," Joint Research Centre, 2021. [Online]. Available: https://ec.europa.eu/jrc/en/pvgis. [Accessed 2021].

[34] WAsP, "GLOBAL WIND ATLAS," DTU, 2021. [Online]. Available: https://globalwindatlas.info/. [Accessed 2021].

[35] Solargis, "GLOBAL SOLAR ATLAS," The World Bank, 2018. [Online]. Available: https://globalsolaratlas.info. [Accessed April 2021].

[36] A. F. García, "Energía producida por un aerogenerador," Curso Interactivo de Física en Internet, 2016. [Online]. Available: http://www.sc.ehu.es/sbweb/fisica3/datos/viento/energia.html. [Accessed 2021].

[37] WINDPOWER, "windpower.org," DANISH WIND INDUSTRY ASSOCIATION, 2003. [Online]. Available: http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/es/tour/wres/index.htm. [Accessed 2021].

[38] Ingelibre, "Influencia de la irradiación y temperatura sobre una placa fotovoltaica," 9 November 2014. [Online]. Available: https://ingelibreblog.wordpress.com/2014/11/09/influencia-de-la-irradiacion-y-temperatura-sobre-una-placa-fotovoltaica/. [Accessed 2021].

[39] TALESUN, "BISTAR TP6H72M High Efficiency Half-Cell Monocrystalline Solar Module".

[40] BOE, "Real Decreto 1183/2020, de 29 de diciembre, de acceso y conexión a las redes de transporte y distribución de energía eléctrica.," Agencia Estatal Boletín Oficial del Estado, 2020.

[41] R. Fu, D. Feldman, R. Margolis, M. Woodhouse and K. Ardani, "U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017," National Renewable Energy Laboratory (NREL), 2017.

[42] A. Jäger-Waldau, "PV Status Report 2019," European Comission, 2019.

[43] C. KOST, S. SHAMMUGAM, V. JÜLCH, H.-T. NGUYEN and T. SCHLEGL, "LEVELIZED COST OF ELECTRICITY RENEWABLE ENERGY TECHNOLOGIES," FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE, 2018.

[44] CFI, "Levelized Cost of Energy (LCOE)," Corporate Finance Institute, CFI, [Online]. Available: https://corporatefinanceinstitute.com/resources/knowledge/finance/levelized-cost-of-energy-lcoe/#:~:text=%20Summary%20%201%20The%20LCOE%20is%20a,Lifetime%29%2F%20%28Present%20Value%20of%20All%20Electricity...%20More%20. [Accessed 2021].

[45] GPD, "Wind and its measurement in wind energy," Green Power Development, [Online]. Available: http://green-power.com.pl/en/home/wiatr-i-jego-pomiar-w-energetyce-wiatrowej/. [Accessed 2021].

[46] UL, "Windographer," 2021. [Online]. Available: https://www.ul.com/resources/apps/windographer. [Accessed 2021].

[47] PVSYST, "Photovoltaic software," Wegenève, 2021. [Online]. Available: https://www.pvsyst.com/. [Accessed 2021].

[48] Google, "Google Earth Pro," 2021. [Online]. Available: https://www.google.com/intl/es/earth/versions/. [Accessed 2021].

[49] E. Vartiainen, G. Masson, C. Breyer, D. Moser and E. Román Medina, "Impact of weighted average cost of capital, capital expenditure,and other parameters on future utility-scale PV levelised cost of electricity," John Wiley & Sons Ltd, 2019.

ANNEX A. Meteorological Mast and Wind Resource Study

Meteorological Mast

To collect the necessary information on the weather conditions of a specific site, it is common to use a measuring tower, a structure where different calibrated sensors are installed to record the wind behavior measuring wind speed and direction through their respective measure instruments, the anemometer and the wind vane. In addition, humidity, temperature, and pressure are recorded trough the barometer, the thermometer, and the hygrometer respectively, in order to set the air density and the sensitivity of the location for the ice accretion.

All the signals generated by the previous sensors are entered in a datalogger, which is an electronic device that has enough memory to make records every few seconds during a defined period, presenting the mean values for usually a 10-minute time interval of all the recorded magnitudes.

Other elements to be installed in a measuring tower are the battery that powers the datalogger, a charge regulator and a photovoltaic panel that powers the battery.

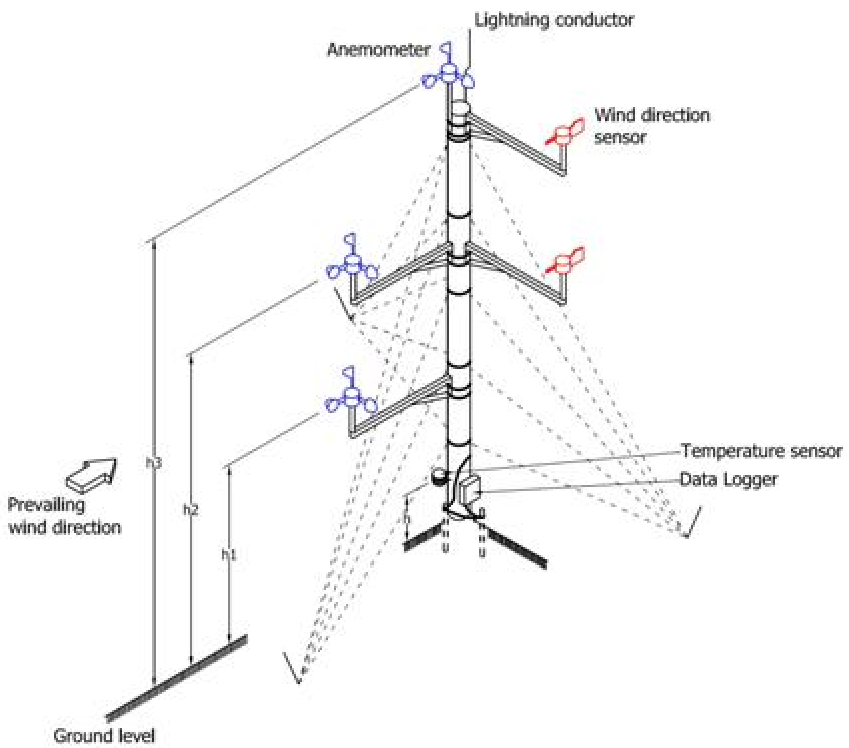

Fig A.1. Tubular meteorological mast example [45]

The current trend is to mount very high stations (above 100 m) for the measurement to be more accurate. This is due to the evolution of wind turbines, that increase the hub height in order to increase the diameter of the rotor.

There are mainly two types of towers: lattice and tubular. The most common are those with a lattice structure, since their assembly is easier and cheaper than the tubular ones. Likewise, meteorological towers can be braced (held by tensors) or self-supporting (with a good foundation).

For the study of a wind farm, the measuring tower must be installed in open field and in a position that is representative of the average ground conditions, due to the great influence of the orography in the wind behavior. [26]

Wind Resource Study

A crucial factor in the development, siting, and operation of a wind farm is the ability to assess and characterize available wind resources. In order to do this, different parameters that characterize the wind are studied for the location of interest, such as, wind speed distribution, variation of wind speed with height (vertical profile), turbulence, aspects related to the address, and long-term representativeness.

Long-term representativeness takes on a special importance in the present study, since as mentioned before, wind varies daily, annually, and seasonally. This means that the average wind speed can fluctuate from year to year and therefore the wind resource of a given site will also vary. To assess in depth what the wind resource of an area is, it would be necessary to have a series of several years of wind measurements. However, in most cases only a few years of measurements are available, so the methodology followed is to correlate the available data with those of a meteorological station that could be considered representative of the wind regime of the area under study and that, in addition, has a long period of measurement. The object of the long-term study is to give a long-term average speed value from a short period of measurements at the site. For this, MCP techniques (measure - correlation - prediction) are used. They are statistical methods that relate the short-term measurements made at the site of the future wind farm with the speeds of nearby stations with a longer period of measurements with the same wind regime. [26]

ANNEX B. TOOLS

Windographer software

The software used for the analysis of the data recorded from the datalogger of the meteorological masts used for this project, is Windographer. The towers are equipped with different sensors such as anemometers, wind vanes, thermo-hygrometers, barometers... that are used to characterize the wind resource. It is necessary to analyze the collected data in order to detect incidents with the sensors previously named.

The software is designed for importing, analyzing and visualizing this measured data. It has the ability to quickly import data from a variety of different formats allowing for rapid quality control and statistical analyses, including measure-correlate-predict (MCP), used for the long-term representativeness, and the functionality to export data to almost any wind flow model that is commonly used within the wind power industry. [46]

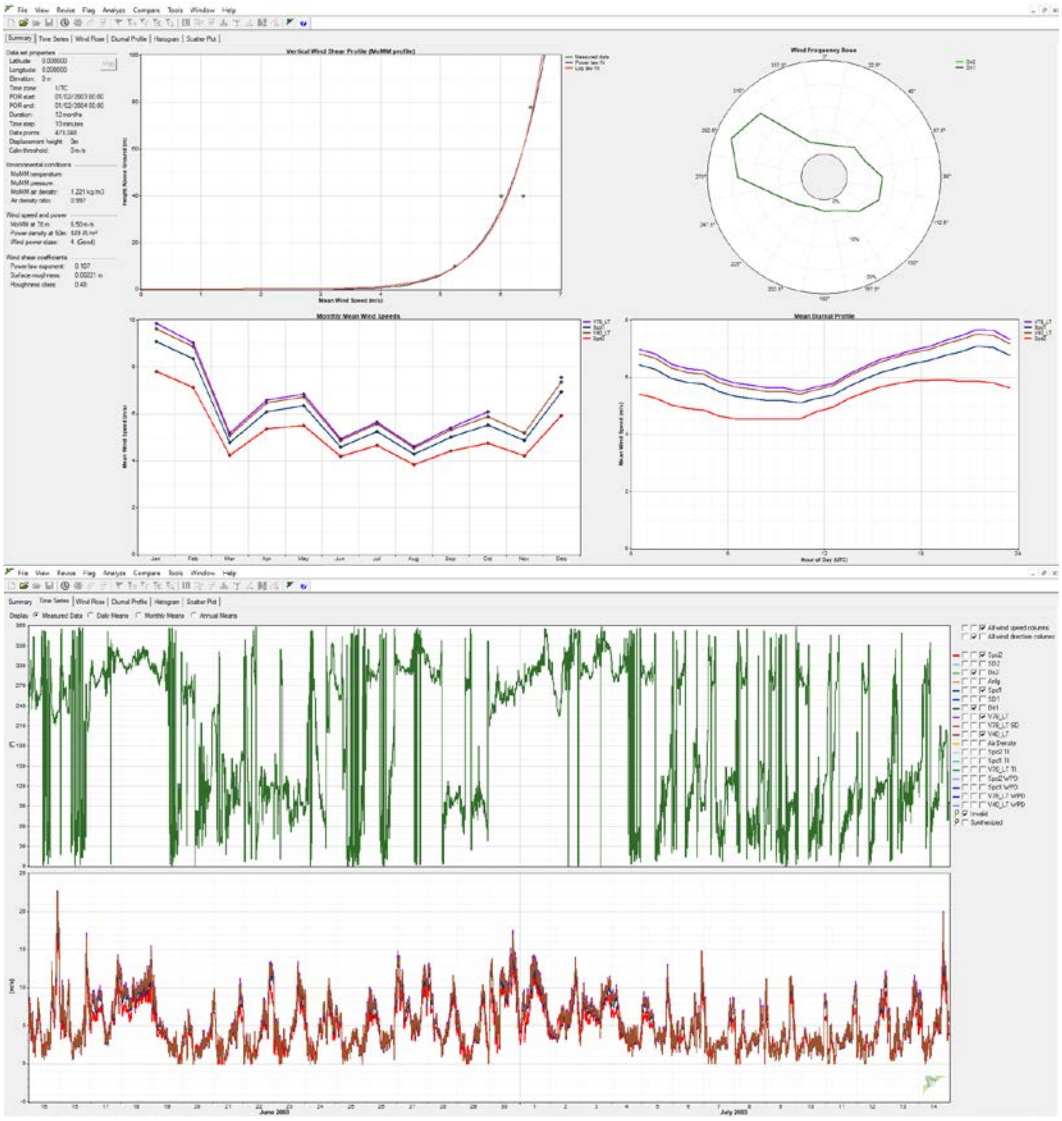

Fig A.2. Windographer software overview [46]

PVGIS

PVGIS has been developed at the European Commission Joint Research Centre. The focus of PVGIS is research in solar resource assessment and in photovoltaic performance studies. The tool is available for any location in Europe and Africa, as well as large part of Asia and America.

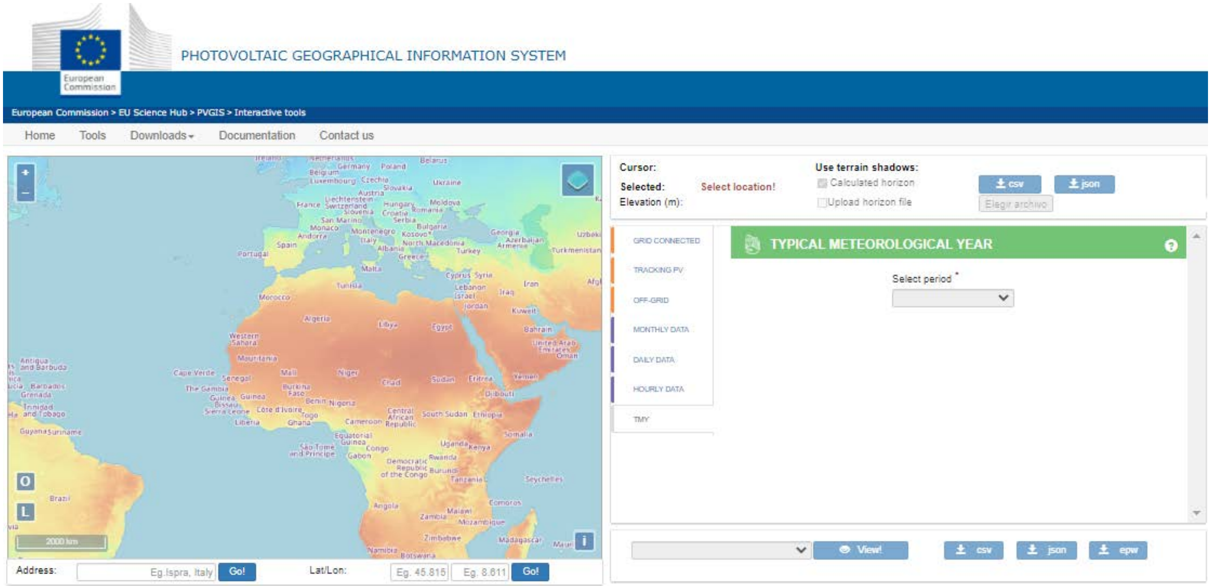

Fig A.3. TMY tool in PVGIS software[33]

A typical meteorological year (TMY) is a set of meteorological data with data values for every hour in a year for a given geographical location. The data is selected from hourly data in a longer time period (normally 10 years or more). The TMY is generated in PVGIS following the procedure described in ISO 15927-4.

The solar radiation database (DB) used is the default DB for the given location, either PVGIS-SARAH, PVGIS-NSRDB or PVGIS-ERA5. The other meteorological variables are obtained from the ERA-Interim reanalysis. [33]

Global Wind Atlas

The Global Wind Atlas application primarily supports wind power development during the exploration and preliminary wind resource assessment phases prior to the installation of meteorology measurement stations on site. It also serves as a useful tool for governments to get a better understanding of their wind resource potential at provincial and local levels.

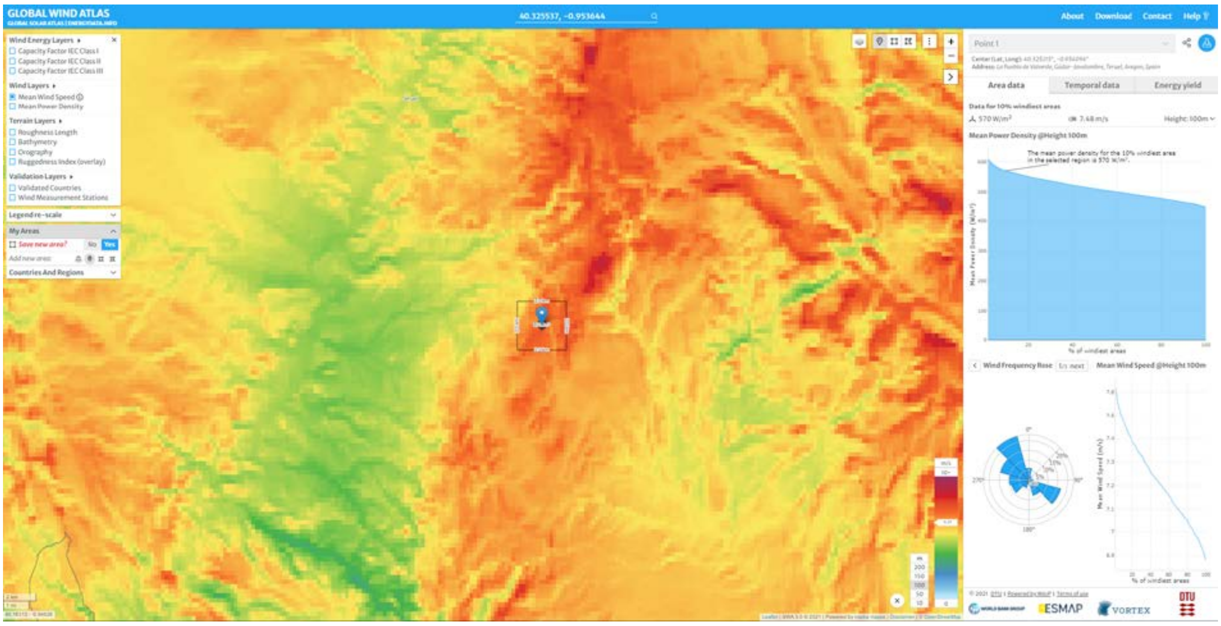

Fig A.4. Global Wind Atlas web-site overview [34]

The GWA uses a downscaling process. Large scale atmospheric data from re-analysis datasets are used as an input into medium scale mesoscale atmospheric models. The output from the mesoscale modeling is generalized to prepare it for use in microscale modeling. The output of the microscale modeling is predicted wind climates, which account for high resolution topography and land use, such as grasslands and forests. The two modeling components can introduce uncertainty into the calculations. [34]

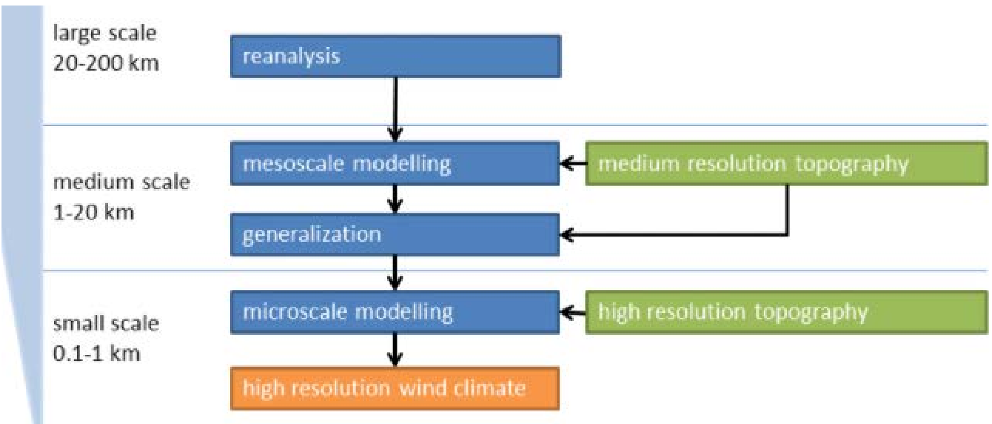

Fig A.5. Schematic showing the methodology of the GWA downscaling [34]

PVSyst

PVSyst is a payment tool developed by the University of Ginebra that allows the design, simulation and data analysis of a photovoltaic installation. This software allows the dimensioning of photovoltaic installations taking into account the solar radiation of a given location thanks to its meteorological and component databases. It also has a 3D design tool for shading simulation and allows performing economic analysis using actual component costs.

- Meteo Databases:

Creation and management of geographical sites, generation of synthetic hourly data file, visualization of hourly meteorological data, comparison of meteo data, import of meteorological data from several predefined sources or from custom files.

- Component Databases:

Database management of manufacturers and PV components, including PV modules, Inverters, Regulators, Generators, Pumps, etc.. [47]

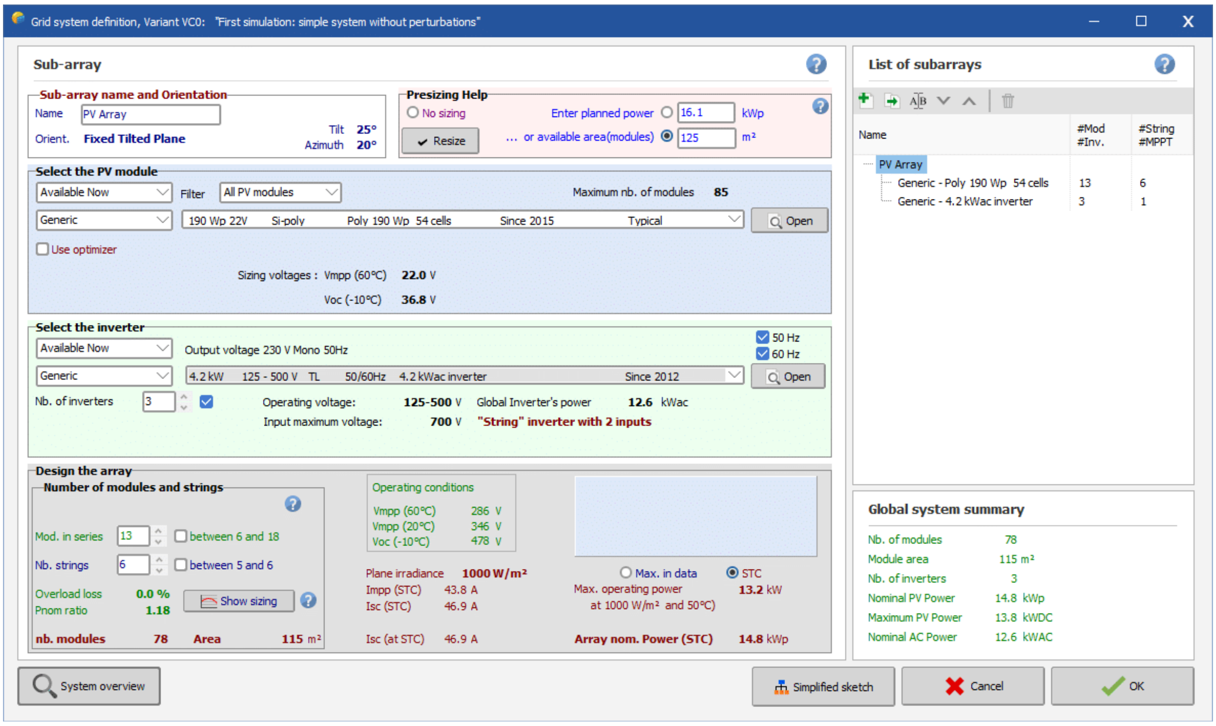

Fig A.6. PVSyst software overview [47]

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

CAPEX: Capital Expenditure

CT: Transformation Center

EPC: Engineering, Procurement and Construction

ES: Electrical Substation

GHG: Greenhouse Gases

GIS: Geographical Information System

GW: Gigawatt

HPP: Hybrid Power Plants

HSE: Health, Safety and Environment

ITCZ: Intertropical Convergence Zone

LCOE: Levelized Cost of Electricity

MITECO: Ministry for Ecological Transition and Demographic Challenge

MPP: Maximum Power Point

MW: Megawatt

NECP: National Energy and Climate Plan

NPV: Net Present Value

OPEX: Operational Expenditure

PPA: Power Purchase agreement

PPC: Power plant controller

PV: Photovoltaics

R+D+i: Research, Development and innovation

RES: Renewable Energy systems

SDG: Sustainable Development Goals

STC: Standard Test Conditions

TMY: Typical Meteorological Year

UN: United Nations

WACC: Weighted Average Cost of Capital