Final Master Project

Master's Degree in Industrial Engineering

Energy transition in Catalonia for the 2021-2030 decade

MEMORY

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Abstract

In order to battle climate change, net zero emissions have to be reached by 2050 according to European directives, involving an important energy transition from fossil fuels to renewable energy sources. This project has the initial objective of studying the current energy utilization in Catalonia, demonstrating that energy transition is an urgent matter to be done here. Afterwards, power plants solutions based on renewable energy sources (concretely, wind energy and photovoltaic energy) are proposed to be implemented throughout Catalonia according to its own policies for the 2021-2030 decade. In this way, relevant guidance about renewable energy sources is provided, which can be useful for similar studies.

The energy utilization research has been done with the analytical method, going from the whole idea to its elemental terms and studying each one of them specifically. Regarding the solution development, when deciding the locations where implement a solution, the main criterion is to consider first the ones with higher potential, considering always the source availability. Furthermore, additional criteria have been considered to avoid massive concentration of solutions. The calculation procedures of the solutions are explained in details.

Finally, the results show that it will be possible but very challenging for Catalonia to comply with energy transition policies because of the very slow pace of this transition during the last past years. Consequently, the deployment of power plants based on renewable energy sources and its costs involved will be huge during the next years. The 2021-2030 decade has to be taken as an opportunity for changing the energy system and adapting it to the requirements of the future.

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1. Glossary

- ***Comarca*** (*comarques* in plural): word in Catalan language which refers to a small territorial division composed of municipalities that share history, natural conditions or neighbour relations.
- **GHI**: Global Horizontal Irradiation. It is the irradiation received from the sun on the horizontal surface of the Earth considering direct and diffuse irradiation.
- **PV**: Photovoltaic. It is the technology where the photovoltaic effect happens, meaning that the energy of the light is converted into electricity using semiconductor materials.
- **RES**: Renewable Energy Sources. They are energy sources which can be renewed by natural means and, therefore, they are considered as inexhaustible.
- **TMY**: Typical Meteorological Year. It gives the representative hourly values of meteorological data in a specific location for one year based on the collection of meteorological data from several years.

2. Preface

This chapter gives a presentation of the object studied in this project. Additionally, here it can be found the origin of the project, the motivation of the author and the previous requirements which have been needed to elaborate it.

2.1. Origin of the project

In the near future, it is well known that climate change will be certainly the most important challenge that humanity will have to face in order to guarantee a prosperous future in this planet. The main reason of climate change is the emission of greenhouse gases, which produce greenhouse effect in the atmosphere and rise the global temperature of the planet. Consequently, nature suffers an environmental disequilibrium which leads to many other problems such as the extinction of animal and plant species, natural disasters, poverty, diseases and food shortage. Actually, climate change effects are usually referred to the future but they are already a reality, and humans must face them from now.

The way humans consume the different resources available to produce energy plays an important role to battle climate change. Energy production has been traditionally related to greenhouse gases emissions, and nowadays it is practically the same because the current global energy production is still strongly based on the consumption of fossil fuels. Moreover, it is very important to manage properly the different sources of energy in order to produce energy according to their availability, and always respecting the environment. It is well known that fossil fuels availability is being exhausted and also that their consumption is not environmentally friendly. In addition, an effort has to be made in terms of energy consumption to guarantee the maximum possible availability of all kind of energy sources for the next generations.

Then, the idea comes up from the necessity to carry out a global energy transition. This new global energy model has to be based on clean energies such as renewable energies. Therefore, the production of energy from fossil fuels has to be significantly reduced or avoided. This is a huge challenge that every country in the world will have to face sooner or later. In this project, the area studied is Catalonia (Spain) and the way proposed to encourage this transition is through the utilization of photovoltaic solar energy and wind energy.

2.2. Motivation

The main motivation is to find solutions to help Catalonia in this energy transition. Catalonia has a big potential in terms of renewable energies, such as solar energy and wind energy, but Catalonia has to take advantage of this potential and it does not seem to happen at the moment, at least as much as it could be. Also, the fact that Catalonia is late in terms of energy transition means that the next years will be specially important to overcome the situation, and this involves additional motivation.

2.3. Previous requirements

Engineering knowledge about energy specialization has been required to elaborate this project. The content of this work is about the implementation of renewable energy sources in the electric system (and ultimately in the energetic system) of a particular area. For this reason, in order to understand this content, it is needed a scientific-technical background. Additionally, some knowledge about the geography of Catalonia is required at some point.

3. Introduction

Due to the necessity to carry out an energy transition in the energetic system of Catalonia, this project is focused on studying the implementation of photovoltaic power plants and wind power plants in the electric system. Here below, the objectives and the scope of observation are presented.

3.1. Objectives

This project aims to the following objectives:

- Analysing the current situation regarding the use of energy in Catalonia. Moreover, analysing the current situation regarding the utilization of renewable energy sources in Catalonia.
- Increasing the contribution of renewable energy sources in final energy consumption by means of increasing the electricity production from renewable energy sources according to current energy transition policies in Catalonia.
- Providing guidance about the implementation of renewable energy sources in Catalonia (calculation procedures can be extrapolated to similar locations).
- Demonstrating the viability to comply with energy transition policies for this decade in Catalonia. This means measuring the real deployment of power plants based on renewable energy sources and estimating its costs involved.

3.2. Scope of observation

The scope of observation is the implementation of photovoltaic power plants (grounded) and wind power plants (onshore) in the territory of Catalonia.

4. Normative framework

In this chapter, the normative framework involved in this project is explained. This normative framework is composed by policies and legislation.

4.1. Energy transition policies

Firstly, the policies regarding the energy transition are explained at all different levels: starting with the global policies from the European Union for its member states; following with the statewide policies from Spain; and finishing with the autonomic policies from Catalonia. It is important to say that some historical background is also explained at some point in order to contextualize the situation.

4.1.1. Policies from the European Union

In 2007, European Union proposed policies to its member states to take action on energy transition and climate change. In 2009, a set of policies were released by European Union to ensure that its state members achieve their climate targets for the year 2020. These targets for 2020 were fundamentally three, and they were popularly known as the 20-20-20 climate targets: 20% less in greenhouse gases emissions (taking 1990 levels as reference), 20% of final energy consumption from renewable energy sources and 20% less consumption through energy efficiency improvement [1].

In the last few years, climate change has been in the spotlight of many countries around the world due to its imminent effects in the environment and the society. In 2015, the representatives of 195 countries around the world plus the European Union gathered in Paris in order to find solutions to this global problem. This meeting was the “2015 United Nations Climate Change Conference”, also known as COP21. There, this issue was discussed in deep, concluding that all parties have to make bigger efforts to reduce greenhouse gases emissions. This was concluded in the Paris Agreement, which supposed a big step to move forward in the climate change battle.

According to the commitments of the Paris Agreement, European Union renewed its climate targets for the next decade with even more ambition than before. In 2016, European Union presented its targets for the year 2030. These new targets for 2030 are: 40% less in greenhouse gases emissions (taking 1990 levels as reference), 32% of final energy consumption from renewable energy sources and 32,5% less consumption through energy efficiency improvement [1].

Additionally, in 2019 the European Union released a normative package called the “Clean energy for all Europeans package”. This package brings considerable benefits to European consumers through the implementation of a new European energy model based on clean energies, and this is done by the use of renewable energies, the improvement of the energy performance in buildings, the implementation of a robust government system for energy regulations and the redesign of the electricity market.

Also in 2019, in line with the Paris Agreement, European Union endorsed a long term strategy in terms of climate change with the objective of reaching climate-neutrality for the year 2050. This means that the European Union objective for 2050 is to reach an economy with zero net greenhouse gases emissions. It has to be said that this is a huge challenge where all parts of society and economic sectors will play an important role (from the power sector to industry, mobility, buildings, agriculture and forestry) [1].

In order to accomplish these objectives, European Union member states are required to elaborate its own national strategies. These strategies have to show how they plan to develop this energy transition process.

4.1.2. Policies from Spain

The Spanish national strategy for the 2011-2020 decade was called “Plan of Renewable Energies” (*Plan de Energías Renovables*, in Spanish language), also known as PER. This plan had the main objective to achieve at least 20% of final energy consumption from renewable energy sources.

The beginning of a new decade brought a new national strategy. In 2021, the Government of Spain approved the Spanish national strategy for the 2021-2030 decade, called “Climate and Energy Integrated National Plan” (*Plan Nacional Integrado de Energía y Clima*, in Spanish language) and also known as PNIEC. This plan follows the same directives than European Union targets for 2030, but adapted to the reality of Spain. According to the studies realized in this plan, the measures considered in this national strategy will lead Spain to achieve in 2030 the following results: 23% less in greenhouse gases emissions (taking 1990 levels as reference), 42% of final energy consumption from renewable energy sources and 39,5% less consumption through energy efficiency improvement. Additionally, this plan contemplates a 74% contribution of renewable energies in the electricity production in 2030. It has to be mentioned that 23% reduction of greenhouse gases emissions taking 1990 levels as reference is equivalent to 38% reduction of greenhouse gases emissions taking 2010 levels as reference. According to PNIEC, this is completely coherent with the European Union objectives to reach climate-neutrality for the year 2050 [2].

Also in 2021, the Government of Spain approved the Spanish Climate Change Law (*Ley 7/2021, de Cambio Climático y Transición Energética*) which follows the directives given by the European Union. This law has the objective to ensure the transition to a neutral emissions economy through the reduction of greenhouse gases emissions. In order to achieve this, the law encourages the utilization of renewable energy sources. It is worth to mention that this law received some popular criticism because of its late approval.

4.1.3. Policies from Catalonia

In order to achieve the energy transition objectives dictated by the European Union, and consequently achieve the objectives of the Spanish Government, the Catalan Government presented in 2017 its own national strategy, called "National Agreement for Energy Transition in Catalonia" (*Pacte Nacional per a la Transició Energètica de Catalunya*, in Catalan language) and also known as PNTE. It is an agreement made by Catalan institutions and civil society representatives in order to build the future energetic model in Catalonia, based on renewable energies and made with the purpose to be decentralized, democratic and sustainable. Specifically, this agreement aims to the abandonment of nuclear energy, the reduction of fossil fuels dependence, the empowerment of the society to take part in the transition into renewable energy sources and the implementation of regulations in the energy market to encourage this energy transition [3].

The principles of this national strategy (PNTE) are in line with the Catalan Climate Change Law (*Llei 16/2017, del Canvi Climàtic*) approved by the Catalan Government also in 2017, which follows the directives given by the European Union. This law aims to reduce greenhouse gases emissions and it encourages the transition to a neutral emissions economy. In addition, it guarantees the coordination of all public institutions of Catalonia and promotes the participation of the society to reduce the energetic dependence of Catalonia. Moreover, it has the purpose to lead the renewable energy transition in Europe in terms of research and through the development of new technologies. However, despite the effort and ambition deposited in this law, in June of 2019 the State of Spain refused the law alleging that the Government of Catalonia does not have the power to make decisions in terms of energy transition. Afterwards, in November of 2019, the Catalan Government approved a Decree Law of urgent measures to deal with climate emergency and also to promote renewable energies (*Decret Llei 16/2019*). And finally, in December of the same year 2019, the Catalan Government approved a new law (*Llei 9/2019*) which modifies the previous Catalan Climate Change Law (*Llei 16/2017, del Canvi Climàtic*) and adapts it to the legislative requirements imposed by the State of Spain. This new law is basically referred to taxes in relation to carbon dioxide emissions from mechanical traction vehicles.

In October of 2021, the Government of Catalonia approved a new Decree Law (*Decret Llei 24/2021*) to accelerate the deployment of renewable energies. This Decree Law pretends to minimize the social impact of the implementation of renewable energies in the territory of Catalonia. Concretely, promoters have to offer the possibility of at least 20% participation in the project to the locals and also promoters need the support of at least 50% of the territory from the owners.

Regarding solar energy, a specific strategy to increase its utilization was initiated by the Catalan Government in 2017. This strategy is called SOLARCAT, and it encourages the implementation of new solar energy power plants and also the self-consumption of solar energy in domestic and industrial sectors. It is well known that solar energy plays an important role in this energy transition because of the fact that almost everybody can easily take profit of it.

As a consequence of the necessity to carry on with the energy transition, relevant studies are being released continuously to inform about the situation at every step of the process. The Catalan Institute of Energy (*Institut Català d'Energia*, in Catalan language), also known as ICAEN, is working in a project about the energetic prospective of Catalonia in 2050 (*Prospectiva Energètica de Catalunya a l'horitzó 2050*, in Catalan language), also known as PROENCAT 2050. The desired energy model which is supposed to be achieved in 2050 has to satisfy absolutely all the energy demand by means of renewable energy sources.

4.2. Applicable legislation

Now, the applicable legislation regarding the use of energy and the environmental protection which concerns the territory of Catalonia when implementing the solutions is explained.

4.2.1. Energy legislation

The energy legislation is explained in two parts: photovoltaic energy legislation and wind energy legislation.

Photovoltaic energy legislation

This legislation principally depends on the scale of electricity production. According to Spanish legislation on photovoltaic energy [4], photovoltaic systems can be separated in three groups: autonomous photovoltaic systems, photovoltaic power plants and self-consumption photovoltaic systems. Each group has its specific legislation. However, there is a general legislation to be complied by all of them. This general legislation is fundamentally composed by two terms. Firstly, there is the Spanish Law of Electric Sector (*Ley 24/2013*) which regulates all the activities related to the electric sector. In practice, this legislation is exposed in the *RD 1955/2000* (Royal Decree) which has always to be considered. And secondly, there is the *RD 842/2002* (Royal Decree) which is really important because it is where the "Electrotechnical Regulation for Low Voltage" is approved, also known as REBT (*Reglamento Electrotécnico para Baja Tensión*, in Spanish language). All low voltage facilities have to comply with REBT. Low voltage for alternating current means lower or equal to 1 kV and low voltage for direct current means lower or equal to 1,5 kV. Those facilities which exceed these values are considered as medium and high voltage facilities, and they have to comply with its specific regulations exposed in the *RD 1955/2000*.

An autonomous photovoltaic system is a PV system which is not connected to the grid. These systems are usually equipped with batteries. Alternatively, they can work in direct solar pumping mode. The specific legislation for these systems depends on the nominal power. However, all autonomous photovoltaic systems have to comply with the particular technical instruction *ITC-BT-40* from REBT, in relation to the electricity production facilities.

- For autonomous PV systems with nominal power lower or equal to 10 kW, the legislation required can be simply complied with the services of a competent electrician (according to the technical instruction *ITC-BT-03* from REBT).

- For autonomous PV systems with nominal power greater than 10 kW, the services of a competent engineer are needed to comply with the legislation required because a technical project has to be made (according to the technical instruction *ITC-BT-04* from REBT).

A photovoltaic power plant is a PV system connected to the grid which is designed to inject the maximum possible electrical energy to the grid. Once again, the specific legislation for these systems depends on the nominal power. However, for all PV power plants with nominal power greater than 10 kW, a technical project has to be made by an engineer as usual.

- For PV power plants with nominal power lower or equal to 100 kW, the main legislation is the *RD 1699/2011* (Royal Decree) which regulates the connection to the grid for this kind of electricity production systems.

- For PV power plants with nominal power greater than 100 kW, the legislation process is much wider. The main regulations are the following ones: the *RD 413/2014* (Royal Decree) regulates the electricity production from renewable energy sources; the *RDL 23/2020* (Royal Decree Law) is about energy regulations to achieve statewide economy reactivation; and finally, it has to be mentioned the *RD 1183/2020* (Royal Decree) about the grid connection.

A self-consumption photovoltaic system is a PV system designed to self-consumption which is connected to the grid. These systems are divided in two subgroups depending on if they generate electricity surplus or not. When there is surplus, it can be dumped to the grid in order to get economical compensation for it. Regardless of this, all self-consumption PV systems have to comply with the *RDL 15/2018* (Royal Decree Law) and the *RD 244/2019* (Royal Decree). The *RDL 15/2018* is about urgent measures for energy transition and the *RD 244/2019* regulates the self-consumption of electric energy. In addition, a technical project has to be made by an engineer in case of self-consumption facilities with nominal power greater than 10 kW.

- Self-consumption PV systems with surplus can be with compensation or without compensation. For self-consumption PV systems with surplus and compensation, it is required to comply with a proximity condition to the grid and also it is strictly required not to exceed a nominal power of 100 kW. When proximity condition is complied but nominal power is greater than 100 kW, the facility does not have compensation and it is regulated according to *RD 1183/2020*. For this reason, PV facilities with nominal power greater than 100 kW are generally designed as PV power plants. Additionally, self-consumption PV systems with surplus and compensation with a nominal power lower or equal to 15 kW require a very simple regulation process exposed in the *RD 244/2019*.

- Self-consumption PV systems without surplus have an electrical device to avoid dumping electricity to the grid. When nominal power is lower or equal to 100 kW, the regulation process is also very simple (*RD 244/2019*). And if nominal power is greater than 100 kW, the facility is considered as a PV power plant and not as a self-consumption PV system.

When explaining the solar self-consumption legislation in Spain, it is worth to emphasize the *RDL 15/2018* about energy transition because of its controversial background. In 2015, the Government of Spain introduced the *RD 900/2015* (Royal Decree), popularly known as “sun tax” (*impuesto al sol*, in Spanish language), which consisted in a tax to all solar energy self-consumption facilities just to be connected to the grid. Obviously, this law involved a lot of criticism among the popular opinion because it clearly went against the encouragement of energy transition and, therefore, against the utilization of renewable energy sources. Finally, the “sun tax” was abolished in 2018 with the *RDL 15/2018*, which takes urgent measures for energy transition and supports the self-consumption of solar energy. This is a good example of how important are the political decisions to encourage in the society the use of renewable energy sources.

Wind energy legislation

In the same way, according to Spanish legislation on wind energy [5], the Spanish Law of Electric Sector (*Ley 24/2013*) regulates wind energy facilities as they are electricity production systems. This legislation is exposed in the *RD 1955/2000*. Additionally, in case of low voltage facilities, there is the *RD 842/2002* where REBT is approved.

A wind power plant is a system connected to the grid which is designed to inject the maximum possible electrical energy to the grid. When the nominal power is lower or equal to 100 kW, the main legislation is the *RD 1699/2011* which is about the connection of low power facilities to the grid. However, they usually have nominal power greater than 100 kW, and their main regulations are the *RD 413/2014* which regulates the electricity production from renewable energy sources, the *RDL 23/2020* which is about energy regulations for the economy reactivation, and finally the *RD 1183/2020* which is about the grid connection. It is worth to remember that a technical project made by an engineer is needed in case of wind power plants with nominal power greater than 10 kW.

A self-consumption wind system is composed by one wind turbine or a group of them designed for self-consumption which have a total nominal power lower or equal to 100 kW. These facilities have to comply with the *RDL 15/2018* about urgent measures for energy transition and the *RD 244/2019* which regulates the self-consumption of electric energy. Additionally, for self-consumption facilities with nominal power greater than 10 kW, a technical project has to be made by an engineer as usual. Finally, it is important to say that the major part of the regulation on self-consumption wind energy is based on the wind power plants regulation. However, in case of horizontal axis wind turbines for self-consumption purposes, each wind turbine must have a swept area lower or equal to 200 m^2 (area of the circle created by the blades when they are moving).

4.2.2. Environmental legislation

When implementing photovoltaic or wind power plants, it is necessary to obtain a positive Environmental Impact Statement (EIS). Photovoltaic power plants have some impacts on the environment such as visual impacts and land cover. Wind power plants have considerable impacts on the environment, and they have to deal with strict measures related to visual impacts, noise limits, birds protection and more.

Regarding the protected natural areas, where it is not possible to implement any power plant, it is important to mention the System of Protected Natural Spaces in Catalonia (*Sistema d'Espais Naturals Protegits a Catalunya*, in Catalan language) [6], which supports the conservation of the natural heritage and biodiversity. This protection system is fundamentally composed by the Plan of Natural Interest Spaces (*Pla d'Espais d'Interès Natural*, in Catalan language) which is also known as PEIN, the Natural Spaces of Special Protection (*Espais Naturals de Protecció Especial*, in Catalan language) which is also known as ENPE, and the European network of natural spaces called Natura 2000. The first mentioned plan, PEIN, was approved in 1992 by the Government of Catalonia through the *Decret 328/1992* (Decree Law) in order to legally protect the natural spaces of Catalonia and conserve its value in terms of ecology, biodiversity and culture. Its origins are in the *Llei 12/1985* (Law), which introduced ENPE in 1985. The natural spaces included in ENPE have special protection and stricter regulations. Finally, Natura 2000 is the most important European network of natural spaces which legally protects the natural heritage of Europe. It was approved in 1992 through the European Directive *92/43/EEC*. To sum up, all these natural spaces are protected by the law and they are not available to implement any power plant.

5. Energy analysis of Catalonia

In this chapter, the energy utilization in Catalonia is analyzed in details. Firstly, it is analyzed the energetic system and, secondly, the electric system.

5.1. Energetic system

The energetic system of a region is directly related to its economic and social development. Catalonia is one of the most developed autonomous communities in Spain. However, the political instability of the last years has been an obstacle in the implementation of renewable energy sources (RES) in the energetic system. This analysis will present firstly the primary energy production, secondly, the primary energy consumption, and finally, the final energy consumption.

As the intention is to know how was the situation just before the 2021-2030 decade, in order to know the starting point of this energy transition, all the data collected for this analysis has to be from the last year before the start of this new decade. However, 2020 was involved in the *COVID-19* pandemic, and the consequences of this pandemic had a significant influence on the use of energy. Therefore, the year analyzed is 2019, because it gives more representative data than 2020.

5.1.1. Primary energy production

The total primary energy production in 2019 was 7.507,4 ktoe (thousands of tonnes of oil equivalent). The nuclear energy was the most produced kind of primary energy with 6.220,4 ktoe (it represents the 82,9% of the total). It has to be said that nuclear energy is considered as own primary energy source in Spain, despite the fact that uranium is generally imported from other countries and enriched in Spain. In second position, there are the renewable energies with 1.112,5 ktoe (14,8%). In third position, there is the non-renewable waste with 138 ktoe (1,8%). And finally, there is the oil with 35,8 ktoe (0,5%) and the natural gas with 0,7 ktoe (negligible production). There is no coal production [7]. Down below, this information is presented in a graphic (Figure 1).

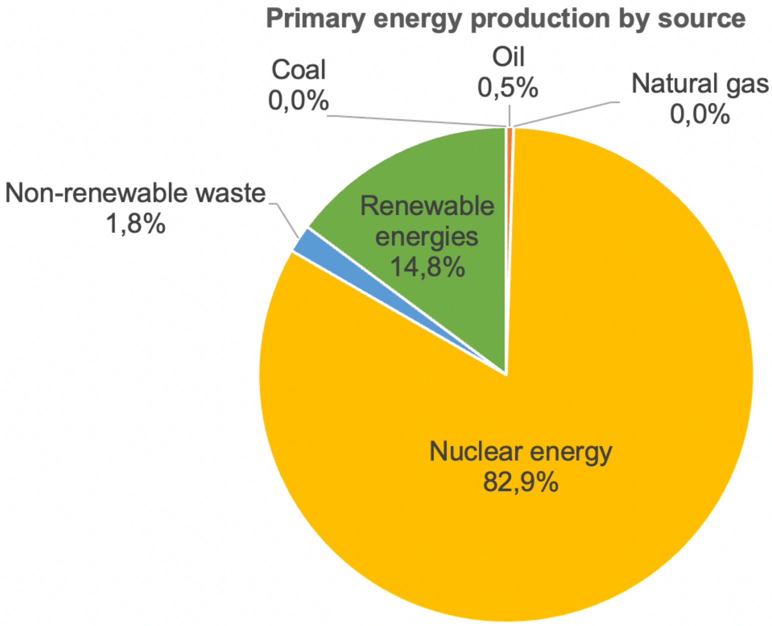

Figure 1. Primary energy production by source in 2019 in Catalonia.

5.1.2. Primary energy consumption

The total primary energy consumption in 2019 was 25.371,2 ktoe. The main source consumed was the oil with 11.673,1 ktoe (it represents the 46% of the total). Oil consumption is elevated principally due to transportation sector, which demands big amounts of this kind of energy over the other sectors. The following ones are the nuclear energy with 6.220,4 ktoe (24,5%) and the natural gas with 5.821,9 ktoe (23%), both with similar weight. After these, there are the renewable energies with 1.359,3 ktoe (5,4%), which is a very low weight. It is important to comment here that primary energy consumption is equal to primary energy production in terms of solar energy, wind energy and hydro energy. And the reason why the primary energy consumption and the primary energy production of renewable energies is not exactly the same is because of the biomass, where the amount of biomass energy consumed is higher than the amount of biomass produced. Finally, there are some more kinds of primary energy consumption: non-renewable waste with 138 ktoe (0,5%), electric exchange budget with 123,9 ktoe (0,5%) and coal with 34,6 ktoe (0,1%) [7]. Down below, this information is presented in a graphic (Figure 2).

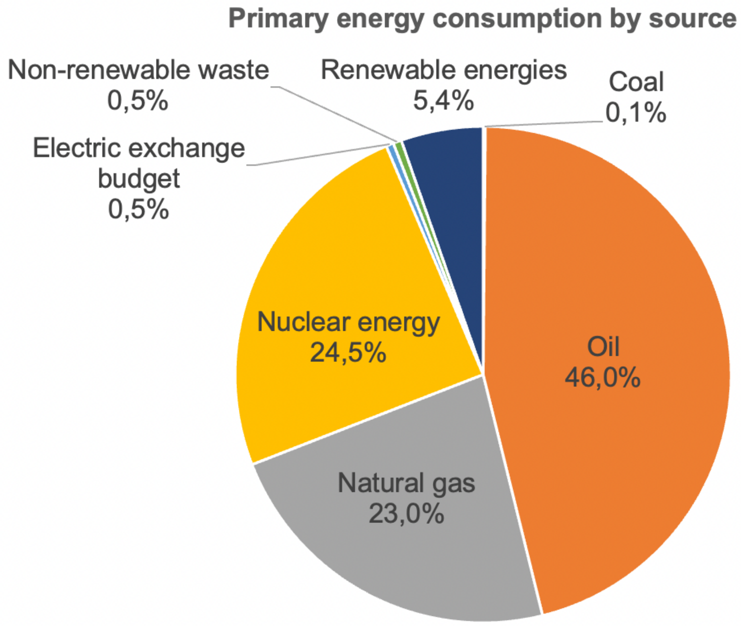

Figure 2. Primary energy consumption by source in 2019 in Catalonia.

Regarding the primary energy, it is important to observe the big difference between the total production (7.507,4 ktoe) and the total consumption (25.371,2 ktoe), which gives evidence of the necessity of making importations in order to satisfy the demand. Consequently, there is a high dependence on primary energy imports to guarantee supply. The most imported primary energy are the ones derived from fossil fuels.

Over the past decade, primary energy consumption in Catalonia has been characterized by a slight incrementation. It has been an incrementation of 9,1% in the time period between 2014 and 2019, which in absolute terms means an incrementation of 2.117,2 ktoe. In addition, the maximum annual value registered of primary energy consumption, in the time period between 1990 and 2019, was in 2007 with 26.966,1 ktoe. In relation to this maximum value, consumption in 2019 was 5,9% lower, positioning 2019 in equivalent consumption values as there were in 2002 and 2003 [7].

5.1.3. Final energy consumption

The total final energy consumption in 2019 was 14.446,7 ktoe. The most consumed final energies are the ones related to oil derived energy resources with 7.195,5 ktoe (it represents the 49,8% of the total). The following ones are the electricity with 3.624,8 ktoe (25,1%) and the natural gas with 2.945,9 ktoe (20,4%). After these, there are the non-electrical renewable energies (that is to say thermal renewable energies such as solar thermal, biomass and biofuels) with 560,8 ktoe (3,9%). Finally, there are some more kinds of final energy consumption: non-renewable waste with 98,2 ktoe (0,7%) and coal with 21,5 ktoe (0,1%) [7]. Down below, this information is presented in a graphic (Figure 3).

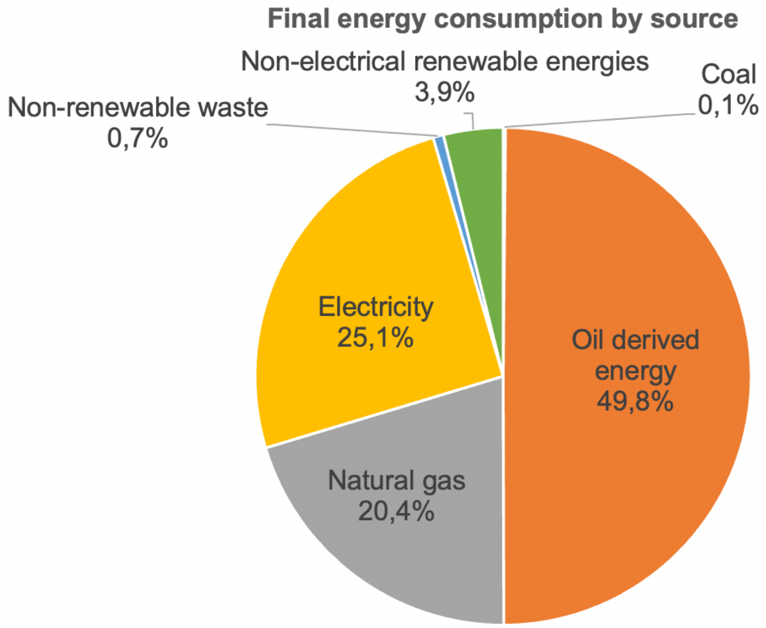

Figure 3. Final energy consumption by source in 2019 in Catalonia.

The difference between primary energy consumption and final energy consumption (10.924,5 ktoe) is fundamentally the loss of energy in the transformation processes of the different forms of energy. But also, there is probably some little statistical error related to the data collection by the data source.

Final energy consumption can be also analyzed by sector. When doing this, once again, it can be seen that transport sector has a big influence in the consumption. It represents the 45,1% of the total final energy consumption. After this predominant sector, there are the following ones: the industrial sector which includes the secondary sector (25,5%); the domestic sector (14,7%); the service sector also known as tertiary sector (13,1%); and the primary sector (1,6%) [7]. As it is well known, fossil fuels reservoirs are expected to be exhausted soon due to enormous and rising consumption around the world, and Catalonia, as many others locations of the world, is highly dependent on fossil fuels mainly in transportation. It has to be commented that, if a reduction of fossil fuels in the final energy consumption is desired, it is needed a strong effort in terms of reducing fossil fuels consumption in transportation.

Regarding the renewable energy sources, the contribution of them represents the 9,9% respect the final gross energy consumption in 2019, being the 7,3% in 2014. As it can be seen, the growth of this contribution is very slow, evidencing the lack of encouragement in these kinds of projects. In addition, although in the last years there has not been any significant incorporation of renewable energies in the Catalan electricity mix, other renewable energy sources have increased their share (renewable energy sources related to thermal use).

Over the past decade, as it happens with primary energy consumption, final energy consumption has been characterized by an incrementation. In terms of final energy consumption, it has been an incrementation of 11,4% in the time period between 2014 and 2019, which in absolute terms means an incrementation of 1.481 ktoe.

5.2. Electric system

First of all, it is important to say that the data collected for this analysis is also from 2019 and the origin of the data is the same, in order to make concordance with previous analysis.

To understand this analysis, some basic concepts about electric systems are going to be explained before. The sum of electricity production from non-renewable energy sources and electricity production from renewable energy sources is called total gross electricity production. Then, it has to be subtracted the auxiliary consumption from electric power plants (which represents their own consumption) in order to get the total net electricity production. Then, it has to be subtracted the pumping consumption related to pumping stages in order to finally get the total available production of electricity. After this value, it can be added the term of electric exchange budget, which refers to the amount of electricity that has been exchanged with other countries. Once explained that, the electric system analysis is explained.

In 2019, the total gross electricity production was 47.530 GWh, where 39.897 GWh (83,9%) were from non-renewable energy sources and 7.633 GWh (16,1%) were from renewable energy sources (see Figure 4 and observe the detailed distribution of electricity production, also known as electricity mix). The auxiliary consumption was 1.711 GWh, and then the total net electricity production was 45.819 GWh. The pumping consumption was barely 175 GWh, which implies a total available production of electricity of 45.644 GWh. And finally, the electric exchange budget was 1.453 GWh, which gives a final result of 47.097 GWh [8].

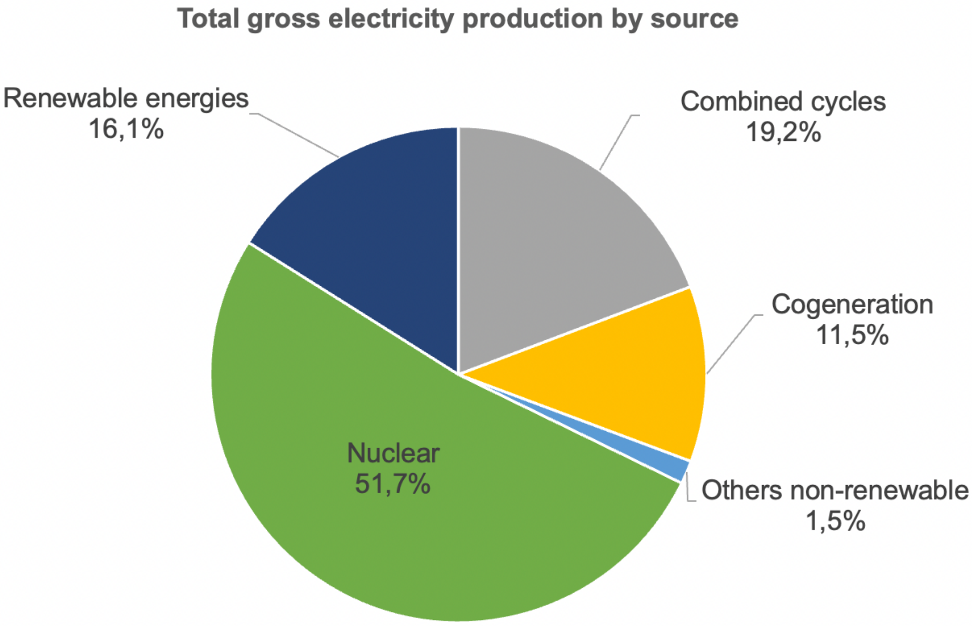

Figure 4. Total gross electricity production by source in 2019 in Catalonia.

Non-renewable energy sources have a considerable weight in electricity production (gross electricity production of 39.897 GWh). From this production, the major part comes from nuclear power plants (24.586 GWh). Following this, there are the combined cycle power plants (9.145 GWh) and the cogeneration plants (5.443 GWh). The rest of electric energy comes from other non-renewable energy power plants related to industrial solid waste, non-renewable urban solid waste and wastewater treatment, but neither from coal power plants nor oil-gas power plants since a few years ago Catalonia stopped producing electricity by these means [8].

Regarding the nuclear power plants, which represents in 2019 the 51,7% of the total gross electricity production, it has to be mentioned that they are supposed to be closed in the next few years, and this represents a huge problem for the Catalan electric system because it is highly dependent on this source of energy. There are three operating nuclear power plants in Catalonia (located in the Province of Tarragona) and all of them are PWR type (Pressurized Water Reactor): *Ascó I* (electric power of 1.033 MW and opened in 1984), *Ascó II* (electric power of 1.027 MW and opened in 1986) and *Vandellós II* (electric power of 1.087 MW and opened in 1988). Estimating a useful life of 40 years for these nuclear plants, they have to close soon. Actually, the Catalan Government initiated plans in 2017 to close all nuclear reactors before 2027, through the Catalan Climate Change Law (*Llei 16/2017, del Canvi Climàtic*). However, the State of Spain, which has the competence to do this closing, refused in 2019 the Catalan Government plans. Moreover, in 2020, the Spanish Government in collaboration with the Spanish Nuclear Safety Council prolonged the useful life of *Vandellós II* to 2030 [9]. And recently, it has been prolonged also the useful life of *Ascó I* and *Ascó II* to 2030 and 2031, respectively. These extensions mean that functional habilitations have to be done in order to adapt the power plants and guarantee safe operations [10]. It is very important to comment that if closed nuclear power plants are desired, a huge power from alternative power plants, such as renewable energy power plants, have to be implemented in short time. It will be very challenging for Catalonia and also for Spain to find a new electric production model which matches the demand before the close of these nuclear power plants.

On the other hand, renewable energy sources have much less weight in electricity production (gross electricity production of 7.633 GWh). The two most important renewable energy sources are hydro (3.656 GWh) and wind (3.153 GWh). Solar energy source is in third position with an electricity production of 485 GWh, where 452 GWh comes from photovoltaics and 33 GWh comes from solar thermoelectric power plants. The rest of electric energy comes from other renewable energy sources such as renewable urban solid waste, biogas and biomass [8]. The following graphic (Figure 5) shows the distribution of renewable energy sources inside the renewable gross electricity production.

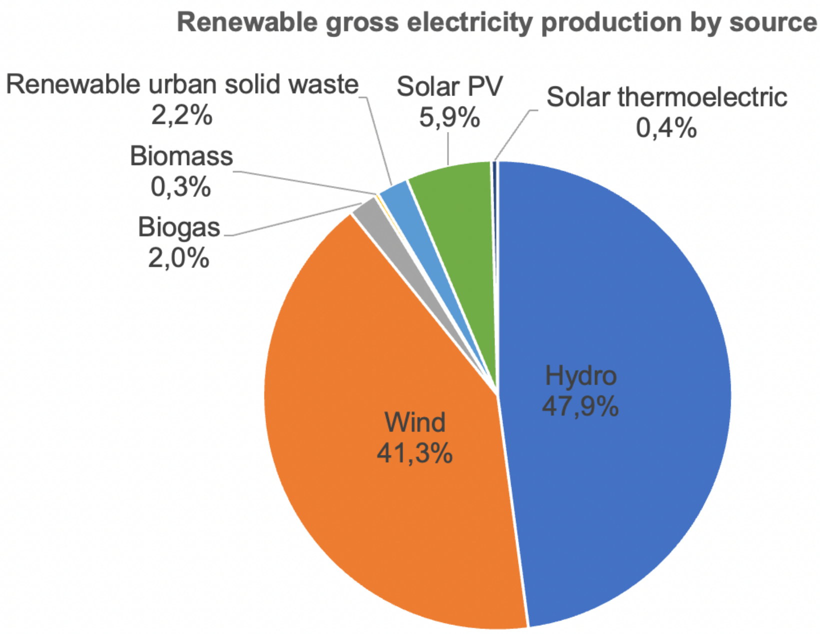

Figure 5. Renewable gross electricity production by source in 2019 in Catalonia.

Regarding the electrical installed power, in 2019 Catalonia had a total gross electrical installed power of 11.882,4 MW, where 7.840,4 MW (66%) were from non-renewable energy sources and 4.042 MW (34%) were from renewable energy sources. The installed power from non-renewable power plants came from: 3.714,2 MW installed power from combined cycle power plants; 3.146,9 MW installed power from nuclear power plants; 833,1 MW installed power from cogeneration power plants; and 146,2 MW from other non-renewable power plants. On the other side, the installed power from renewable power came from: 2.359,3 MW installed power from hydro power plants; 1.271,1 MW installed power from wind power plants; 295,5 MW installed power from solar PV; 61,6 MW installed power from biogas power plants; 26,2 MW installed power from renewable urban solid waste power plants; 24,3 MW installed power from solar thermoelectric power plants; and 4 MW installed power from biomass power plants [8].

In 2020, the installed power from non-renewable sources remained exactly the same, while the installed power from renewable sources increased to 4.091,6 MW. Actually, both types of installed power were quite stable during the past decade. Installed power from non-renewable energy sources tends to decrease, despite a very slight increase in the last five years. On the other side, installed power from renewable energy sources generally tends to increase, but very slowly.

6. Current situation regarding RES

This chapter explains what is the current situation regarding RES and, in particular, how is going the implementation of photovoltaic and wind power plants, as it is the scope of observation of this project.

At the end of the past decade, the weight of RES in final energy consumption was considerably low. According to the analysis realized previously, in 2019, the contribution of RES in final gross energy consumption was under 10% (approximately 8%). From this contribution, 3,9% comes from non-electrical renewable energies and almost 4,1% comes from electrical renewable energies (25,1% of electricity contribution in final energy consumption multiplied by 16,1% of RES contribution in total gross electricity production). Therefore, the real contribution of RES in final energy consumption is really far away from the forecasted contribution (which is 20% for 2020 and 32% for 2030, in line with European Union objectives). See Figure 6.

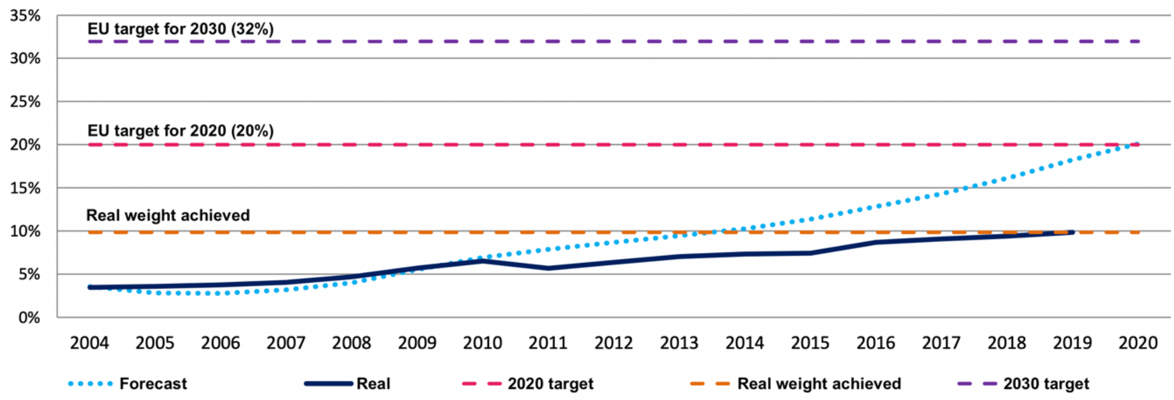

Figure 6. Evolution of RES weight in final energy consumption in Catalonia [8].

In relation to Figure 6, it has to be said that in 2011 came into effect a regulation on biofuels sustainability criteria. Biofuels are fuels which have its origins in biomass (RES). Then, this regulation helped to raise RES weight in final energy consumption. On the other hand, in 2012 the subventions for opening electric power plants based on RES were suppressed, and that slowed down slightly the ascending evolution of RES weight in final energy consumption. Additionally, in 2015 the RES weight raised again because of the Paris Agreement.

6.1. Current situation regarding PV and wind energy

Photovoltaic solar energy

Regarding PV solar energy in Catalonia, in the last years, the installed power from self-consumption facilities has been growing while the growth of installed power from power plants is stuck. The next table (Table 1) shows the evolution of PV installed power in the last years of the past decade.

Year	Total PV [MW]	New PV [MW]	New PV self-consumption [MW]	New PV power plants [MW]
2014	266,4	1,5	0,1	1,4
2015	267,1	0,7	0,4	0,3
2016	267,2	0,1	0,1	0
2017	268,6	1,4	1,4	0
2018	272,7	4,1	4,1	0
2019	295,5	22,8	21,9	0,9
2020	344,5	49,0	49,0	0

Table 1. Increase of PV installed power in the last years (data from [8]).

In 2020, the total installed power was 344,5 MW, which was composed by 249,7 MW from self-consumption facilities and 94,8 MW from power plants. That year, the new installed power from self-consumption facilities was approximately 49 MW, and it was distributed among 5.869 facilities, giving an average new installed power of 8,4 kW/facility. On the other hand, there was not any new installed power from power plants. In 2020, the gross electricity production from PV was 484 GWh [8].

Analyzing the total number of PV facilities in 2020 by installed power, the 75,5% of all of them (self-consumption and power plants) were from facilities with installed power lower or equal to 5 kW, which are generally for domestic use. Additionally, the 18,6% were from facilities with installed power between 5 kW and 25 kW (included), the 5,3% were from facilities with installed power between 25 kW and 100 kW (included), and finally the 0,6% were from facilities with more than 100 kW of installed power. Moreover, analyzing the PV installed power in 2020 (which was 344,5 MW) by power range, the 24,9% of that power was from facilities with installed power lower or equal to 5 kW. Additionally, the 17,6% was from facilities with installed power between 5 kW and 25 kW (included), the 33,7% was from facilities with installed power between 25 kW and 100 kW (included), and finally the 23,8% was from facilities with more than 100 kW of installed power [8]. Therefore, at the end of the past decade, the 0,6% of the total amount of PV facilities had more than 100 kW of installed power and they represented the 23,8% of the total installed power in Catalonia.

The distribution of PV facilities throughout the territory of Catalonia is quite regular. The most populated areas are usually the ones with more PV facilities because of the self-consumption. However, the available land out of these areas is occasionally used to implement PV power plants.

Wind energy

Regarding wind energy in Catalonia, in the last years, the growth of installed power is completely stuck. The next table (Table 2) shows the evolution of wind installed power in the last years of the past decade.

Year	Total wind [MW]	New wind [MW]
2014	1.268,7	1,8
2015	1.268,7	0
2016	1.268,7	0
2017	1.268,7	0
2018	1.271,1	2,4
2019	1.271,1	0
2020	1.271,1	0

Table 2. Increase of wind installed power in the last years (data from [8]).

In 2020, there was not any new installed power from wind energy and the total installed power was 1.271,1 MW (this value is referred to total wind energy, including self-consumption, although its contribution is insignificant compared to wind power plants). Concerning the gross electricity production from wind energy, in 2020 this production was 2.637 GWh [8].

The most occupied areas by wind turbines are located in the south of Catalonia. Approximately the 70% of wind turbines are located in the *comarques* of *El Baix Ebre*, *La Terra Alta*, *L'Anoia*, *Les Garrigues* and *La Conca de Barberà*. It is important to notice that the concentration of wind turbines in some of these *comarques* is starting to be really high and a balanced distribution throughout all the territory of Catalonia could be needed at some point.

7. Prospective situation regarding RES

This chapter explains in details a proposal which can lead Catalonia to achieve its objectives in terms of energy transition. This proposal is based on a change in the energetic system model.

An increase of RES weight in final energy consumption can be achieved with the electrification of this final energy consumption. That is to say, if final energy demand is mainly based on electricity demand, the utilization of RES can be profitable. However, the electrification of final energy consumption can't be achieved rapidly because it depends on the demand and not on the production. The electrification of final energy demand in 2019 was 25,1% (approximately only a quarter of final energy consumption was electricity) and it has to be increased in the following years. This electrification process can be understood as economy electrification because it involves all sectors of the society.

The main sectors which need to be electrified urgently due to its huge emissions of greenhouse gases are transport, industry and buildings. The solutions taken in transport sector are related to the implementation of electric mobility and the solutions taken in buildings are mostly related to the implementation of electric heating devices. Regarding the industry, the electrification of industrial processes has to be implemented wherever possible. Obviously, in order to promote all these changes in the society, some rigorous measures must be applied when consuming fossil fuels (for example, every consumer pays the cost of its emissions through taxes) and some other measures must be removed when consuming clean energy (for example, facilitate the use of renewable self-consumption devices instead of preventing it).

Additionally, it is important to also aim the long-term objective to reduce the consumption of final energy. This involves energy savings and also a very efficient use of energy. Energy savings can be achieved through the reduction of consumption of goods and services, the use of new goods and services which require lower energy consumption, the change of old habits for more sustainable habits and also through the circular economy in productive sectors. Energy efficiency can be achieved through the use of high efficiency technologies such as electric vehicles and electric heat pumps. Although these measures must be applied from now and some positive results would appear soon, being realistic, it is difficult to achieve a significant reduction in final energy consumption before 2030 because some time is needed to educate the society on this new way of life. For this reason, in this project, final energy consumption will be assumed as constant during the 2021-2030 decade (taking 2019 as reference value). However, it is thought that energy demand reduction will be significant in the following decades. Then, energy intensity will decrease because energy demand will decrease. Just to remember, energy intensity is a measure of the energy efficiency of an economy and it is defined as the energy demand divided by the GDP (Gross Domestic Product). A high energy efficiency is achieved when a low energy intensity is obtained, because it means that the cost of converting energy into wealth is low.

In the same way that total electricity production increases due to the electrification of final energy demand, the electricity production from RES power plants have to increase because the idea is always to satisfy the demand through RES and not through fossil fuels. Therefore, new RES power plants have to be implemented. By doing this, the contribution of RES in the electricity mix increases and, ultimately, the RES weight in final energy consumption also increases. The RES contribution in total gross electricity production (electricity mix) in 2019 was 16,1% and it has to be greatly increased in the following years. Concretely, the objective is to increase this value to 50% for 2030. It is a huge challenge because Catalonia is late in this matter but this is the way to achieve an electricity mix 100% based on RES for 2050, which is the ultimate goal defined by the energy transition policies in Catalonia.

Therefore, according to policies from Catalonia, the gross electricity production from RES has to be increased to 34.334 GWh for 2030 [11] (this means an increase of 26.701 GWh compared to 2019 production, which was 7.633 GWh). Then, in order to reach a 50% contribution of RES in the electricity mix, the total gross electricity production has to be increased to 68.668 GWh for 2030 (this means an increase of 21.138 GWh compared to 2019 production, which was 47.530 GWh). The difference between the increase of the gross electricity production from RES and the increase of the total gross electricity production is 5.563 GWh, and this represents the gross electricity production from non-renewable power plants (such as fossil fuels power plants) which has to be removed for 2030.

The following table (Table 3) shows the prospective gross electricity production for every renewable energy source according to these policies.

RES	2019 electricity production [GWh]	2030 electricity production [GWh]
Hydro	3.656	4.283
Wind offshore	0	4.100
Wind onshore	3.153	**13.652**
PV self-consumption	294	3.768
PV grounded	158	**7.638**
Others	372	893
TOTAL	7.633	**34.334**

Table 3. Prospective gross electricity production from RES (data from [11]).

As it can be seen in the Table 3, the electricity production from hydro increases compared to 2019, but no additional installed power is strictly needed because with the current installed power is possible to generate such production (it has been higher some years before with the same installed power). Regarding the production from offshore wind, it will be achieved with the implementation of 1.000 MW of installed power (500 MW *Parc Tramuntana* [12] and 500 MW *Parc Gavina*, both already projected) inside *Golf de Roses* in the *comarca* of *L'Alt Empordà*. On the other hand, the production from onshore wind has to increase to 13.652 GWh/year. Regarding the production from PV self-consumption facilities in roofs or urbanized areas, it has to be increased to 3.768 GWh/year. For this purpose, it is necessary the encouragement of self-consumption in the society. Additionally, the production from PV grounded power plants has to increase to 7.638 GWh/year. Finally, the production from other kinds of RES such as renewable urban solid waste, biogas, biomass and solar thermoelectric has to increase to 893 GWh/year.

The resulting electricity mix for 2030 will be composed by 50% of renewable energy sources and 50% of non-renewable energy sources. Regarding the renewable part, the contribution of each source over the total renewable production will be: 12,5% hydro; 51,7% wind; 33,2% solar PV; and 2,6% others. Regarding the non-renewable part, its contribution will be composed mainly by nuclear energy (it is expected that nuclear power plants will be still operating at the end of this decade).

It is worth to remember that the fact of substituting conventional power plants based on fossil fuels for power plants based on RES is not simple. The main characteristic of RES power plants is the intermittency of its production (this represents an important disadvantage in comparison with fossil fuel power plants, which can produce less or more adapting the production to the demand). Then, in order to match production to demand, energy storage systems are needed. According to these policies, it is estimated that it will be necessary approximately 200 MW of new batteries and 1.500 MW of new pumped hydro for 2030 [11].

Thereupon, this project will study the implementation of onshore wind power plants to generate these additional 10.499 GWh/year from onshore wind and the implementation of PV power plants to generate these additional 7.480 GWh/year from solar PV at the end of 2030.

As it could be seen previously, in 2020 there was not any additional installed power from wind and PV power plants. Then, in 2019 the installed power from these two kinds of power plants was the same than in 2020. Furthermore, the data from 2021 is not available at the moment of elaborating this project. Therefore, the starting point for the proposed solutions is the year 2019.

8. Solution development

This chapter proposes solutions to generate 7.480 GWh/year through photovoltaic power plants and 10.499 GWh/year trough wind power plants. The viability of implementing these solutions in the time period of this decade will be evaluated. As the greatest electric generation will come from wind energy, it is explained in first term. Then, in second term, solar energy is explained.

8.1. Wind energy

In order to know where are the best locations to implement wind power plants it is fundamental to know where are the best wind conditions. The Figure 7 shows the mean wind speed at 100 m height above the ground in a map of Catalonia. Notice that mean speed is evaluated at this height because this is the approximated height where common wind turbines are located above the ground.

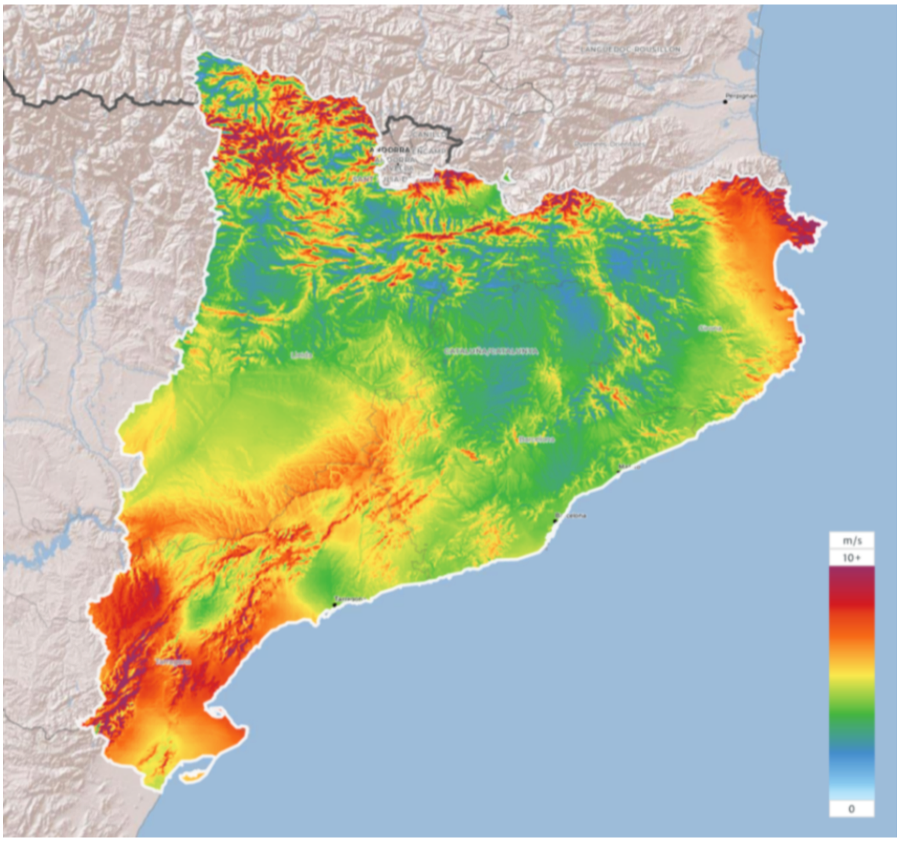

Figure 7. Mean wind speed at 100 m height above the ground in Catalonia [13].

As it can be seen in the previous map, excluding the high mountain locations situated in the very north of Catalonia which present high speeds because of its special mountain conditions, the highest wind speeds are located in the northeast (*comarca* of *L'Alt Empordà*) and in the south part of Catalonia. In addition, the south-central part of Catalonia also presents good conditions. The northeast part is particularly interesting for offshore wind power plants, which are already projected to be implemented during this decade, as it was mentioned in the prospective situation. Then, the best areas to produce electricity through onshore power plants are located in the south and central part of Catalonia.

The *comarques* which have higher potential in terms of wind energy installed power are *Les Garrigues*, *La Conca de Barberà*, *L'Anoia* and *La Ribera d'Ebre*. It is estimated that each one of them could potentially hold more than 1.200 MW of wind installed power, although always under the condition of obtaining a positive Environmental Impact Statement (EIS) [14]. Therefore, these *comarques* will be evaluated to know how much wind installed power is currently implemented and, ultimately, how much more can be implemented. The order chosen when analyzing them and implementing wind turbines has the intention to encourage a proper distribution of wind turbines throughout the territory of Catalonia. Moreover, the estimated potential of each *comarca* mentioned before is actually higher than 1.200 MW, however, it has been fixed in just 1.200 MW to avoid excessive concentrations of wind turbines.

Before starting with the analysis of each comarca and the implementation of wind turbines, it has to be explained the characteristics of the wind turbine model selected and the procedure to calculate the electric generation based on wind data.

The manufacturer of wind turbines chosen is VESTAS because of its worldwide reputation in the wind energy sector. For choosing the model, first, it has been analyzed the installed power of the wind turbines already implemented in similar areas like those studied. Then, it has been concluded that the proper installed power of the wind turbine model selected should be around 2 MW. Finally, after checking the wind turbine models from this manufacturer, it has been decided that the model selected for the study of this project is VESTAS V90 2 MW (Figure 8).

Figure 8. Wind turbine VESTAS V90 2 MW [15].

Regarding the datasheet [15], the nominal power of this wind turbine is 2.000 kW. The cut-in wind speed is 3 m/s, the rated wind speed is 13 m/s and the cut-out wind speed is 25 m/s. The diameter of the rotor is 90 m, which gives a swept area of 6.362 m^2. It has three blades constructed in fiberglass/carbon. Notice that blades can be painted to reduce considerably bird collision. The generator is asynchronous with 690 V voltage and 50 Hz frequency. The tower is conical, constructed in steel and painted for corrosion protection. The hub height is 100 m. Finally, the total weight of a single wind turbine is 328.000 kg.

The Figure 9 shows the power curve of the selected wind turbine, built from the power data provided by the datasheet. As it was mentioned before, the wind turbine starts giving power at wind speeds higher than 3 m/s, and the power increases with the wind speed received till 13 m/s, where the power remains nominal till 25 m/s. For wind speeds higher than 25 m/s, there is no power generation for safety reasons.

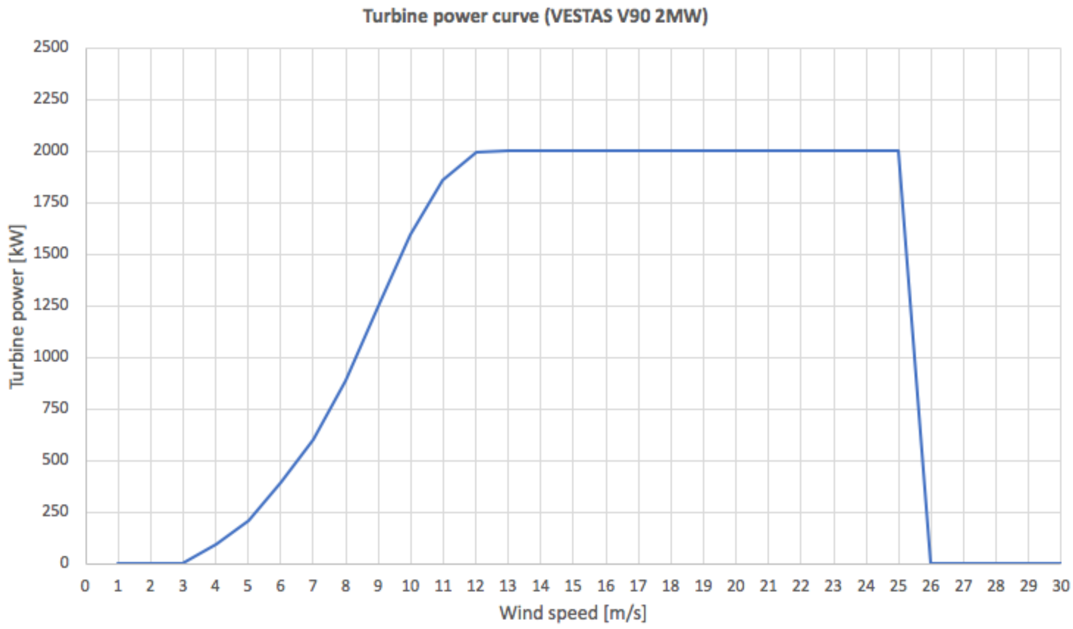

Figure 9. Turbine power curve.

In order to calculate the power generation between 3 and 13 m/s, it has been obtained the power curve expression inside this wind speed interval. This curve expression has been estimated with a sixth degree polynomic trendline, which gives the best adjustment with an R^2 equal to 1. See Figure 10.

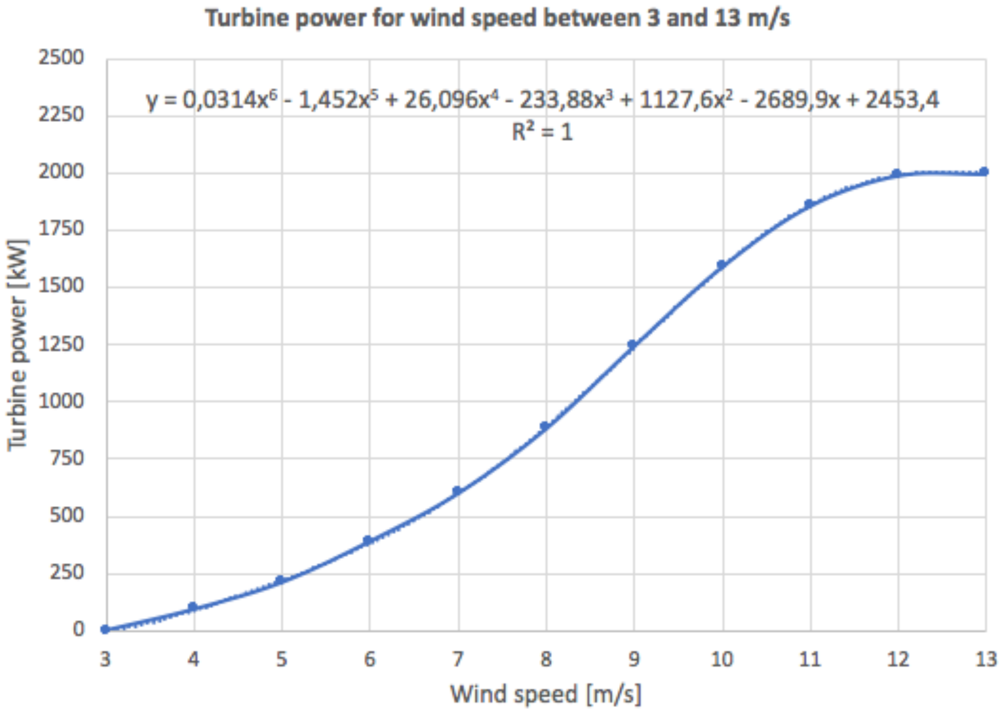

Figure 10. Turbine power curve and expression for wind speed between 3 and 13 m/s.

Now, given any wind velocity, it is possible to calculate the electric power generation. The *Excel* formula created to calculate this is the following one, where A1 is the value of the first wind velocity.

fx= IF(A1<=3; 0; IF(AND(3<A1; A1<13); 0,0314*A1^6 -1,452*A1^5 +26,096*A1^4 -233,88*A1^3 +1127,6*A1^2 -2689,9*A1 +2453,4; IF(AND(13<=A1; A1<=25); 2000; IF(A1>25; 0; 0))))

The wind data has been obtained for every hour of the year. As wind data can substantially change from one year to another, the data has been obtained from a Typical Meteorological Year (TMY), which gives a good representation about the weather in a specific location. This yearly data is built based on historical data collected from more than 10 years. In particular, the database selected is SARAH2 which collects data from 2005 to 2020 [16]. It is important to notice that, as the data comes from a TMY, it is not expected to obtain atypical data (which could happen as a consequence of an occasional big storm, for example). Additionally, it is important to say that only the absolute value of wind speed is taken, and not its direction, because wind turbines orientate themselves automatically.

As the wind speed data collected is only available at 10 m height, and the rotor of the wind turbine is at 100 m height, it has been needed to estimate the wind speed at this height through the wind profile logarithmic formula, which considers the surface roughness [17].

$$v_z = v_{ref} \cdot \frac{\ln\left(\frac{Z}{Z_0}\right)}{\ln\left(\frac{Z_{ref}}{Z_0}\right)}$$

Where:

- V_z [m/s] is the estimated wind speed at the height of Z [m].
- V_{ref} [m/s] is the reference wind speed at the height of Z_{ref} [m].
- Z_0 [m] is the roughness longitude, which represents the surface roughness.

Therefore, from the wind speed collected (V_{ref}) at 10 m height (Z_{ref}), it is obtained the desired wind speed (V_z) at 100 m height (Z), knowing the value of the roughness longitude (Z_0).

Regarding the surface roughness, for every *comarca* analyzed, it has been obtained the wind speeds from a representative point with flat terrain and certain roughness. This point is used as a reference for all the *comarca* and it is assumed that wind speeds are practically the same throughout all the *comarca* in order to simplify calculations. This assumption has been needed to elaborate this project because of the huge number of wind turbines that have to be implemented. However, it is important to say that wind speeds are usually higher in particular locations such as mountain areas. For this reason, the electricity production can be even higher, because wind turbines will be located in places like those or even better. If the scope of observation was smaller, it would be always recommended to obtain the wind speed for the precise location of every wind turbine.

Once explained that, the roughness longitude (Z_0) considered is 0,25. This value is equivalent to normal roughness and it is for natural areas with cultivation, some porous obstacles and small edifications [17].

Now, wind data is prepared for some calculations. First of all, wind power is calculated with the following equation.

$$P_{wind} = \frac{1}{2} \cdot \rho_{air} \cdot A_{swept} \cdot v^3$$

Where:

- P_{wind} [W] is the wind power.
- ρ_{air} [kg/m^3] is the density of air, which is constant and equal to 1,225 kg/m^3.
- A_{swept} [m^2] is the swept area of the wind turbine, which is 6.362 m^2.
- V [m/s] is the wind speed which moves the wind turbine.

The wind power (P_{wind}) is calculated for every hour of the year. Then, if every P_{wind} is multiplied per 1 hour, the wind energy is obtained. And finally, the sum of all the wind energy obtained for every hour of the year gives the theoretical annual kinetic energy of the wind.

However, not all this theoretical annual kinetic energy is actually available. According to Betz's law, only the 59,3% of wind power can be captured (Betz's limit) as it is shown in the following equation.

$$P_{max} = \frac{16}{27} \cdot P_{wind}$$

Where:

- P_{max} [W] is the maximum wind power capturable according to Betz's law.
- P_{wind} [W] is the wind power calculated previously.

In the same way, multiplying the maximum power of each hour per 1 hour and making the sum of all of them, the annual available wind energy is obtained.

8.1.1. Les Garrigues

The *comarca* of *Les Garrigues* (Lleida) has a current wind installed power of 173,5 MW [18] and it is thought that it can be at least 1.200 MW. Therefore, it is still possible to implement 1.026,5 MW of wind installed power. Currently, there are 87 wind turbines in total, giving an average installed power per wind turbine of 1,99 MW.

The wind data has been obtained from a representative point near the municipality of *Les Borgues Blanques*. The Figure 11 shows the wind chronological chart for this location throughout the year. The maximum value of wind speed is 25,99 m/s, the average wind speed is 6,49 m/s and the standard deviation is 3,98 m/s.

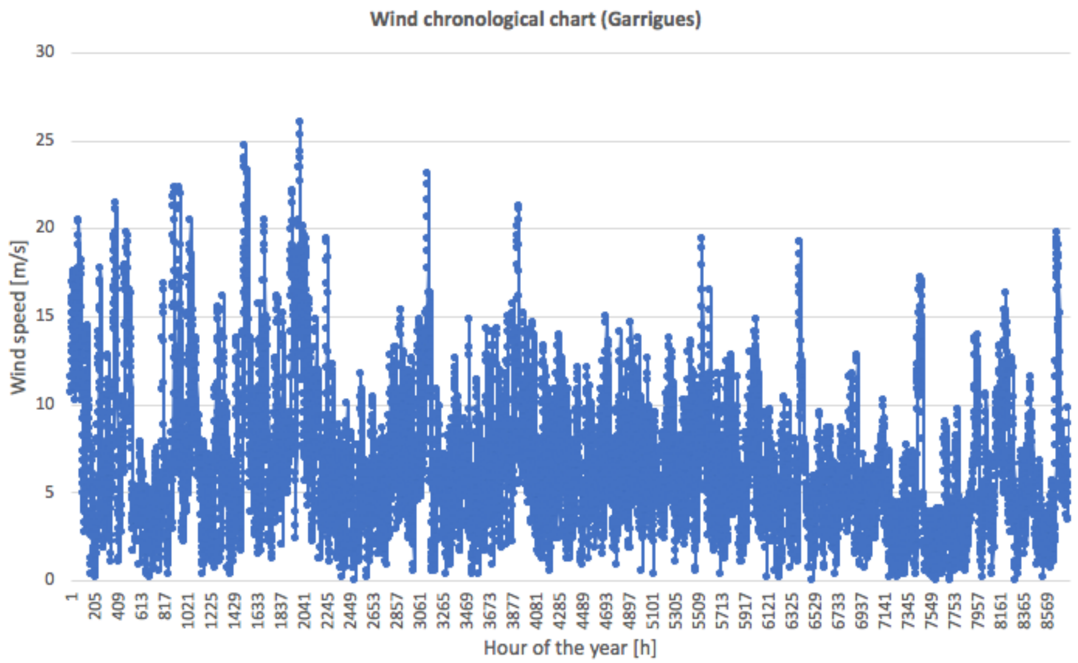

Figure 11. Wind chronological chart (*Garrigues*).

If wind speeds are sorted from the highest one to the lowest one, the result is the wind duration curve, which gives an idea of how many hours per year the wind speed is above one certain velocity. See Figure 12.

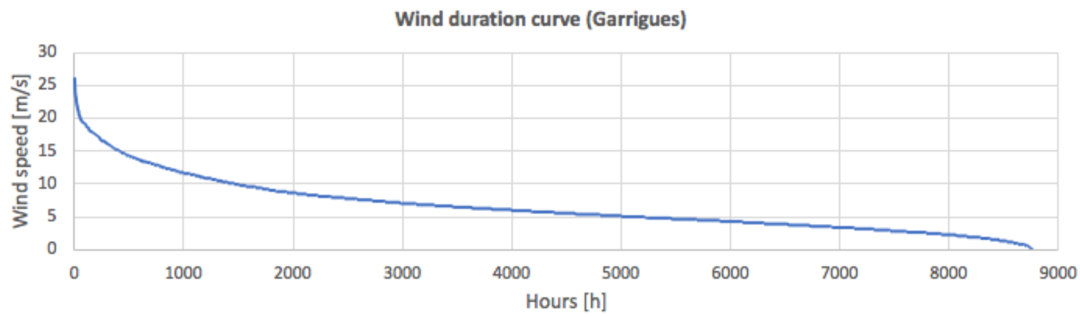

Figure 12. Wind duration curve (*Garrigues*).

Regarding the wind energy calculations, for one wind turbine, the theoretical annual kinetic energy of the wind is 22.529,89 MWh/year and the annual available wind energy (according to Betz's law) is 13.360,23 MWh/year.

Then, the Figure 13 shows the turbine power chronological chart for this location throughout the year.

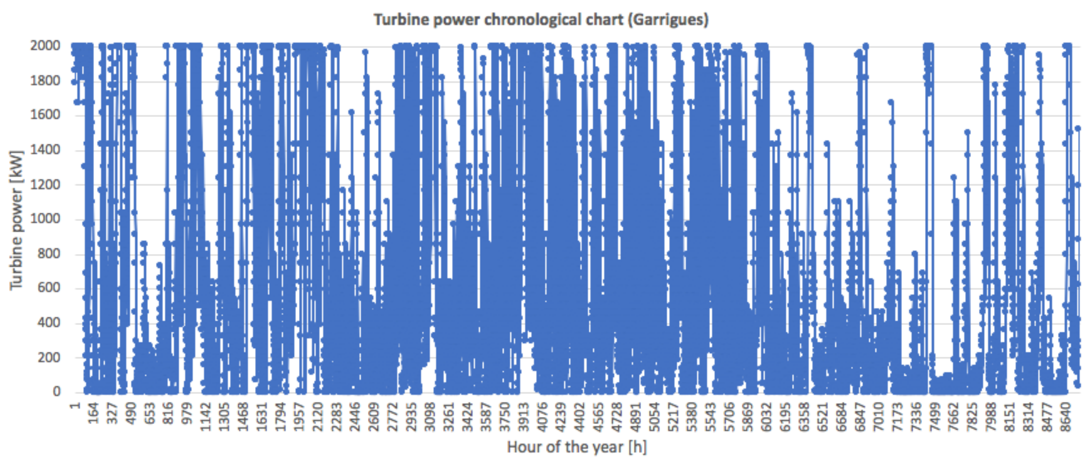

Figure 13. Turbine power chronological chart (*Garrigues*).

If turbine power values are sorted from the highest one to the lowest one, the result is the turbine power duration curve (Figure 14), which gives an idea of how many hours per year the turbine is working above one certain turbine power. In this location, the wind turbine is working 721 h/year at maximum load (8,23% of the year), 5.190 h/year at less than half maximum load (59,25% of the year) and 7.305 h/year in total (which means a yearly time utilization of 83,39%).

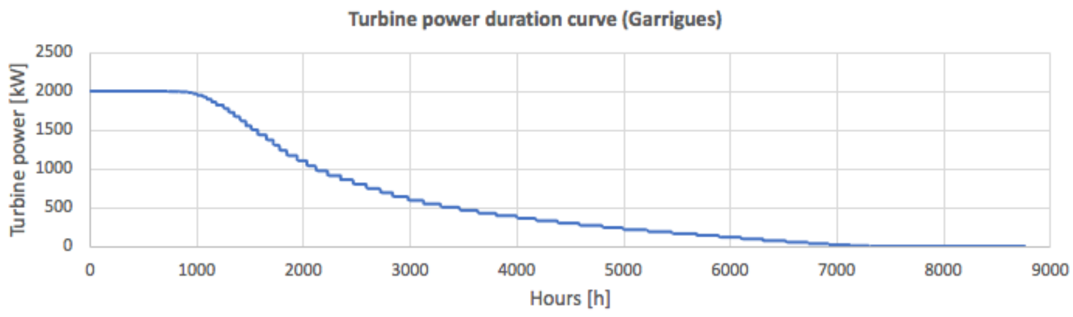

Figure 14. Turbine power duration curve (*Garrigues*).

Therefore, regarding the electric energy produced, for one wind turbine (2 MW of installed power), the annual electricity production is 5.366,20 MWh/year. Consequently, with the implementation of 513 wind turbines (1.026 MW of total installed power), the total annual electricity production would be 2.752,86 GWh/year.

The capacity factor in this location would be 30,63%, which means the energy utilization of the wind turbine. That is to say, it is the actual amount of electric energy produced divided by the maximum amount of electric energy which could be produced if the wind turbine was working at nominal power every hour of the year.

With this solution, there would be 600 wind turbines in total (87 already implemented and 513 projected to be implemented). Therefore, the wind turbines density in the territory of this *comarca* would be 0,75 wind turbines per square kilometer (600 wind turbines divided by 797,7 km^2). It is a high density but feasible.

8.1.2. La Conca de Barberà

The *comarca* of *La Conca de Barberà* (Tarragona) has a current wind installed power of 231,5 MW [18] and it is thought that it can be at least 1.200 MW. Therefore, it is still possible to implement 968,5 MW of new wind installed power. Currently, there are 126 wind turbines in total, giving an average installed power per wind turbine of 1,84 MW.

The wind data has been obtained from a representative point near the municipality of *Montblanc*. The Figure 15 shows the wind chronological chart for this location throughout the year. The maximum value of wind speed is 29,84 m/s, the average wind speed is 6,21 m/s and the standard deviation is 4,30 m/s.

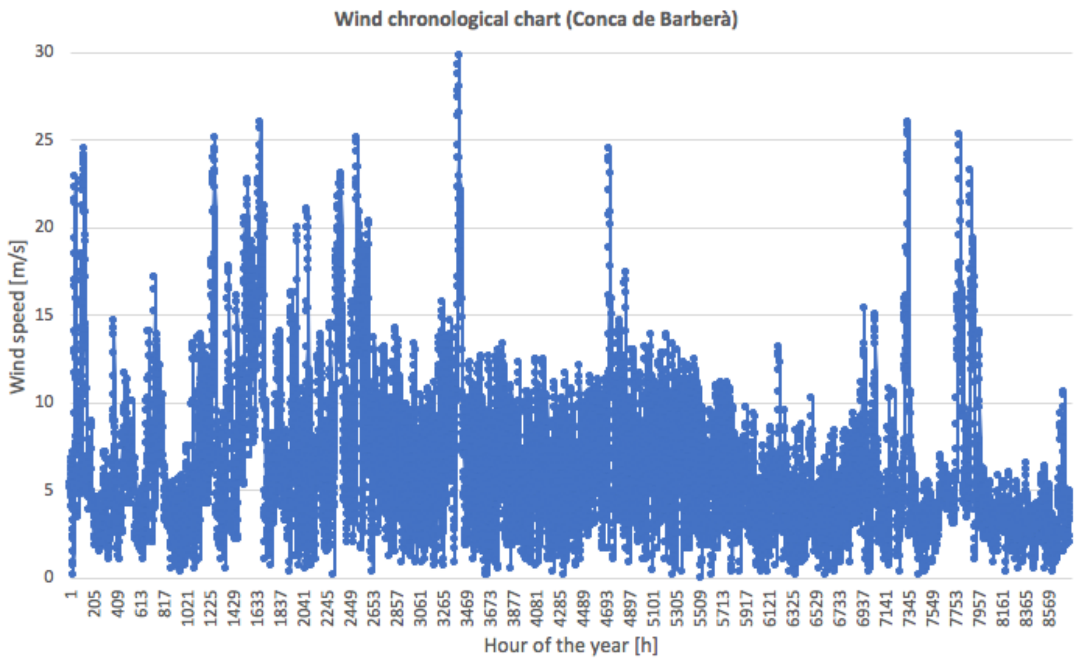

Figure 15. Wind chronological chart (*Conca de Barberà*).

Then, wind speeds are sorted from the highest one to the lowest one, and the wind duration curve is obtained (Figure 16).

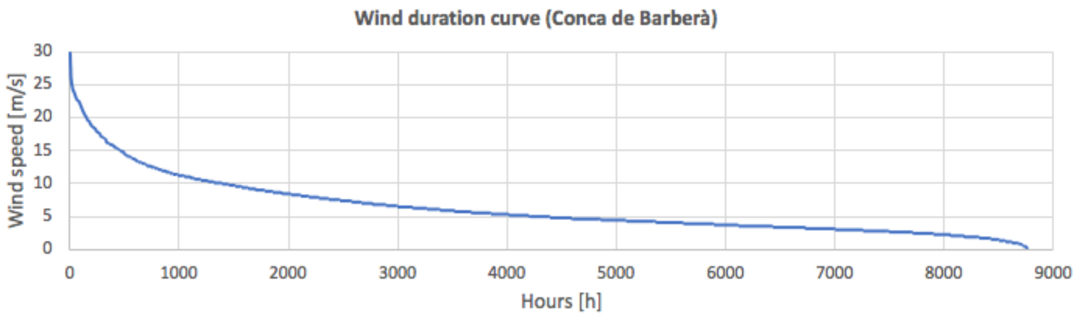

Figure 16. Wind duration curve (*Conca de Barberà*).

Regarding the wind energy calculations, for one wind turbine, the theoretical annual kinetic energy of the wind is 24.516,75 MWh/year and the annual available wind energy (according to Betz's law) is 14.538,43 MWh/year.

Then, the Figure 17 shows the turbine power chronological chart for this location throughout the year.

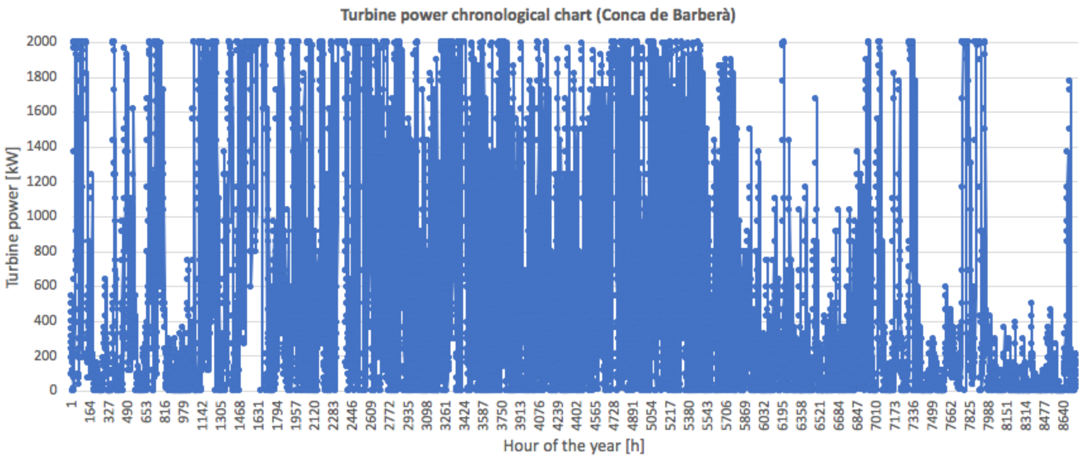

Figure 17. Turbine power chronological chart (*Conca de Barberà*).

Then, turbine power values are sorted from the highest one to the lowest one, and the turbine power duration curve is obtained (Figure 18). In this location, the wind turbine is working 665 h/year at maximum load (7,59% of the year), 4.980 h/year at less than half maximum load (56,85% of the year) and 6.986 h/year in total (which means a yearly time utilization of 79,75%).

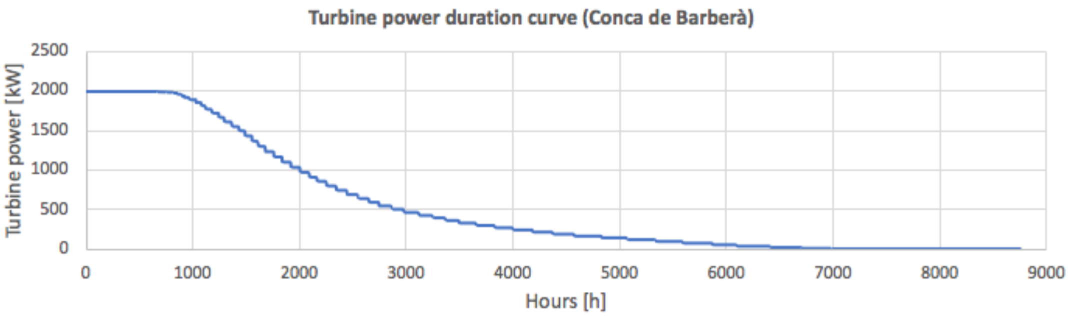

Figure 18. Turbine power duration curve (*Conca de Barberà*).

Therefore, regarding the electric energy produced, for one wind turbine (2 MW of installed power), the annual electricity production is 4.803,17 MWh/year. Consequently, with the implementation of 484 wind turbines (968 MW of total installed power), the total annual electricity production would be 2.324,73 GWh/year.

The capacity factor in this location would be 27,42%, which means the energy utilization of the wind turbine.

With this solution there would be 610 wind turbines in total (126 already implemented and 484 projected to be implemented). Therefore, the wind turbines density in the territory of this *comarca* would be 0,94 wind turbines per square kilometer (610 wind turbines divided by 650,2 km^2). It is a quite high density but feasible.

8.1.3. L'Anoia

The *comarca* of *L'Anoia* (Barcelona) has a current wind installed power of 204,85 MW [18] and it is thought that it can be at least 1.200 MW. Therefore, it is still possible to implement 995,15 MW of wind installed power. Currently, there are 121 wind turbines in total, giving an average installed power per wind turbine of 1,69 MW.

The wind data has been obtained from a representative point near the municipality of *Igualada*. The Figure 19 shows the wind chronological chart for this location throughout the year. The maximum value of wind speed is 23,82 m/s, the average wind speed is 5,90 m/s and the standard deviation is 3,61 m/s.

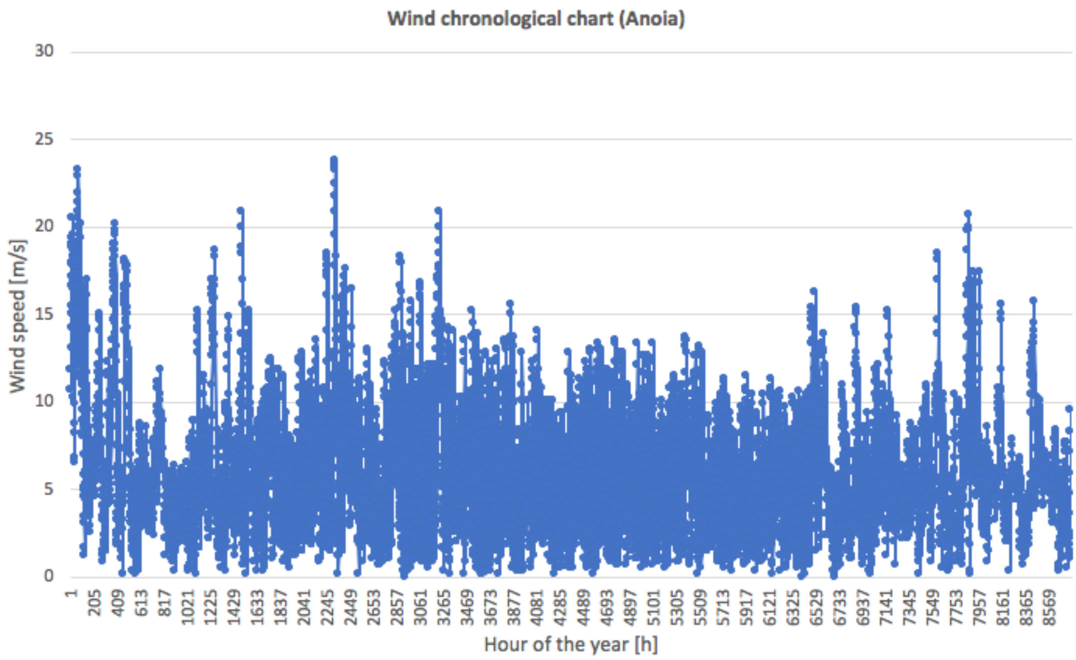

Figure 19. Wind chronological chart (*Anoia*).

Then, wind speeds are sorted from the highest one to the lowest one, and the wind duration curve is obtained (Figure 20).

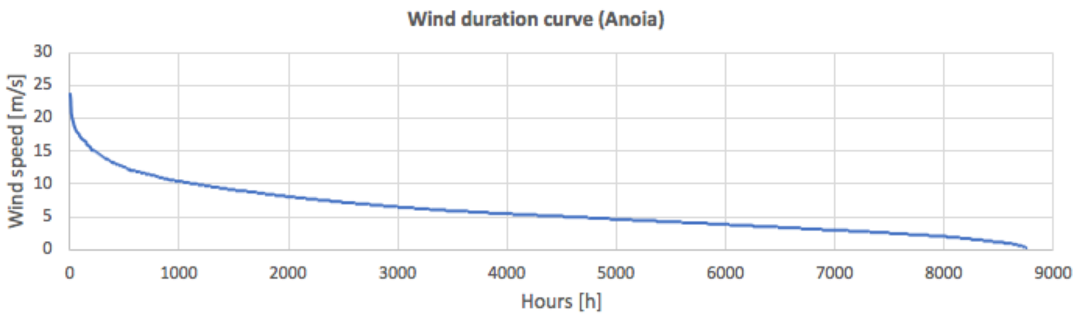

Figure 20. Wind duration curve (*Anoia*).

Regarding the wind energy calculations, for one wind turbine, the theoretical annual kinetic energy of the wind is 16.731,59 MWh/year and the annual available wind energy (according to Betz's law) is 9.921,83 MWh/year.

Then, the Figure 21 shows the turbine power chronological chart for this location throughout the year.

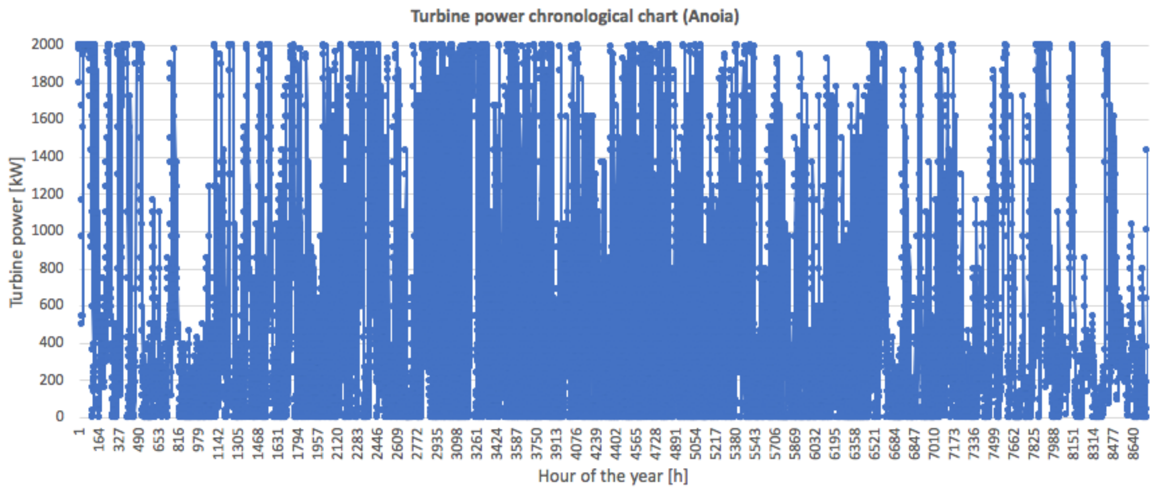

Figure 21. Turbine power chronological chart (*Anoia*).

Then, turbine power values are sorted from the highest one to the lowest one, and the turbine power duration curve is obtained (Figure 22). In this location, the wind turbine is working 442 h/year at maximum load (5,05% of the year), 5.010 h/year at less than half maximum load (57,19% of the year) and 6.885 h/year in total (which means a yearly time utilization of 78,60%).

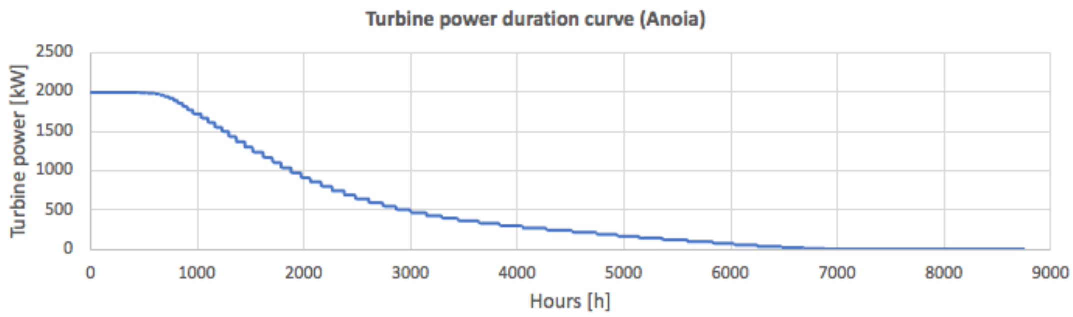

Figure 22. Turbine power duration curve (*Anoia*).

Therefore, regarding the electric energy produced, for one wind turbine (2 MW of installed power), the annual electricity production is 4.665,79 MWh/year. Consequently, with the implementation of 497 wind turbines (994 MW of total installed power), the total annual electricity production would be 2.318,90 GWh/year.

The capacity factor in this location would be 26,63%, which means the energy utilization of the wind turbine.

With this solution there would be 618 wind turbines in total (121 already implemented and 497 projected to be implemented). Therefore, the wind turbines density in the territory of this *comarca* would be 0,71 wind turbines per square kilometer (618 wind turbines divided by 866,3 km^2). It is a high density but feasible.

8.1.4. La Ribera d'Ebre

The *comarca* of *La Ribera d'Ebre* (Tarragona) has a current wind installed power of 51,71 MW [18] and it is thought that it can be at least 1.200 MW. Therefore, it is still possible to implement 1.148,29 MW of wind installed power. Currently, there are 25 wind turbines in total, giving an average installed power per wind turbine of 2,07 MW.

The wind data has been obtained from a representative point near the municipality of *Móra d'Ebre*. The Figure 23 shows the wind chronological chart for this location throughout the year. The maximum value of wind speed is 27,64 m/s, the average wind speed is 7,92 m/s and the standard deviation is 5,14 m/s.

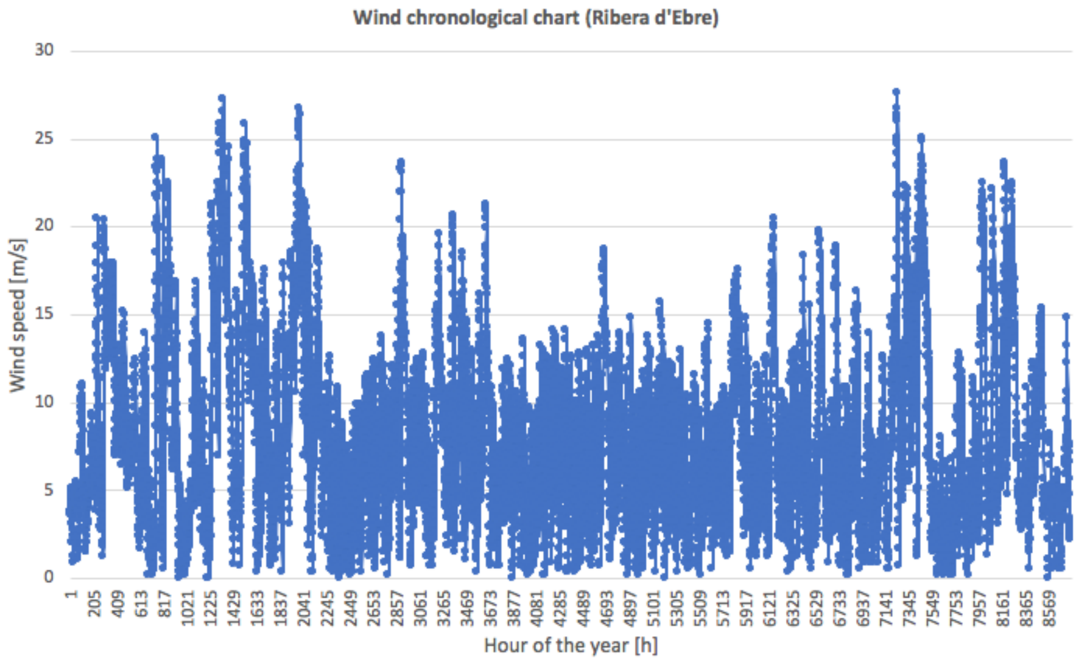

Figure 23. Wind chronological chart (*Ribera d'Ebre*).

Then, wind speeds are sorted from the highest one to the lowest one, and the wind duration curve is obtained (Figure 24).

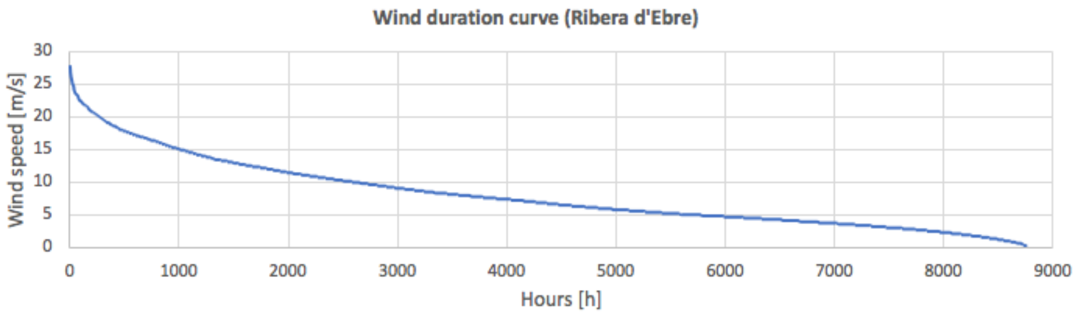

Figure 24. Wind duration curve (*Ribera d'Ebre*).

Regarding the wind energy calculations, for one wind turbine, the theoretical annual kinetic energy of the wind is 42.862,94 MWh/year and the annual available wind energy (according to Betz's law) is 25.417,72 MWh/year.

Then, the Figure 25 shows the turbine power chronological chart for this location throughout the year.

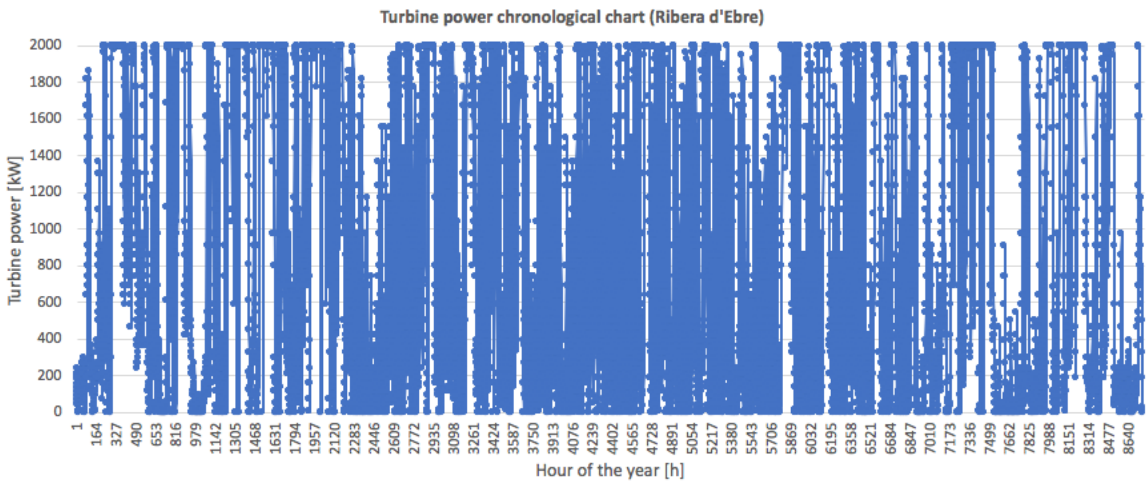

Figure 25. Turbine power chronological chart (*Ribera d'Ebre*).

Then, turbine power values are sorted from the highest one to the lowest one, and the turbine power duration curve is obtained (Figure 26). In this location, the wind turbine is working 1.467 h/year at maximum load (16,75% of the year), 4.139 h/year at less than half maximum load (47,25% of the year) and 7.450 h/year in total (which means a yearly time utilization of 85,05%).

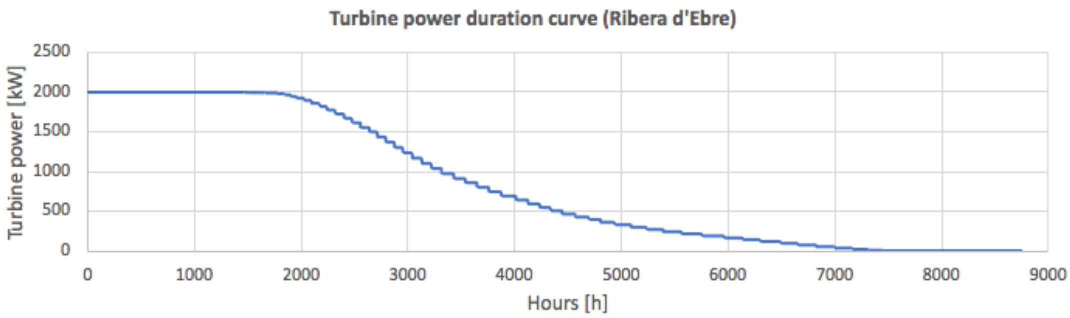

Figure 26. Turbine power duration curve (*Ribera d'Ebre*).

Therefore, regarding the electric energy produced, for one wind turbine (2 MW of installed power), the annual electricity production is 7.346,37 MWh/year. Consequently, with the implementation of 423 wind turbines (846 MW of total installed power), the total annual electricity production would be 3.107,51 GWh/year.

The capacity factor in this location would be 41,93%, which means the energy utilization of the wind turbine.

With this solution there would be 448 wind turbines in total (25 already implemented and 423 projected to be implemented). Therefore, the wind turbines density in the territory of this *comarca* would be 0,54 wind turbines per square kilometer (448 wind turbines divided by 827,3 km^2). It is a normal density and completely feasible.

8.2. Photovoltaic solar energy

In the same way, in order to know where are the best locations to implement PV power plants it is fundamental to know where are the best solar conditions. Solar irradiation describes the energy per unit area received from the sun, and it can be given in different forms. Firstly, it can be given as Direct Normal Irradiation which is the perpendicular direct beam measured at the surface of the Earth. Also, it can be given as Diffuse Horizontal Irradiation which is the diffused sky irradiation that has been scattered by the atmosphere and measured at the surface of the Earth. Then, there is the Global Horizontal Irradiation (GHI) which represents the global irradiation received from the sun on the horizontal surface of the Earth and it considers both parts of solar irradiation (direct and diffuse). Therefore, GHI is the measurement typically used to determine locations where implement PV power plants.

The Figure 27 shows the daily mean GHI in a map of Catalonia. It has to be said that Catalonia has such a good solar irradiation, especially in the south and central part. The north part receives slightly less irradiation because it is located farther from the equator and also because of some mountain conditions. Anyway, the southern areas of Europe receive high values of solar irradiation and Catalonia is rich in this source. Then, it makes all the sense to take profit of that and encourage the production of electricity by means of solar energy.

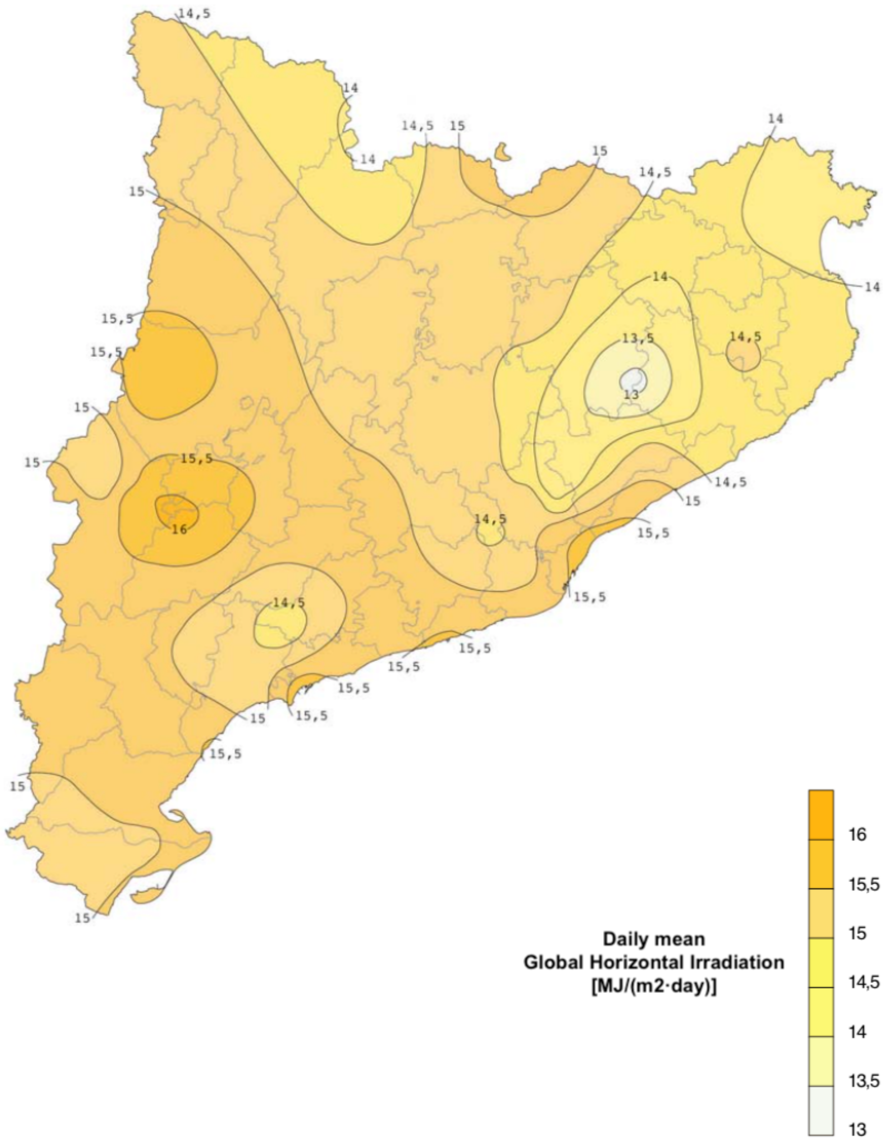

Figure 27. Hill chart of daily mean Global Horizontal Irradiation in Catalonia [19].

The *comarques* which have higher potential in terms of available land for grounded photovoltaic power plants are *La Noguera* and *La Segarra*. Each one of them could potentially hold more than 2.000 MW of nominal power. Additionally, the *comarques* of *El Segrià*, *L'Urgell* and *El Solsonès* have also such a good potential. It is estimated that each one of them could potentially hold between 1.000 and 1.500 MW of nominal power. These estimations have considered restrictions such as the use of land, slopes, orientations and environmental compatibility [14]. Because of its availability and high solar irradiation, these five *comarques* are the ones evaluated.

In order to avoid excessive concentrations of PV modules, the potential nominal power has been initially fixed in 2.000 MW each one for *La Noguera* and *La Segarra*, and 1.250 MW each one for *El Segrià*, *L'Urgell* and *El Solsonès*. The *comarques* with higher potential will be the first ones to be filled, because it is thought that it will be easier to implement PV power plants there because of its high land availability. Moreover, notice that the potential has been given in terms of nominal power, which is referred to the inverter power (power delivered by the electronic device which transforms the direct current from PV modules to alternating current suitable for general consumption). Generally, nominal power is the parameter which limits the electricity production because it is not possible to produce more electricity than what the inverter can convert. Therefore, photovoltaic facilities usually have a peak power (installed power) higher than its nominal power, trying to cover all the capacity of the inverter during the maximum amount of time. The peak power of a PV module is defined as the maximum power that can be produced in Standard Test Conditions (solar irradiance 1.000 W/m^2, cell temperature 25 ºC and air mass 1,5). Once explained that, the scale factor can be presented as the peak power divided by the nominal power.

$$Scale\ Factor = \frac{P_{peak}}{P_{nominal}}$$

Generally, the scale factor is between 1 and 1,3. If it is too high, the inverter could not convert all the power received from the PV modules. On the other hand, if it is too low, the cost of the inverter would rise significantly. Actually, the scale factor depends on the latitude of the location where the PV modules are implemented. For example, in locations further from the equator where solar irradiation is not really high, scale factors can be high because the power delivered by the PV modules is low. And, in locations near the equator where solar irradiation is really high, scale factors should be close to 1 in order to take profit of all the power delivered by the PV modules. For the case studied, the scale factor considered is 1,15. Then, according to the previous expression, the potential implementation of PV grounded power plants is 2.300 MWp each one for *La Noguera* and *La Segarra*, and 1.437,5 MWp each one for *El Segrià*, *L'Urgell* and *El Solsonès*.

The criteria chosen to decide the number of PV modules implemented in each *comarca* is the following one. Firstly, it has been decided to leave a margin equal or higher than 500 MWp in each *comarca* to avoid exhausting all the potential and, definitely, to leave certain flexibility for future implementations. Secondly, it has been decided that the area occupied by the PV modules in every *comarca* does not have to represent more than 2% of the area of the *comarca* with land slopes lower than 20% (it has been taken the area with slopes lower than 20% [20] because this is considered the useful area to implement grounded solar parks, that is to say, the implementation of grounded solar parks in places where the slope is very steep it is not feasible at all because it may cause erosion in the land and stability problems in the structures that sustain the PV modules). In order to calculate the area occupied by the PV modules, previously, it has to be calculated the density of PV modules per unit of area occupied (Wp/m^2). Then, dividing the total peak power implemented by the density of PV modules, the total area occupied is obtained.

All the PV modules are fixed, grounded, tilted and oriented to the south (this orientation guarantees the reception of the maximum solar irradiation through the day in the locations studied, and consecutively, the maximum electricity production). In order to calculate the density of PV modules, it is needed to calculate before the occupation ratio which gives a relation between the area of the PV modules (module area that produces energy) and the area of the land occupied by them. The occupation ratio calculation considers the necessary distance between module strings to avoid shading between them. It is fundamental to consider this distance because otherwise they would produce shades and its disposition would not be optimal at all. In addition, as the land itself has always certain slope, the inclination of the modules in relation to the ground will be slightly different in every case in order to be adapted to the ground and reach the desired optimal tilt angle. This means that depending on the land slope the modules will have more or less inclination. For estimating the occupation ratio, it has been assumed an inclination of 30º in relation to the ground. Notice that the optimal tilt angle for the five *comarques* considered is around 37º, which guarantees the maximum perpendicularity of the solar beams in relation to the module surface throughout all months of the year (because they are fixed and its tilt angle is the same all the year).

As the width of the module is the same than the width of the ground area occupied, the occupation ratio can be calculated considering only one dimension, that is to say, dividing the longitude of the module by the longitude between the beginning of one module string and the beginning of the following one. The Figure 28 shows the disposal of the module strings just explained, with the necessary distance between module strings (*d*) indicated. In addition, the figure shows the height of the module string (*h*), the longitude of the module (*L*) and the inclination of the module in relation to the ground.

Figure 28. Disposal of PV modules to avoid shading.

The distance between strings (*d*) is formulated as the following form [21]:

$$d = \frac{h}{\tan\left(61^{\circ} - latitude\right)}$$

Then, the expression of the occupation ratio is:

$$Occupation\ ratio = \frac{\frac{h}{\sin\left(inclination\right)}}{\frac{h}{\tan\left(inclination\right)} + d}$$

As it can be seen, the value of the height of the module string (*h*) is not needed and the final expression to calculate the occupation ratio is:

$$Occupation\ ratio = \frac{\frac{1}{\sin(inclination)}}{\frac{1}{\tan(inclination)} + \frac{1}{\tan(61º - latitude)}}$$

Finally, knowing the inclination which has been taken in 30º and the latitude where PV modules are implemented which is approximately 41,8º (obviously it is different for every location but, as they are really close each other, it is practically the same and it does not affect the distance between strings), the occupation ratio obtained is 0,43. This means that 0,43 m^2 of PV modules surface can be implemented per 1 m^2 of available land.

Now, with the occupation ratio estimated, it is possible to calculate the density of PV modules (Wp/m^2 land occupied) multiplying the occupation ratio estimated before (m^2 module surface/m^2 land occupied) and the peak power per unit of surface area of the PV module (Wp/m^2 module surface). The last parameter described depends on the PV module characteristics. In advance, the model selected for this study has a peak power of 365 Wp and a surface area of 1,94 m^2 (1.960 mm x 991 mm). Then, multiplying 0,43 m^2 module surface/m^2 land occupied and 365 Wp/1,94 m^2 module surface, the density of PV modules per unit of area obtained is 80,8 Wp/m^2 land occupied. It has to be said that the density of PV modules obtained is quite good because of the high efficiency of the PV module model selected. If the model selected had lower efficiency, the parameter Wp/m^2 module surface would be lower (because it would have less peak power per unit of module surface area), the density would be lower and, definitely, the land occupied would be greater (because it would be needed more land to produce the same amount of energy).

The model of the PV module has been selected from the manufacturer JA SOLAR, which is one of the most important manufacturers in the PV solar energy sector. In order to select properly a model for large-scale electricity production purposes, it has been analyzed some of the current PV power plants near the locations studied, and it has been concluded that the peak power should be around 350 Wp/module and, additionally, that it should be monocrystalline (higher efficiency than polycrystalline). Then, it has been decided that the model selected is JA SOLAR JAM72S01 365/PR (365 Wp and monocrystalline). See Figure 29.

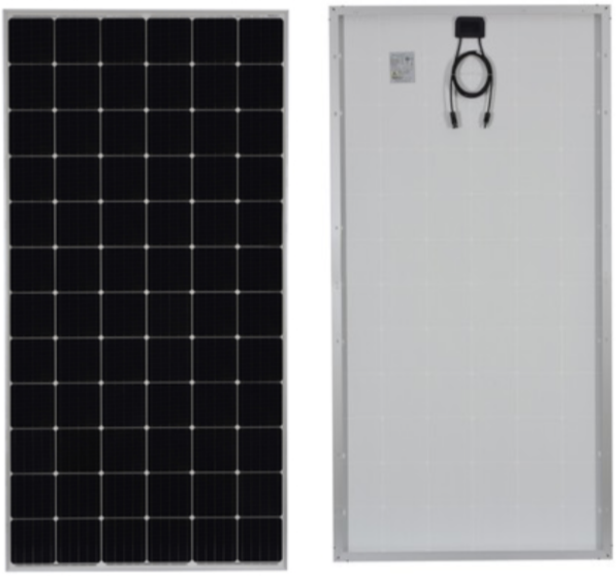

Figure 29. PV module JA SOLAR JAM72S01 365/PR [22].

Regarding the datasheet [22], the peak power is 365 Wp and its dimensions are 1.960 mm x 991 mm x 40 mm. Therefore, the module efficiency is 18,8%. Additionally, the temperature coefficient of power is -0,38%/ºC. Furthermore, the NOCT (Nominal Operating Cell Temperature) is 45ºC. As it can be seen, the module has a total number of 72 monocrystalline cells (6x12). The module weight is 22 kg.

Some of these PV module characteristics will be used afterwards to analyze the necessary implementation in each *comarca* studied. The procedure used to calculate the electric generation based on solar data is explained next.

Although GHI gives an idea of how much solar irradiation receives a particular surface on Earth, the solar irradiation received on a PV module surface will be higher because of its tilted position in relation to the ground. The tilt angle depends on the latitude of the location where they are implemented. As the locations studied are near each other, the optimal tilt angle is practically the same (around 37º). Therefore, the Global Tilted Irradiation is actually the variable used for calculating the electricity production of PV modules. Additionally, in this calculation it has been considered the air temperature variable because, as it also happens with solar irradiation, it has influence on the cell temperature and, definitely, it affects the PV module efficiency.

The solar data (Global Tilted Irradiance and air temperature) has been obtained for every hour of the year from the database SARAH2 and the year studied is 2019 [16].

First of all, the cell temperature of the PV module is calculated with the NOCT (Nominal Operating Cell Temperature) expression.

$$T_{PV} = T_{air} + \frac{NOCT - 20\ ºC}{800\ W/m^2} \cdot G_{glob,PVsurface}$$

Where:

- T_{PV} [ºC] is the cell temperature.
- T_{air} [ºC] is the air temperature.
- $NOCT$ [ºC] is the Nominal Operating Cell Temperature (temperature of the PV module at certain conditions: solar irradiance 800 W/m^2, air temperature 20ºC and wind speed 1 m/s). It is constant and equal to 45ºC.
- $G_{glob,PVsurface}$ [W/m^2] is the Global Tilted Irradiance.

Then, the real efficiency of the PV module is calculated with the following expression.

$$\eta_{PV} = \eta_{STC} \cdot [1 - \beta_p \cdot (T_{PV} - 25\ ºC)]$$

Where:

- η_{PV} is the real efficiency of the PV module.
- η_{STC} is the efficiency of the PV module at Standard Test Conditions (solar irradiance 1.000 W/m^2, cell temperature 25ºC and air mass 1,5). It is constant and equal to 18,8%.
- β_p is the temperature coefficient of power of the PV module, which is constant and equal to 0,38%/ºC.
- T_{PV} [ºC] is the cell temperature calculated previously.

Finally, the power of the PV module is calculated with the following expression.

$$P_{PV} = G_{glob,PVsurface} \cdot A \cdot \eta_{PV}$$

Where:

- P_{PV} [W] is the power of the PV module.
- $G_{glob,PVsurface}$ [W/m^2] is the Global Tilted Irradiance.
- A [m^2] is the surface area of the PV module, which is constant and equal to 1,94236 m^2.
- η_{PV} is the real efficiency of the PV module calculated previously.

Therefore, the PV module power (P_{PV}) is calculated for every hour of the year. Then, if every P_{PV} is multiplied per 1 hour, the electric energy produced is obtained. And finally, the sum of all the electric energy delivered by the PV module for every hour of the year gives the total annual electricity produced.

The system losses (such as inverter losses and cable losses) have to be considered in order to calculate the amount of electricity actually dumped on the grid. Consequently, the electricity delivered to the grid is lower than the electricity produced by the PV modules. The system efficiency has been estimated in 86%.

Then, the annual electricity produced by a single PV module is multiplied per the system efficiency (86%) and the annual electricity delivered to the grid from a single PV module is obtained.

8.2.1. La Noguera

The *comarca* of *La Noguera* (Lleida) has a potential of 2.300 MWp in terms of photovoltaic power plants. Therefore, considering a peak power of 365 Wp/module, it is possible to hold approximately 6.300.000 modules.

The solar data has been obtained from a representative point near the municipality of *Balaguer*. For this location, the PV modules are oriented to the south with an optimal tilt angle of 37º. The Figure 30 shows the sum of Global Tilted Irradiation received for every month of the year 2019.

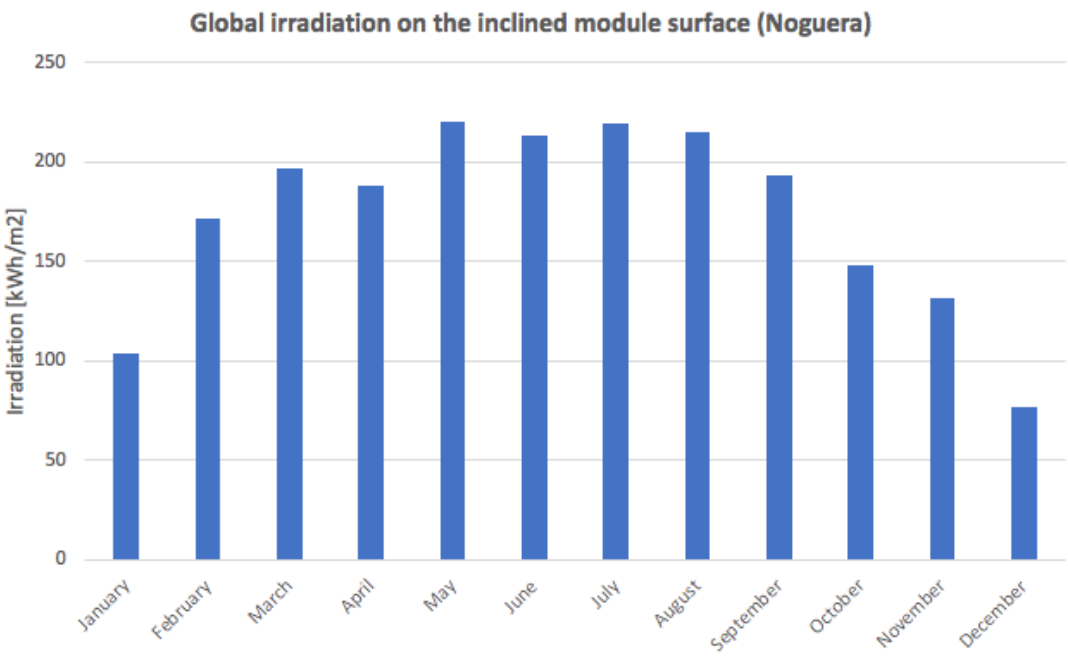

Figure 30. Global irradiation on the inclined module surface (*Noguera*).

As it can be seen, the different seasons of the year have influence on the amount of irradiation received. Nevertheless, excluding the first month and the last three months of the year, the irradiation received throughout the year is quite regular. The total amount of Global Tilted Irradiation received in 2019 was 2.079,03 kWh/m^2.

Then, based on the previous data, the electric energy produced by a single PV module is calculated, giving a total electric energy produced of 704,58 kWh/year. Following this, the electricity delivered to the grid from a single PV module is calculated (see Figure 31).

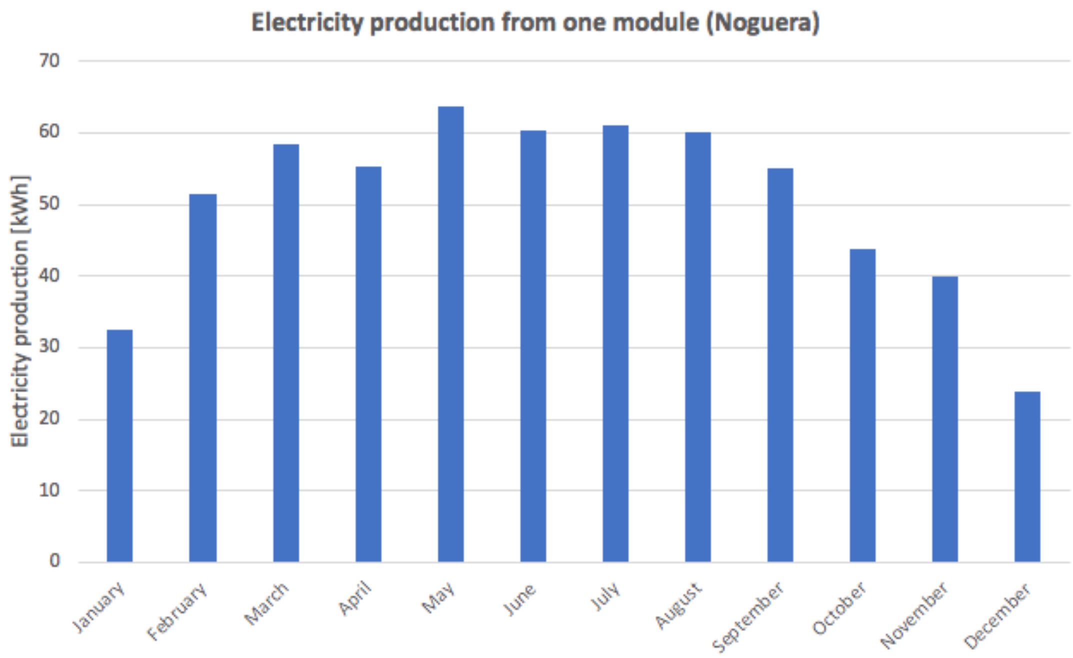

Figure 31. Electricity production delivered to the grid from one module (*Noguera*).

The annual electricity production delivered to the grid from a single module is 605,94 kWh/year. The capacity factor in this location would be 22,04%, which means the energy utilization of the PV module. That is to say, it is the actual amount of electric energy produced divided by the maximum amount of electric energy which could be produced if the PV module was working at maximum power every hour of the year.

Regarding the number of modules to implement, according to the chosen criteria (peak power margin higher than 500 MWp and percentage of land occupied lower than 2% of the useful land in the *comarca*), the implementation is 4.200.000 modules (1.533 MWp in total), which would produce 2.544,93 GWh/year.

All these modules would take 18,97 km^2 of land, which represent the 1,06% of the total land (1.784,1 km^2) and the 1,95% of the useful land (slope lower than 20%, which is 973,3 km^2) in the *comarca*.

8.2.2. La Segarra

The *comarca* of *La Segarra* (Lleida) has a potential of 2.300 MWp in terms of photovoltaic power plants. Therefore, it is possible to hold approximately 6.300.000 modules.

The solar data has been obtained from a representative point near the municipality of *Cervera*. For this location, the PV modules are oriented to the south with an optimal tilt angle of 37º. The Figure 32 shows the sum of Global Tilted Irradiation received for every month of the year 2019.

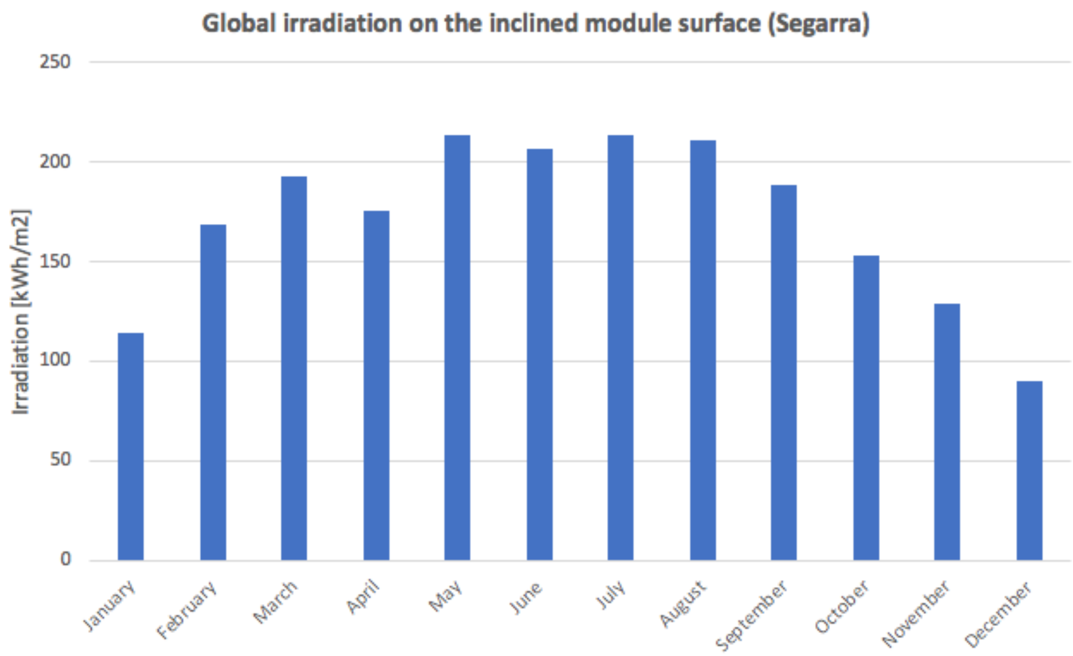

Figure 32. Global irradiation on the inclined module surface (*Segarra*).

In the same way, the different seasons of the year have influence on the irradiation received. The total amount of Global Tilted Irradiation received in 2019 was 2.058,33 kWh/m^2.

Then, based on the previous data, the electric energy produced by a single PV module is calculated, giving a total electric energy produced of 704,64 kWh/year. Following this, the electricity delivered to the grid from a single PV module is calculated (see Figure 33).

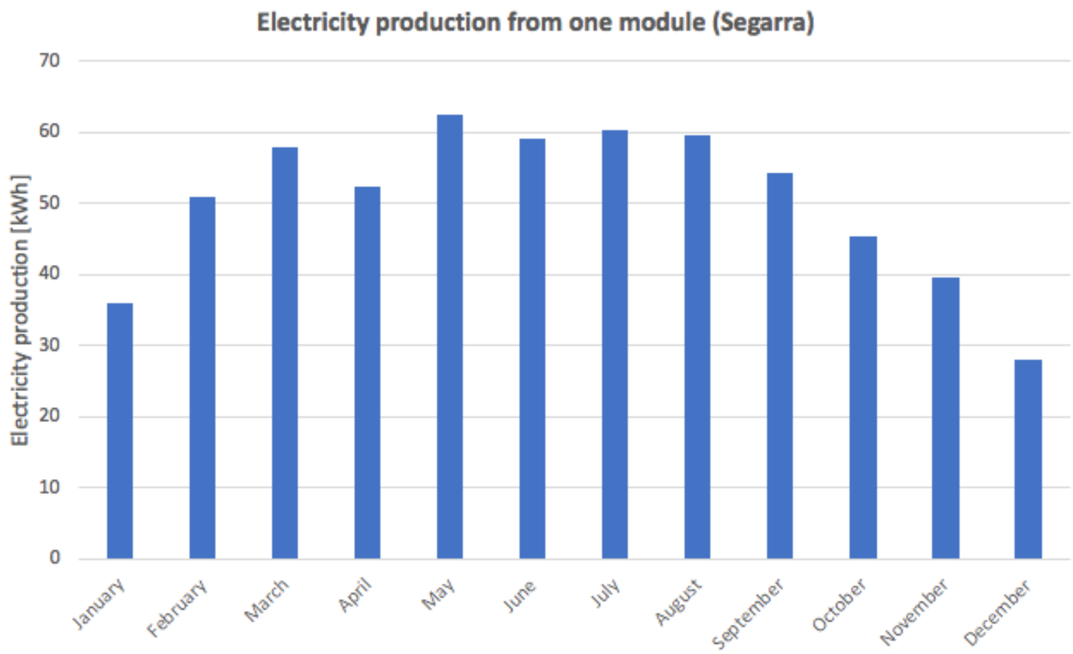

Figure 33. Electricity production delivered to the grid from one module (*Segarra*).

The annual electricity production delivered to the grid from a single module is 605,99 kWh/year. The capacity factor in this location would be 22,04%, which means the energy utilization of the PV module.

Regarding the number of modules to implement, according to the chosen criteria, the implementation is 2.500.000 modules (912,5 MWp in total), which would produce 1.514,98 GWh/year.

All these modules would take 11,29 km^2 of land, which represent the 1,56% of the total land (722,7 km^2) and the 1,93% of the useful land (585,5 km^2) in the *comarca*.

8.2.3. El Segrià

The *comarca* of *El Segrià* (Lleida) has a potential of 1.437,5 MWp in terms of photovoltaic power plants. Therefore, it is possible to hold approximately 3.940.000 modules.

The solar data has been obtained from a representative point near the municipality of *Lleida*. For this location, the PV modules are oriented to the south with an optimal tilt angle of 37º. The Figure 34 shows the sum of Global Tilted Irradiation received for every month of the year 2019.

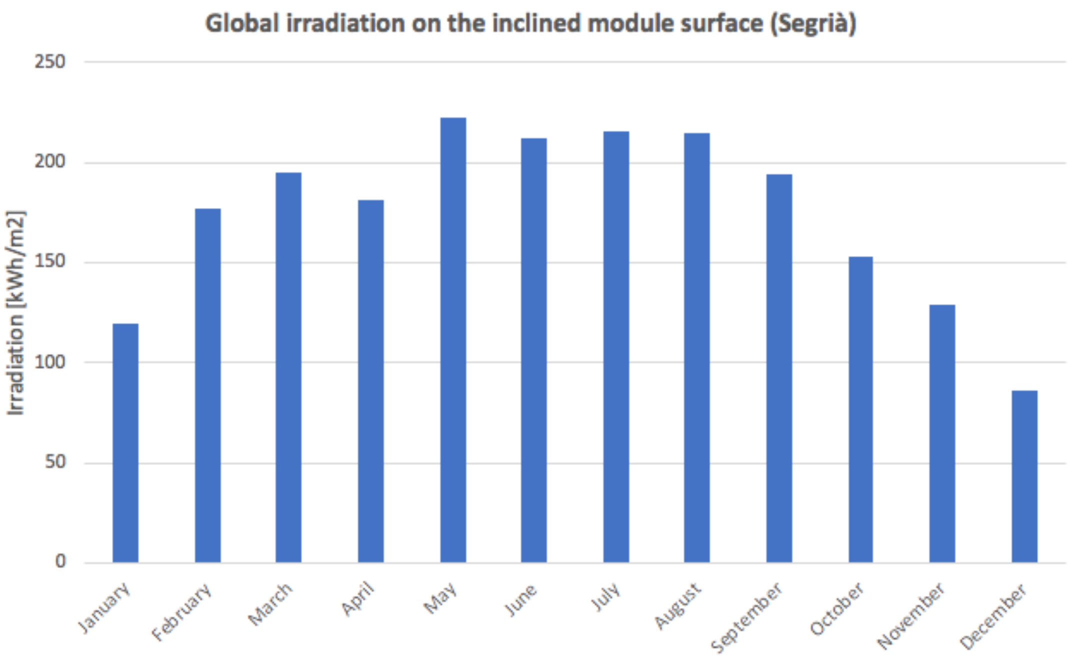

Figure 34. Global irradiation on the inclined module surface (*Segrià*).

Similarly, the different seasons of the year have influence on the irradiation received. The total amount of Global Tilted Irradiation received in 2019 was 2.099,31 kWh/m^2.

Then, based on the previous data, the electric energy produced by a single PV module is calculated, giving a total electric energy produced of 711,76 kWh/year. Following this, the electricity delivered to the grid from a single PV module is calculated (see Figure 35).

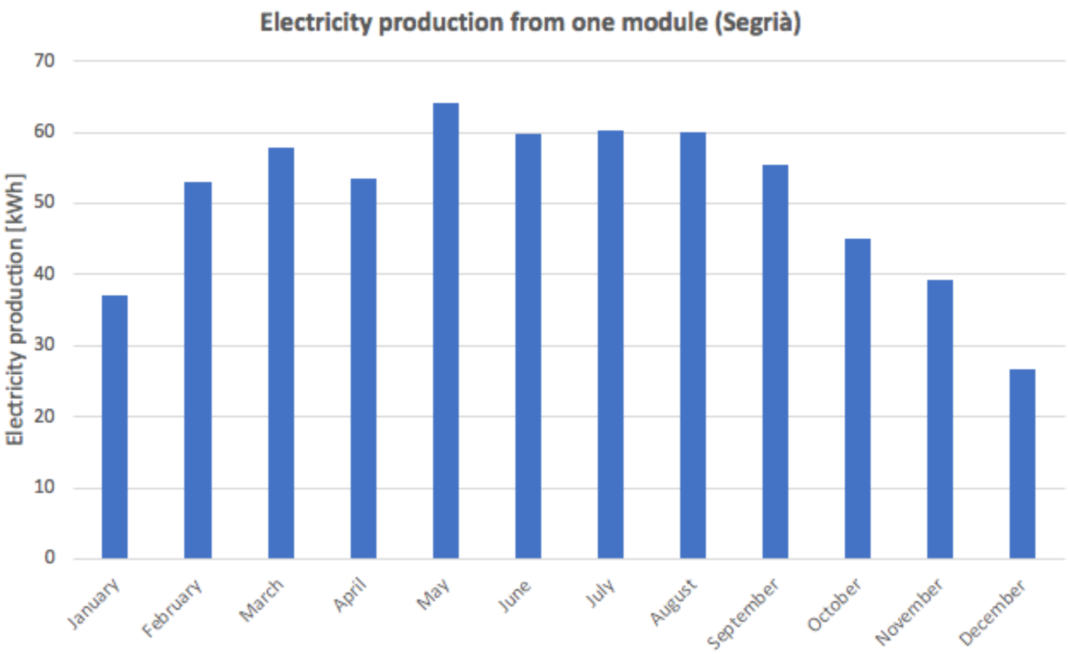

Figure 35. Electricity production delivered to the grid from one module (*Segrià*).

The annual electricity production delivered to the grid from a single module is 612,12 kWh/year. The capacity factor in this location would be 22,26%, which means the energy utilization of the PV module.

Regarding the number of modules to implement, according to the chosen criteria, the implementation is 2.300.000 modules (839,5 MWp in total), which would produce 1.407,87 GWh/year.

All these modules would take 10,39 km^2 of land, which represent the 0,74% of the total land (1.396,7 km^2) and the 0,81% of the useful land (1.282,4 km^2) in the *comarca*.

8.2.4. L'Urgell

The *comarca* of *L'Urgell* (Lleida) has a potential of 1.437,5 MWp in terms of photovoltaic power plants. Therefore, it is possible to hold approximately 3.940.000 modules.

The solar data has been obtained from a representative point near the municipality of *Tàrrega*. For this location, the PV modules are oriented to the south with an optimal tilt angle of 37º. The Figure 36 shows the sum of Global Tilted Irradiation received for every month of the year 2019.

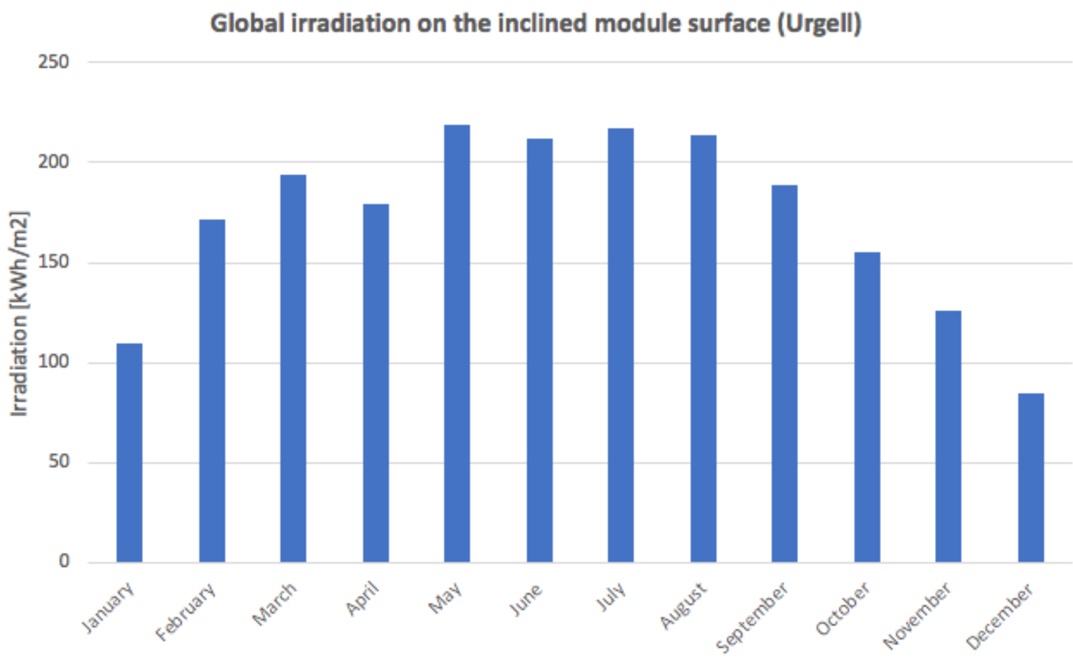

Figure 36. Global irradiation on the inclined module surface (*Urgell*).

In the same way, the different seasons of the year have influence on the irradiation received. The total amount of Global Tilted Irradiation received in 2019 was 2.068,69 kWh/m^2.

Then, based on the previous data, the electric energy produced by a single PV module is calculated, giving a total electric energy produced of 705,88 kWh/year. Following this, the electricity delivered to the grid from a single PV module is calculated (see Figure 37).

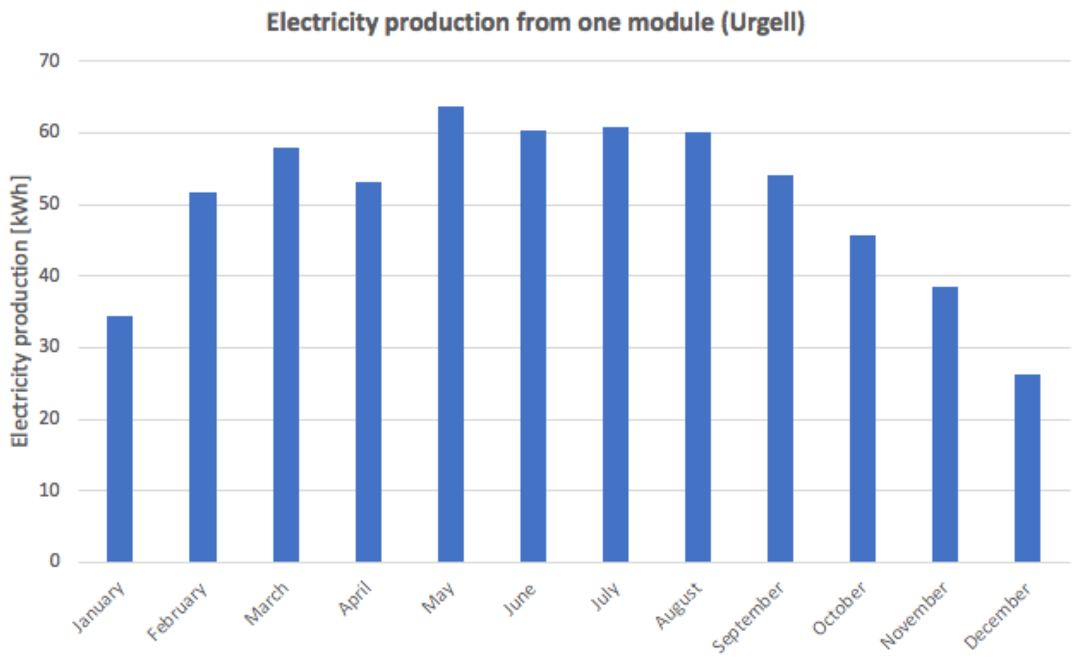

Figure 37. Electricity production delivered to the grid from one module (*Urgell*).

The annual electricity production delivered to the grid from a single module is 607,06 kWh/year. The capacity factor in this location would be 22,08%, which means the energy utilization of the PV module.

Regarding the number of modules to implement, according to the chosen criteria, the implementation is 2.300.000 modules (839,5 MWp in total), which would produce 1.396,23 GWh/year.

All these modules would take 10,39 km^2 of land, which represent the 1,79% of the total land (579,7 km^2) and the 1,85% of the useful land (562,7 km^2) in the *comarca*.

8.2.5. El Solsonès

The *comarca* of *El Solsonès* (Lleida) has a potential of 1437,5 MWp in terms of photovoltaic power plants. Therefore, it is possible to hold approximately 3.940.000 modules.

The solar data has been obtained from a representative point near the municipality of *Solsona*. For this location the PV modules are oriented to the south with an optimal tilt angle of 38º. The Figure 38 shows the sum of Global Tilted Irradiation for every month of the year 2019.

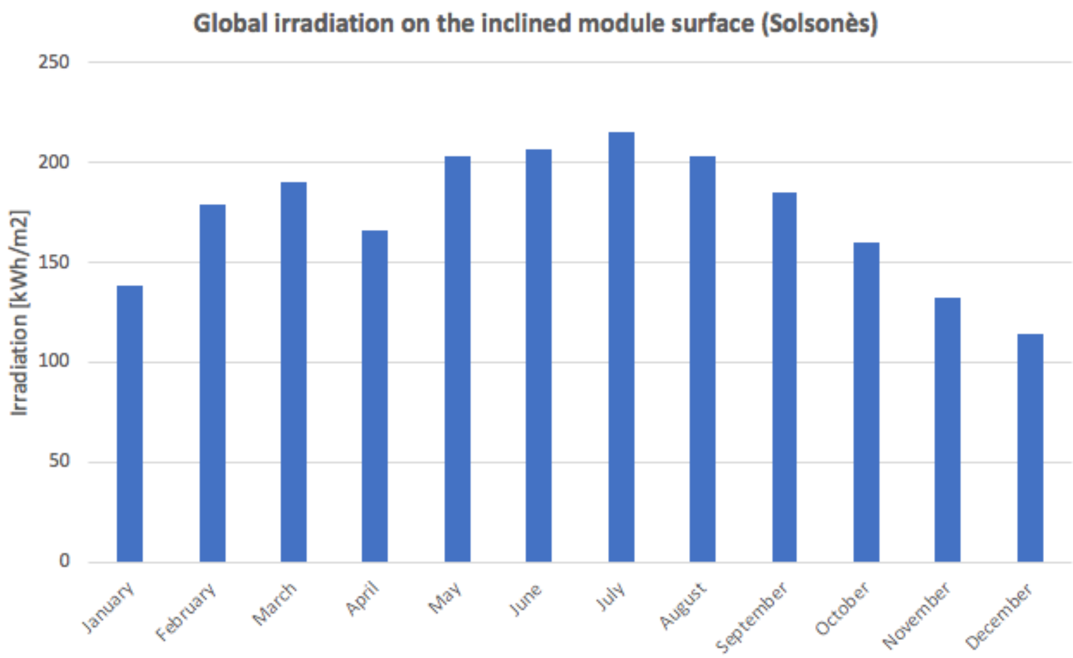

Figure 38. Global irradiation on the inclined module surface (*Solsonès*).

Similarly, the different seasons of the year have influence on the irradiation received. The total amount of Global Tilted Irradiation received in 2019 was 2.093,75 kWh/m^2.

Then, based on the previous data, the electric energy produced by a single PV module is calculated, giving a total electric energy produced of 722,09 kWh/year. Following this, the electricity delivered to the grid from a single PV module is calculated (see Figure 39).

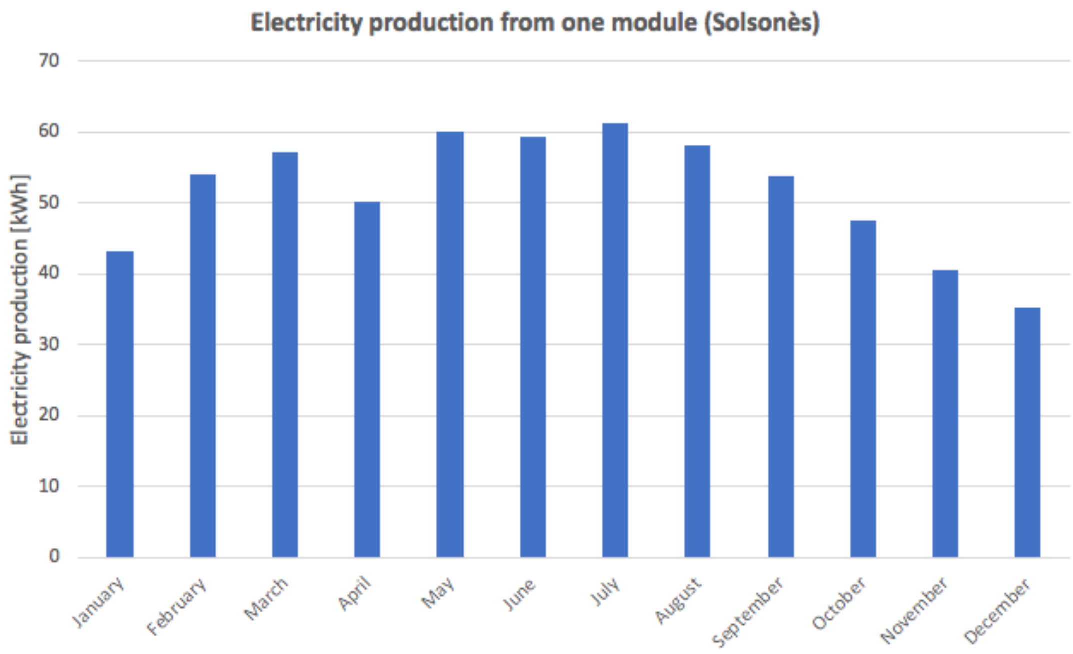

Figure 39. Electricity production delivered to the grid from one module (*Solsonès*).

The annual electricity production delivered to the grid from a single module is 620,99 kWh/year. The capacity factor for this location would be 22,58%, which means the energy utilization of the PV module.

Regarding the number of modules to implement, according to the chosen criteria, the implementation is 1.000.000 modules (365 MWp), which would produce 620,99 GWh/year.

All these modules would take 4,52 km^2 of land, which represent the 0,45% of the total land (1.001,2 km^2) and the 0,63% of the useful land (719,2 km^2) in the *comarca*.

8.3. Energy storage

It is worth to remember the importance of considering energy storage systems when producing electricity by means of renewable energy sources because of the intermittency of its production. In order to match production to demand, energy storage systems are needed. Concretely, it is estimated that it would be needed approximately 135 MW of new batteries and 1.010 MW of new pumped hydro to support these new 17.979 GWh/year of electricity produced at the end of this decade (10.499 GWh/year generated from onshore wind and 7.480 GWh/year generated from solar PV). In this way, the energy storage needed would be 63,7 kW per each GWh/year of electricity produced. From this energy storage, the 11,8% would come from batteries and the 88,2% would come from pumped hydro, in relation to energy transition policies from Catalonia [11].

9. Economic study

As it was shown in the previous chapter, in order to comply with the Catalan energy transition policies for the 2021-2030 decade in terms of photovoltaic and wind onshore power plants, the implementation needed for these two sources is estimated in 4.489,5 MW for solar PV and 3.834 MW for wind onshore.

The Table 4 shows the estimated costs of such implementations based on the current project costs in Spain. Regarding the project costs of wind onshore power plants, the major part comes from the wind turbines and the rest comes from the cost of implementation (such as civil engineering and electric facilities). Regarding the project costs of PV grounded power plants, the cost of the PV modules is significant but there are also some other costs involved such as the inverters, the structures of the modules and, obviously, the cost of implementation (civil engineering and electric facilities). Notice that the project costs are given in USD currency and are converted into EUR currency multiplying by a conversion factor of 0,9 (it has been considered that 1 USD is equal to 0,9 EUR).

RES	Installed power implemented [MW]	Project costs [USD/MW] (data from [23])	Project costs [EUR/MW]	Project costs of implementation [millions EUR]
Wind onshore	3.834	1.515.000	1.363.500	5.227,66
PV grounded	4.489,5	761.000	684.900	3.074,86

Table 4. Estimated project costs for each source implemented.

Therefore, the total costs are estimated in 8.302,52 millions EUR. This is the estimated cost of complying with the Catalan policies for this decade in terms of wind onshore and PV grounded power plants. However, it is thought that it will be higher because of some other costs involved such as energy storage systems, the use of land, the improvement of the electricity grid and transport costs.

10. Environmental impact

First of all, it has to be said that producing electricity by means of wind energy and solar energy does not produce any emissions of greenhouse gases. Then, producing electricity by these means, instead of producing electricity by means of conventional fossil fuels power plants, involves a huge benefit for the environment. However, the utilization of wind energy and solar energy has some other impacts on the environment which have to be mentioned.

Wind energy

- The landscape is highly affected by the presence of wind turbines, producing a significant visual impact.
- Wind turbines cause some aerodynamic and mechanical noise when they are working, producing noise impact.
- The rotation movement of the blades cause bird collisions which means bird mortality, producing an impact on the wildlife.
- The land occupied by a wind turbine is not really big because its support surface is relatively small, however, it must exist some space between wind turbines. Therefore, wind power plants take big extension areas of land but the land is compatible for other purposes such as farming and hiking paths. Assuming a distance between wind turbines of 500 m, each wind turbine needs a radium of 250 m from the tower and, therefore, each wind turbine takes 0,196 km^2 (approximately 5 wind turbines per square kilometer). Then, knowing that 1.917 wind turbines are needed to be implemented, the total land occupation would be 376,4 km^2, which represents the 1,17% of the total land of Catalonia.

Photovoltaic solar energy

- The landscape is highly affected by the presence of PV modules on the ground, producing a significant visual impact.

- The implementation of PV modules causes a reduction of land where can potentially live plants and animals, producing an impact on the wildlife.

- The land occupied by PV modules is quite big because they are all on the ground. Therefore, PV power plants take big extension areas of land and this land is not compatible for other purposes. The total land occupation for the 12.300.000 PV modules needed has been estimated in 55,56 km^2, which represents the 0,17% of the total land of Catalonia. Notice that this land occupation is referred only to PV modules, therefore, it has to be added for example the land occupied by inverters, batteries and paths for maintenance.

Conclusions

The conclusions obtained from the realization of this project are the following ones.

- If energy transition is not accelerated in Catalonia, it can become energy dependent in the near future (it would be necessary to import energy from Aragon or France). The 2021-2030 decade is fundamental to encourage energy transition because of the near close of nuclear power plants in Catalonia (expected for the following decade), which have a significant contribution in the electric system (currently, half of the total electricity produced in Catalonia comes from nuclear energy).

- In order to substitute fossil fuels for renewable energy sources, it is needed an electrification of the economy, which means increasing the weight of electricity in final energy consumption (this involves all sectors of the society). Therefore, electricity production should be increased during the following years and this new electricity should be produced by means of clean energy such as renewable energy sources.

- The consumption of fossil fuels to produce electricity in power plants has to be reduced during the 2021-2030 decade. It is thought that it can be reduced from combined cycle power plants, which use natural gas to produce electricity. Although this kind of power plant is very useful to regulate the electricity production at certain moments of the electricity demand, it is thought that it can be reduced if alternatives are implemented (power plants based on renewable energy sources with energy storage systems). Furthermore, it has to be said that natural gas is an imported fossil fuel which nowadays cause a high energy dependency.

- It has been estimated that, according to Catalan energy transition policies, 3.834 MW of wind onshore power plants and 4.489,5 MW of photovoltaic grounded power plants have to be implemented before the end of the 2021-2030 decade.

- Although a regular distribution of them should be necessary throughout the territory of Catalonia, it has been concluded that the best locations are the south for wind onshore energy and the west for photovoltaic solar energy.

- The *comarques* which have higher potential in terms of wind onshore energy (*Les Garrigues*, *La Conca de Barberà*, *L'Anoia* and *La Ribera d'Ebre*) and photovoltaic grounded solar energy (*La Noguera*, *La Segarra*, *El Segrià*, *L'Urgell* and *El Solsonès*) should be considered first. Although there are some other *comarques* which can present also good characteristics, it is thought that it is easier and faster to implement solutions there because of its availability to hold projects like those studied.

- The electricity production of the stated installed power in these *comarques* would be 10.504 GWh/year for wind onshore and 7.485 GWh/year for photovoltaic solar.

- The electricity produced by the solutions depends on the exact location where they are implemented. For wind turbines, it can be higher if they are properly implemented in strategic locations such as mountain areas (actually, for these locations, wind turbines with higher nominal power could be interesting). Additionally, electricity produced by photovoltaic panels can be higher if sun tracking devices are considered (costs would raise considerably).

- Wind speed is particularly unpredictable and aleatory (much more than solar irradiation). Therefore, electricity production from wind has been calculated from TMY data.

- The useful life of both solutions is estimated in 25-30 years, with a proper maintenance. Consequently, if they are implemented during the 2021-2030 decade, they would arrive to 2050 still working, but at the end of its useful life.

- It is believed that the calculation procedure proposed and described in this project to calculate electricity productions from wind energy and photovoltaic energy can be useful to provide guidance in other similar projects.

- Finally, it has been concluded that energy transition policies in Catalonia are very ambitious considering the current situation and the pace of the transition during the last past years. It will be really hard to carry out these policies inside the deadlines set, however, it is thought that it can be possible if the corresponding institutions make a huge effort and the society starts seeing energy transition as an opportunity for a better future.

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