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Environmental and Land Engineering

Towards 100% renewable energy supply in Catalonia using scenario analysis

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Summary

Abstract

The exponential increase in carbon dioxide emissions and the now imminent depletion of fossil fuels put the issue of energy at the forefront with the aim of investigating possible alternatives to the unsustainable modern energy system. The end point is represented by an autonomous and smart energy system.

Over the years, research and studies have increased confidence in achieving the goal of a national energy system without fossil fuels, in which renewable sources lead the entire energy supply.

The current energy system is characterized by a simple configuration in which the energy flows from the generation point to the customers without interconnections between the different sector. The transition to the new energy supply can be possible with different steps that involves the increasing capacity of renewable sources, introduction of bioenergy and improvement in storage capacity to deal with intermittency of renewable energies. In this study will be analysed the possibility of Catalonia to achieve 100% of renewable energy supply modelling future scenarios in 2030 and 2050 in EnergyPlan. Starting from the reference scenario of Catalonia in 2019, several changes will be introduced in the model in order to achieve the cited goal. The validation of the reference scenario will be achieved comparing outputs from the model with the actual values, for instance, of emissions of carbon dioxide, electricity share of renewables, nuclear energy production and others. In scenario 2030, the changes refer to higher capacity of wind and solar installations, reduction of individual boilers with introduction of heat pumps capacity, increasing of electricity storage with V2G (Vehicle to Grid).

In 2050 scenario, instead, the renewable energy system was expected to be reached. The methodology followed for this scenario was related to the introduction of different kinds of storage (thermal, electric), electrolysers, absorbed heat pumps, bioenergy and waste incineration with the aim of 100% electrical share of RES and the replacement of fossil fuels. The results show satisfactory values emissions of carbon dioxide and renewable energy production but still high values of natural gas consumption. The difficulties found for the full replacement of natural gas are considered related to the assumption of analysing future scenarios considering the same demand of 2019. It has been demonstrated the importance and the need to reduce the energy demand to achieve the goals set for the transition to smart energy system. For this reason, future works are needed, in which demand changes, land use study and further economic analysis are implemented to increase the knowledge and the possibility to make Catalonia 100% sustainable and autonomous in the energy sector.

1 Introduction

According to Paris agreement goals, based on keeping the temperature raise below 2 degrees and to make efforts to prevent an increase above 1.5 degrees, the energy management and generation need to be refunded following the purpose of a new system in which renewable energies will be the key. This project aims to get on track with this purpose towards a scenario with a high implementation of renewable energies that must be accomplished in order to deal with the climate crisis.

The novelty in this research is in extending previous modelling work at a national scale using the modelling tool EnergyPLAN [1] to a regional level. This project will investigate if the region of Catalonia in Spain can become energy autonomous from a technical perspective and the usefulness of EnergyPLAN in achieving this goal.

The cited model represents a suitable tool for a conscious evaluation of different strategies in the energy transition pathway. EnergyPLAN is set to form a basis for an informed analysis of an energy system after the comparison of multiple alternatives.
Initially the information will be obtained in order to build up in EnergyPlan, the actual scenario in Catalonia. The analysis carried out of this paper is a scenario analysis in which the results of actual energy management is compared with 2030 and 2050 scenarios with the highest use of renewable sources. Finally a revenue-costs analysis will be performed.

The objective is to reach a smart grid in which the energy flow is not in only one direction ("tree system": from a few production plants to a large number of users or customers) but, thanks to implementation of renewable plants (solar panels, wind farms, ecc..) and storage systems, it will be in an a bidirectional flow of electricity and information to create an automated and distributed energy network.

The goal in the model is to achieve a cross-sectoral interaction of the different sector in order to improve the flexibility of the system without fossil fuels.

1.1 Expected future scenarios in Catalonia

There are already several studies on the energy future of Catalonia, in which the current fossil fuel-dependent management is put under scrutiny.

One of these studies is "PROENCAT 2050" [2], conducted by "Institut Catala d'Energia" [3], that investigates the strategy to be adopted for the next few years in order to respect the energy perspective for 2050.

As stated by [2], the energy use by end consumers, in 2019, accounted for 71.2% of CO2 emissions in Catalonia. Only the electricity production represents the 16% of the emissions in the same year.

In the following figure it is possible to appreciate the evolution of CO2 emissions through the years in the past and that predicted for the future thanks to the strategies proposed.

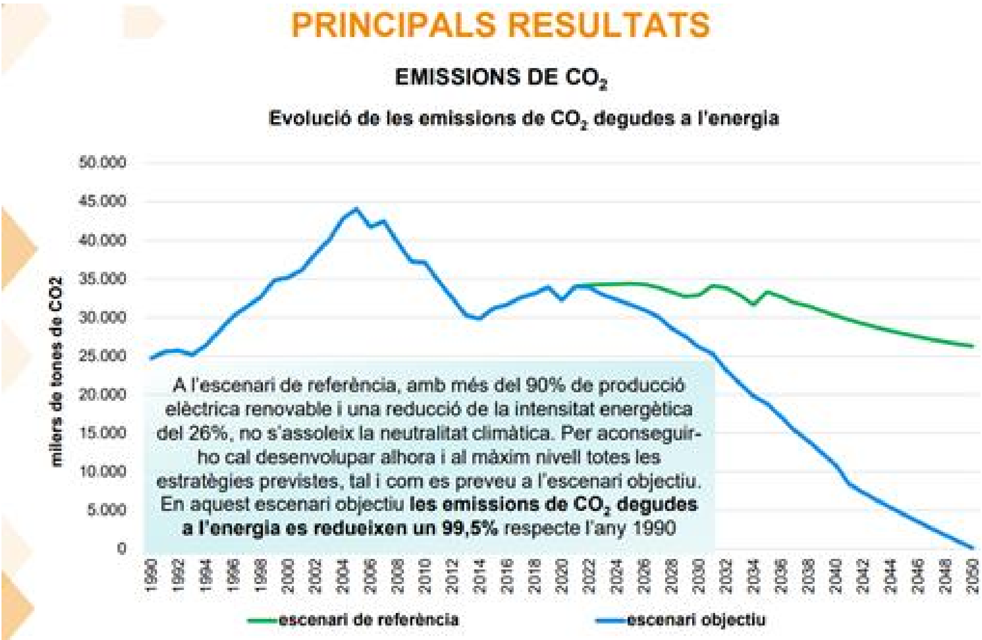

Figure 1 Emissions of carbon dioxide in Catalonia from [2]

The installed power capacity for renewable energies is expected to increase 18 times in the period 2017-2050, achieving around 60 thousand MW. By 2030, Catalunya is expected to have 1,000 MW of offshore wind energy, while by 2050 the need for this offshore energy source is estimated at 3,500 MW. Regarding the solar panels, photovoltaic power (344 MW) should be increased 18-fold by 2030 (6,272 MW) and 68-fold by 2040 (23,885 MW), which gives an idea of the challenge posed or the difficulties in changing to a scenario without nuclear power. The capacity of combined cycle thermal plants would be reduced by 54% in 2030 and their presence would disappear by 2040. By 2040, nuclear power plants are expected to be closed and completely replaced. These information are crucial in order to analyse if it will be possible to reach the goal of 100% of renewables in future scenarios (2030 and 2050).

1.2 The potential transition to 100% renewable energy system

Achieving clean electricity by 2035 and clean energy system by 2050 represents the main ambition and challenge for a scenario that no longer depends on fossil fuels. Nowadays fossil fuels constitute the primary source for energy production to answer the heating, cooling, and electricity demand. Currently the 80% of energy is supplied by fossil fuels. For a 100% renewable transition, a complex and interconnected energy supply system is required to fully replace the fossil fuels consumption.

The current energy system is characterized by a simple configuration in which the energy flows from the generation point to the customers without interconnections between the different

sector. The crucial feature that makes fossil fuels so difficult to replace is the flexibility that they provide to the system. In the existing energy system, one type of source can meet the demands of all sectors and this is due to their very large amount of stored energy.

As a consequence, the following chapters will analyse how to provide the same flexibility to the system without fossil fuels.

1.2.1 Existing energy system

Today the three sectors that are considered as energy consumer in our society are mobility, electricity and heating/cooling. The fossil fuels are the foundations for each of them in a simple structure in which each sector is independent and isolated from one another.

As the source and the demands are defined, the remaining component to build up an energy system is composed by the conversion technologies used in order to match the production with the demand. Today, the main technologies used for producing electricity and heat are respectfully power plants and individual boilers. For what concerns the mobility sector, the combustion engines are widely used in which heavy transport constitutes one of the largest source of emissions of pollutants (figure 2).

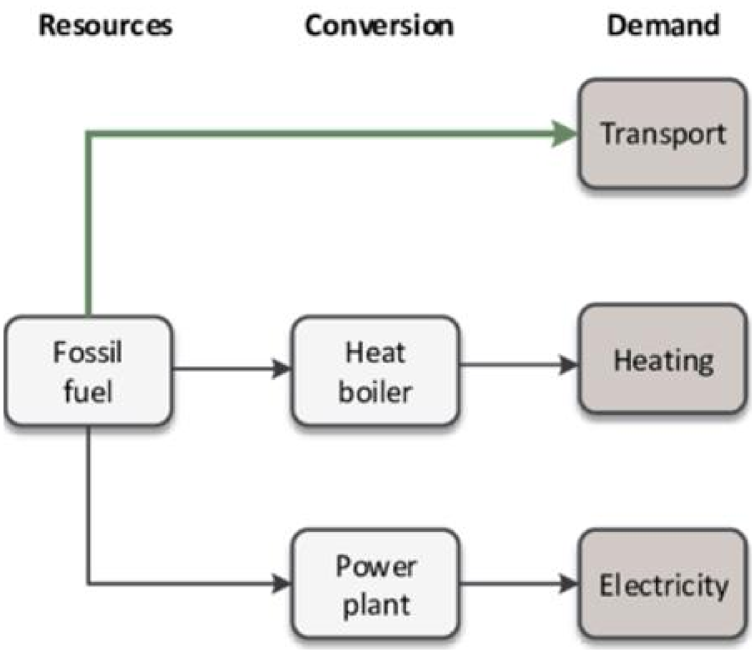

Figure 2 Scheme of current energy system [4]

1.2.2 The evolution to a smart energy system

As mentioned in section 1.1, the most important characteristic of fossil fuels their flexibility. They can be transformed into any type of energy; coal can be used to produce electricity; oil is used to obtain other fuels (e.g. gasoline for transportation and/or heating) and natural gas is often used for heating through combustion energy and in combined cycles. For this reason, as the aim is to replace fossil fuels, the same flexibility is needed to be implement in the new system. This flexibility is achievable only by adding more complexity with connected sectors, improving the storage capacity, and increasing renewable energy production.

In this chapter will be discuss one of the possible way, introduced by [1] to properly achieve this transition. The first possible action is related to the replacement of fossil fuels with bioenergy. Coal can be replaced by biomass, gas by biogas and oil can be replaced by biofuel (i.e., biodiesel and ethanol). This could be enough to have a 100% renewable energy supply system but replacing all the current request of fossil fuels would not be enough as more land to grow all the bioenergy would be required and is limited. Consequentially, further steps are necessary.

To reduce the quantity of biogas used, it is indispensable to bring changes to the conversion part in the energy system. Replacing power plants with CHP plants (Combined Heat and Power) can increase the efficiency of the system as CHP can produce electricity and thermal energy at the same time (figure 3). The efficiency of the system is improved by designing this district heating that connects the electricity with the heating sector.

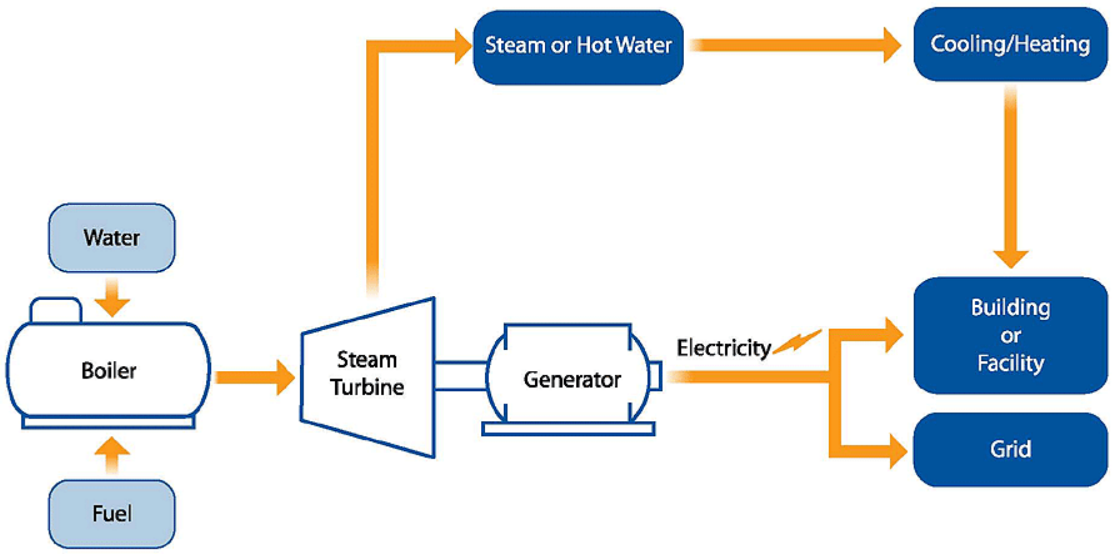

Figure 3 Scheme of a Combined Heat and Power plant [5]

The other benefit resulting in applying the CHP plants in the system, is it opens the field of possibility to use new resources of heat as large scale of solar plants, geothermal heat plants and waste incineration system. As a result of these installations, the pressure of producing biogas energy demand is highly reduced but still not in the order of making feasible this kind of system. Improving the capacity of renewable energy as wind and solar energy is clearly a crucial step, but other flexible solutions are mandatory to deal with the intermittency of these sources that sees high standard deviation in their production throughout the year.

The first affordable and easy way to improve the flexibility in the system is related to the installation of thermal storage. This technology costs roughly 50 times less than electricity storage devices. At the same time it allows to improve the percentage of electricity production from renewable sources (reducing the demand from CHP plants) with more flexibility.

To directly connect the renewable sources with the heating sector, introducing heat pumps is required (figure 4). Heat pumps are widely efficient in converting electricity into heat. For every one unit of electricity, 3 units of heat are produced (considering a standard value of COP around 3).

Introducing heat pumps in the system, the renewable sources of electricity are directly connected to thermal storage, with the benefit of a direct access to energy stored in the form of heat. The heat pumps can produce heat in the district heating but also in the individual heating with the installations in the buildings.

In this step of the transition path, the individual boilers were completely replaced.

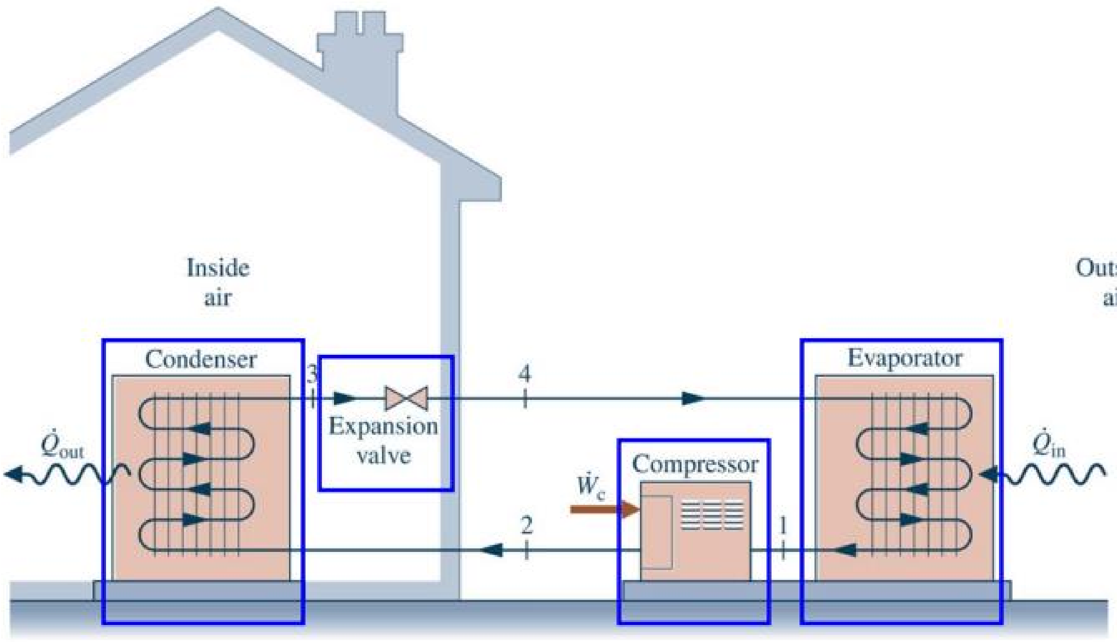

Figure 4 Scheme of a heat pump installed in building [6]

At this phase of transition, heating and electricity sector are largely connected to one another. The system now demands more interconnection with the mobility sector.

The first procedure that can be promoted is increasing the production and use of electric vehicles (EVs), in parallel with the improvement of the grid capacity. With a large replacement of the current individual cars (70-80% by 2050) with EVs, it is possible to connect the electricity produced by renewable sources with the transport sector. In addition, the liquid fuel used for the combustion engines are replaced by the electricity.

One of the toughest challenges regards the reduce of the liquid and gas fuel demand for heavy transport (trucks, airplanes and ships). The key that can enhance this change is the introduce of synthetic fuels. In the broadest definition, a synthetic fuel is a liquid fuel that is not derived from natural occurring crude oil.

To create a synthetic fuel, electricity is occurred to generate hydrogen which, in turn, is combined with carbon. The carbon needed can be captured directly from CO_2 generate by power plants or from bioenergy sources.

The production of synthetic fuels can generate liquid or gases hydrocarbon that can replace fossil oil or natural gas in the combustion engines for heavy duty transport. In addition, electricity production is now connected with heavy transport sector. So, hydrogen is created from electrolysers and carbon can be captured from different sources as biomass, biogas, air, etc..

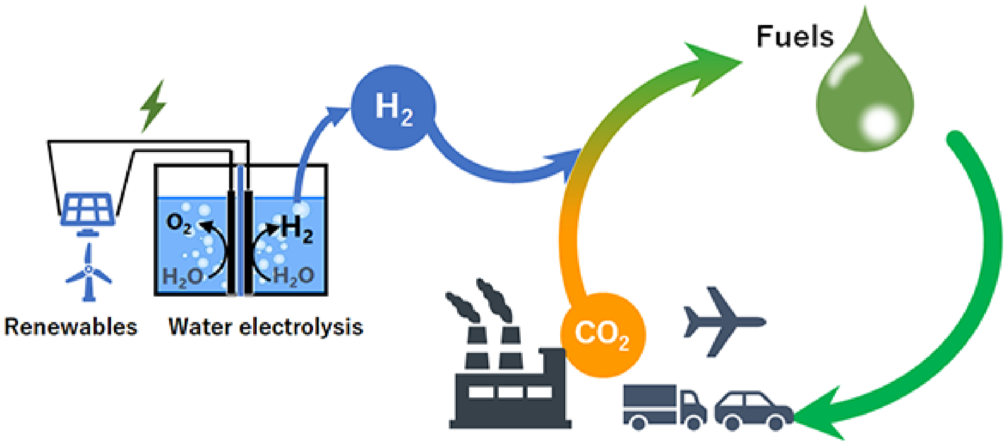

Figure 5 Synthetic fuels generation [7]

The dependency on bioenergy production is significantly reduced by this important change made in the energy system. But one of the most essential benefits, from this change, is the possibility to introduce a new fuel storage into the system with the result of a connection between intermittent resources with an extremely large amount of energy storage.

The flexibility required by the system, after the replacement of fossil fuel, is now completely introduced in the new smart energy system. As analysed in this chapter, a more complex conversion system with more relations between each sector and with improvement of energy storage technology can provide the transition to a 100% renewable energy system by 2050.

In the following figure, it is shown how a smart energy system is composed as a whole:

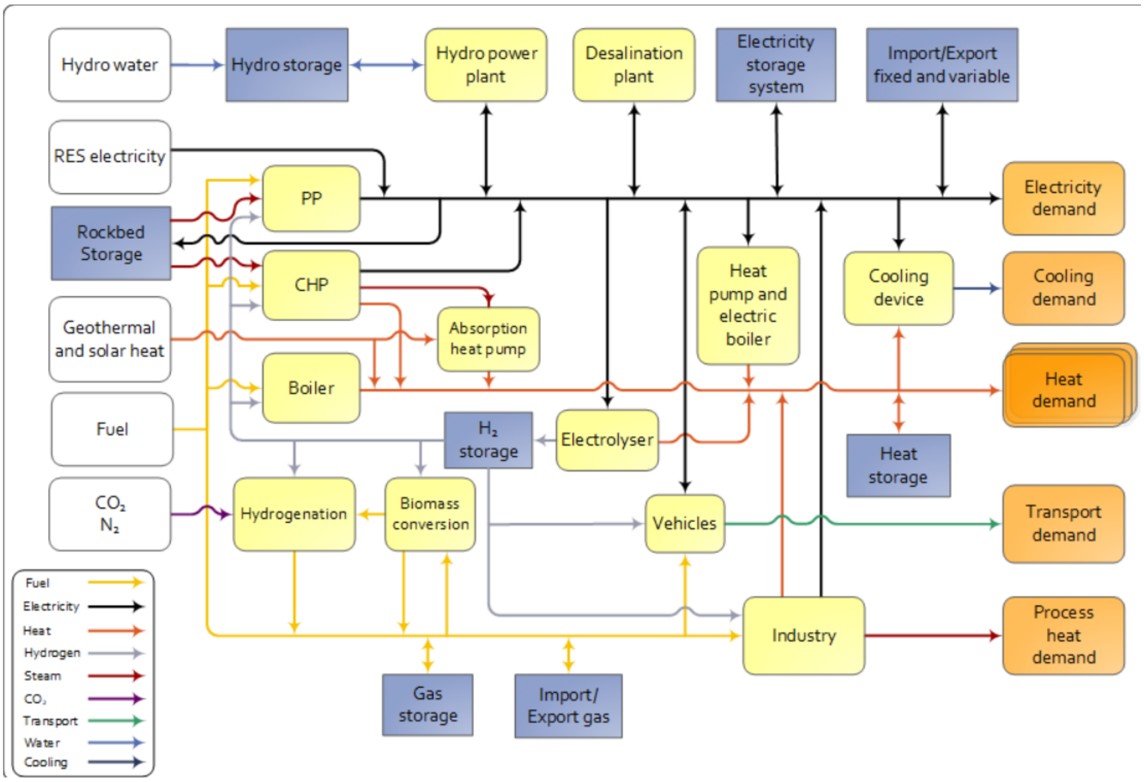

Figure 6 Scheme of a smart energy system from EnergyPlan [1]

2 Objectives

This project has the aim of analyse the feasibility of the scenarios proposed for the future energy production in Catalonia with the help of EnergyPlan [1]. It will be built up the reference scenario of 2019 in the software in order to bring the crucial and expected changes that can help Catalonia to achieve the goals cited in 1.1 for 2030 and 2050 scenarios. Assuming that the region of Catalonia has the possibility, in terms of space available, to install the cited power capacity of renewable energies in the territory, it will be investigated the contour actions to be done in order to completely replace fossil fuels and nuclear energy production.The installed capacity of renewable sources will be increased by the year 2030 and 2050 following the objectives stated by the government of Catalonia.

It will be followed the transition path explained in the chapter 1.2, assuming that the technologies related to store and stabilisation share of renewable sources will be improved by the year 2050.

3 Methodology

3.1 EnergyPlan model

The EnergyPLAN model has been developed in 1999 and since that date is in continuous evolution [1]. It can be classified as a simulation tool. The main purpose of the EnergyPLAN model is to analyse the energy, environmental, and economic impact of various energy strategies. That can be analysed different options in order to be able to compare one scenario with another, so in this way is possible to illustrate more possibilities rather than only one solution. Furthermore, the aim of EnergyPLAN is to study the future scenarios and how the energy system can be modified for improvement. The focus is placed on the future energy system and how that will operate, rather than on today's energy system. Therefore, EnergyPLAN includes relatively detailed modelling of future technologies such as biomass gasification and synthetic fuels. The model refers to an entire national or regional energy system taking into consideration all the main sectors as heat and electricity and the transport and industrial. Usually, the technical parameters required by EnergyPLAN are related to the production or demand in one year (i.e TWh/year), the capacity installed (i.e MW) and the hourly distribution related to the total annual production/demand. The distributions always required 8784 values (every hour) and each value represents a percentage (from 0 to 1) of the production/demand. The distribution is simply adjusted to reflect the total annual production/demand. The model is a deterministic input/output model. Inputs are demands, capacities, renewable energy sources and costs.

Outputs are energy balances and resulting annual productions, fuel consumption, import/export of electricity, and total costs.The overall structure of the energy system analysis is the following:

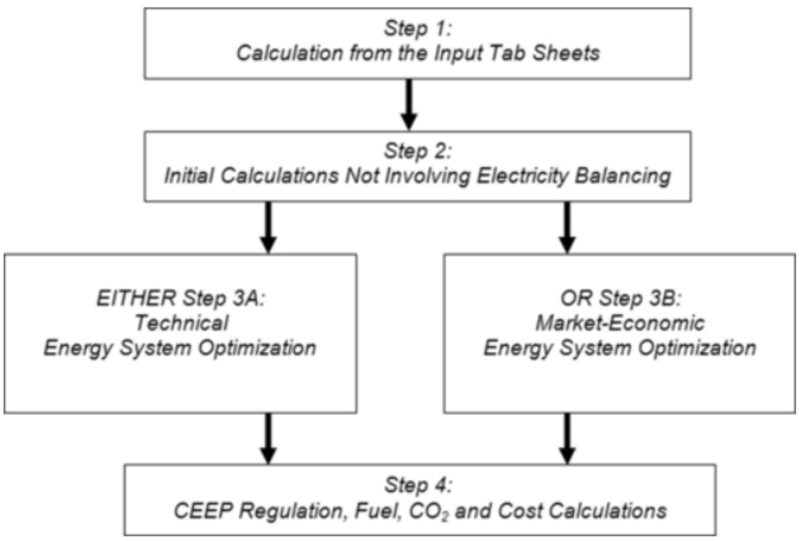

Figure 7 Overall structure of the energy system analysis from [8]

In which as a first step, calculations are based on a small computation, which is made simultaneously with the typing of input data in the input and cost tab sheets. The next step consists of a series of initial calculations that do not involve electricity balancing. Then the procedure is divided into either a technical or a market-economic optimization.

The technical optimization minimizes the import/export of electricity and seeks to identify the least fuel-consuming solution. On the other hand, the market-economic optimization identifies the least-cost solution on the basis of the business economic costs for each production unit. In both situations, the model can calculate the socioeconomic consequences that provide important information for the design of different public regulation measures [8].

3.2 Current scenario on EnergyPLAN

As the aim of this study is to understand the steps to follow in order to achieve 100% of renewable supply in the energy management of the region of Catalunya, the first action needed is to build up a model on EnergyPlan that depicts as much as possible the actual situation.

This process required a pursuit of several information, in terms of demand and supply in different sectors, and several steps that can be found in a helpful manual from EnergyPlan [9]. A large part of data have been found in the Insitut Català d'Energia [1]. The historical year taken into account is 2019 since is the closest period until the pandemic of Covid-19 that affects the market and the management in general of energy.
It is important to mention that a series of assumptions have been made to reach the base scenario in order to get the data and not the importance of the data.

3.2.1 Demand specifications

As it is mentioned before, EnergyPLAN needs several inputs data that represents the demand of energy in each sector. This is included in the Demand Tab of the program.

The necessary source used for reaching these informations is the energy balance of Catalunya in 2019 [1] , that provides data of primary and final energy. The second one have been used as input in this model.

Table 1 Energy balance of Catalonia [3]

Font d'energia	TOTAL [7]	Carbó	Lignit	Altres carbons	Petroli cru i productes intermedis	Productes petrolífers gasosos	GLP²	Gasos de refineria	Productes petrolífers lleugers	Naftes	Gasolines	Productes petrolífers mitjans	Querosens	Gas-oil	Productes petrolífers pesants
Producció d'energia primària	7,507.4	0.0	0.0	0.0	35.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Saldo importació -exportació[1]	17,863.8	34.6	1.3	33.3	8,362.3	1,030.0	941.6	88.4	1,673.9	1,941.8	-267.9	2,059.8	565.3	1,494.5	-762.3
Consum d'energia primària	**25,371.2**	**34.6**	**1.3**	**33.3**	**8,398.1**	**1,030.0**	**941.6**	**88.4**	**1,673.9**	**1,941.8**	**-267.9**	**2,059.8**	**565.3**	**1,494.5**	**-762.3**
Transformació d'energia (generació elèctrica)	-5,332.8	0.0	0.0	0.0	0.0	-11.4	0.0	-11.4	0.0	0.0	0.0	-3.1	0.0	-3.1	-25.3
Transformació d'energia (refineries i plantes d'olefines)	-246.6	0.0	0.0	0.0	-8,398.1	1,205.0	209.6	995.4	1,322.8	41.1	1,281.7	3,673.8	865.2	2,808.6	1,053.5
Transformació d'energia (total)	**-5,579.4**	**0.0**	**0.0**	**0.0**	**-8,398.1**	**1,193.6**	**209.6**	**984.0**	**1,322.8**	**41.1**	**1,281.7**	**3,670.7**	**865.2**	**2,805.5**	**1,028.2**
Consums propis sector energètic	1,751.8	0.0	0.0	0.0	0.0	1,069.0	0.0	1,069.0	0.0	0.0	0.0	0.0	0.0	0.0	13.7
Pèrdues transport i distribució	360.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Energia disponible per al consum final	**17,679.8**	**34.6**	**1.3**	**33.3**	**0.0**	**1,154.6**	**1,151.2**	**3.4**	**2,996.7**	**1,982.9**	**1,013.8**	**5,730.5**	**1,430.5**	**4,300.0**	**252.2**
Usos no energètics	3,233.1	13.1	0.5	12.6	0.0	983.7	983.7	0.0	2,047.5	1,982.9	64.6	0.0	0.0	0.0	170.9
Consum d'energia final	**14,446.7**	**21.5**	**0.8**	**20.7**	**0.0**	**170.9**	**167.5**	**3.4**	**949.2**	**0.0**	**949.2**	**5,730.5**	**1,430.5**	**4,300.0**	**81.3**
sector transport	6,515.9	0.0	0.0	0.0	0.0	15.4	15.4	0.0	949.2	0.0	949.2	5,091.7	1,430.5	3,661.2	65.3
sector industrial	3,685.7	21.5	0.8	20.7	0.0	11.2	7.8	3.4	0.0	0.0	0.0	62.2	0.0	62.2	16.0
sector domèstic	2,123.0	0.0	0.0	0.0	0.0	93.8	93.8	0.0	0.0	0.0	0.0	233.3	0.0	233.3	0.0
sector serveis	1,898.1	0.0	0.0	0.0	0.0	38.2	38.2	0.0	0.0	0.0	0.0	195.7	0.0	195.7	0.0
sector primari	224.0	0.0	0.0	0.0	0.0	12.3	12.3	0.0	0.0	0.0	0.0	147.6	0.0	147.6	0.0

Font d'energia	TOTAL [7]	Gasos manufacturats	Gas natural	Energia nuclear [3]	Energia hidràulica [4]	Energia eòlica [4]	Energia solar fotovoltaica [4]	Energia solar termoelèctrica	Energia elèctrica [5]	Biomassa	Biomassa agrícola, animal i forestal	Residus renovables	Bioetanol	Biodiesel	Biogàs	Energia solar tèrmica	Residus industrials no renovables [6]
Producció d'energia primària	7,507.4	0.0	0.7	6,220.4	303.4	271.1	38.8	8.7	0.0	457.5	210.4	172.1	0.0	26.5	48.5	33.0	138.0
Saldo importació -exportació[1]	17,863.8	0.0	5,821.2	0.0	0.0	0.0	0.0	0.0	123.9	246.8	0.0	0.0	22.3	224.5	0.0	0.0	0.0
Consum d'energia primària	**25,371.2**	**0.0**	**5,821.9**	**6,220.4**	**303.4**	**271.1**	**38.8**	**8.7**	**123.9**	**704.3**	**210.4**	**172.1**	**22.3**	**251.0**	**48.5**	**33.0**	**138.0**
Transformació d'energia (generació elèctrica)	-5,332.8	0.0	-2,313.5	-6,220.4	-303.4	-271.1	-38.8	-8.7	4,072.5	-176.5	-9.9	-130.1	0.0	0.0	-36.5	0.0	-33.1
Transformació d'energia (refineries i plantes d'olefines)	-246.6	0.0	-111.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Transformació d'energia (total)	**-5,579.4**	**0.0**	**-2,425.0**	**-6,220.4**	**-303.4**	**-271.1**	**-38.8**	**-8.7**	**4,072.5**	**-176.5**	**-9.9**	**-130.1**	**0.0**	**0.0**	**-36.5**	**0.0**	**-33.1**
Consums propis sector energètic	1,751.8	0.0	432.8	0.0	0.0	0.0	0.0	0.0	229.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.7
Pèrdues transport i distribució	360.2	0.0	18.2	0.0	0.0	0.0	0.0	0.0	342.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Energia disponible per al consum final	**17,679.8**	**0.0**	**2,945.9**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**3,624.8**	**527.8**	**200.5**	**42.0**	**22.3**	**251.0**	**12.0**	**33.0**	**98.2**
Usos no energètics	3,233.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Consum d'energia final	**14,446.7**	**0.0**	**2,945.9**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**3,624.8**	**527.8**	**200.5**	**42.0**	**22.3**	**251.0**	**12.0**	**33.0**	**98.2**
sector transport	6,515.9	0.0	31.3	0.0	0.0	0.0	0.0	0.0	89.7	273.3	0.0	0.0	22.3	251.0	0.0	0.0	0.0
sector industrial	3,685.7	0.0	1,695.0	0.0	0.0	0.0	0.0	0.0	1,396.1	132.0	87.0	38.0	0.0	0.0	7.0	0.5	93.1
sector domèstic	2,123.0	0.0	832.2	0.0	0.0	0.0	0.0	0.0	866.1	74.9	74.9	0.0	0.0	0.0	0.0	22.7	0.0
sector serveis	1,898.1	0.0	377.5	0.0	0.0	0.0	0.0	0.0	1,237.2	34.6	27.1	4.0	0.0	0.0	3.5	9.8	5.1
sector primari	224.0	0.0	9.9	0.0	0.0	0.0	0.0	0.0	35.7	13.0	11.5	0.0	0.0	0.0	1.5	0.0	0.0

3.2.1.1 Electricity

Once the data of electricity demand for domestic, industrial and services use have been collected, the input data required by the software were the total value in TWh per one year and the hourly distribution.

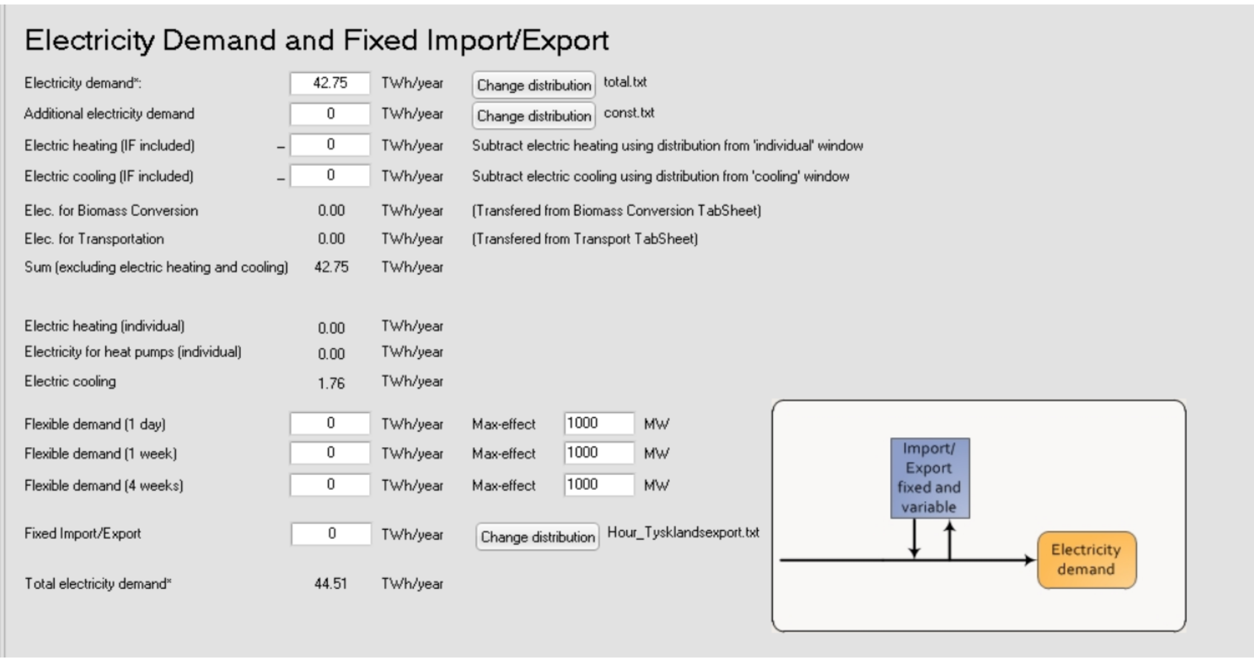

Figure 8 Electricity demand tab in EnergyPlan

3.2.1.2 Heating and cooling

For what concerns the heating demand tab, the software divides the sections in individual and district heating.

Even if Catalonia represents the first region in Spain in terms of district heating installation [16] , the values of production are negligible compared to the overall demand and as a consequence, only the individual demand has been taken into account.

The total heat demand is the result of fuel inputs (oil boiler, natural gas boiler, etc..) and hourly distributions of heat demand. Regarding this last input, the best suitable data was represented by the reference model of Italy in 2010 [10] considering the similar weather and the assumption of a similar request of individual heating.

Figure 9 Heating demand tab in EnergyPlan

The same assumption has been used for cooling demand, taking into account the difference in terms of population. The input requested in this section were the electricity consumption for cooling and the distributions for natural cooling and cooling demand.

Once again, in this sector only the individual consumption has been considered.

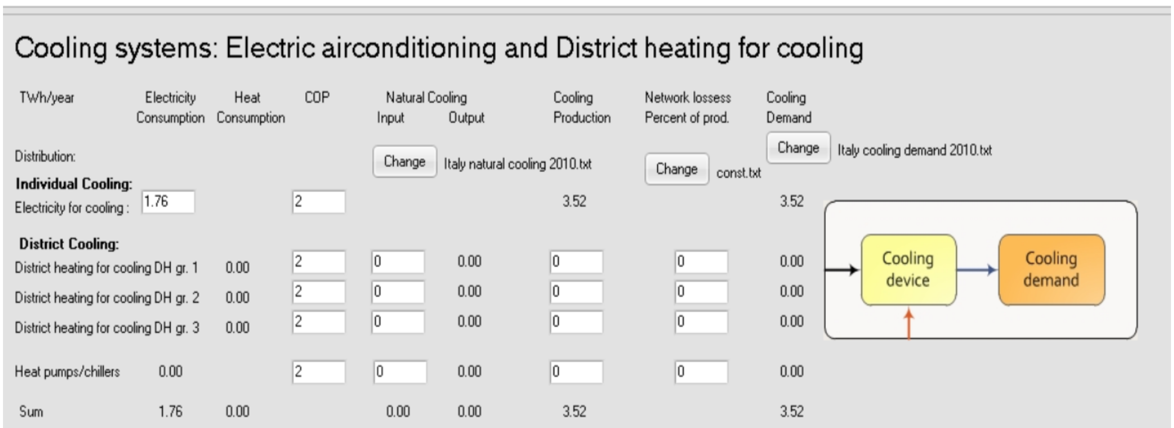

Figure 10 Cooling demand tab in EnergyPlan

3.2.1.3 Fuel consumption for industry and transport sector

Finally, in order to complete the inputs for building up the country demand in the model, the different kind of fuels used in the sector of transportation and industry were analysed.

For what concerns the industry sector, the kind of fuels request are coal, natural gas, oil and biomass during one year of consumption.

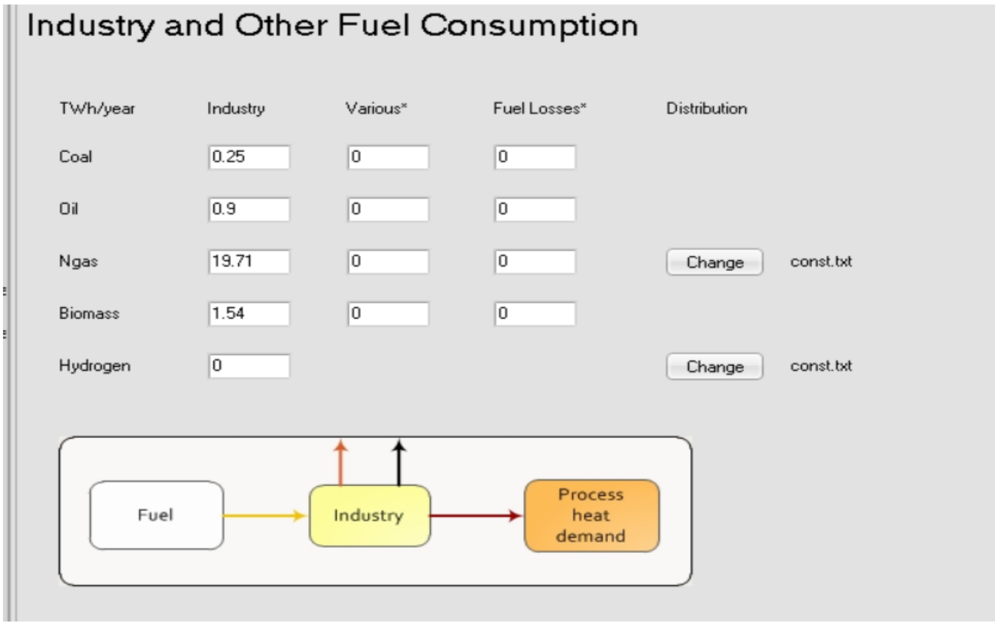

Figure 11 Industry fuel demand in EnergyPlan

The transport sector includes Jet Fuel, Diesel, Petrol , Natural Gas and LPG consumed in one year.

In this model is also possible to implement the specifications of electric vehicle and electro fuel consumption.

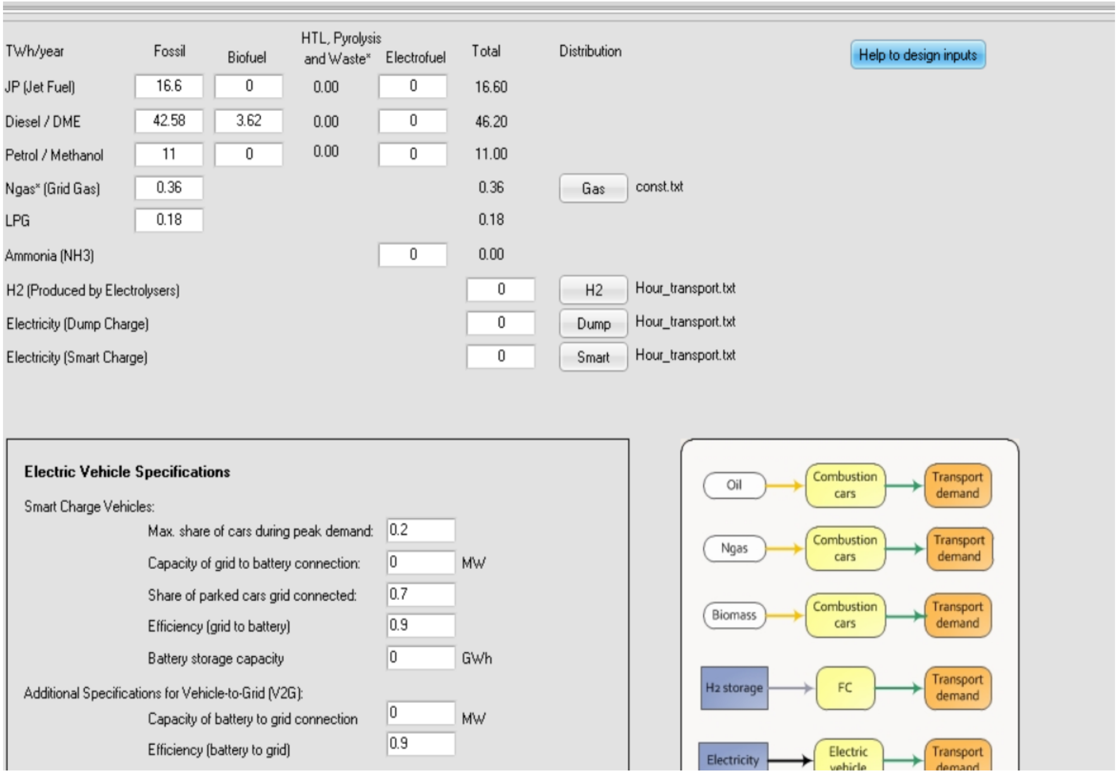

Figure 12 Transport fuel demand tab in EnergyPlan

3.2.2 Energy supply

2.2.2.1 Heat and electricity

In EnergyPLAN all boilers, CHP stations, and so forth that produce heat for district heating are grouped into three district heating systems. They are specified in the Supply Tab

District heating demand is defined in the same way as the electricity demand: it uses an annual demand (TWh/year) and a selected distribution dataset. The model divides district heating supply into three groups, and the demand of each group must be defined. The first group comprises traditional district heating stations with boilers, the second group consists of small CHP stations, and the third group includes large CHP stations based on thermal extraction stations.With regard to the energy systems analysis, the model focuses on electricity demand and district heating demand. However, all sectors are included in the model, and industry as well as individual heating and transportation may be included in the electricity and district heating balancing of demand and supply. If industrial CHP stations produce electricity or district heating, these can be specified for each of the three district heating groups. The production is specified in the same way as the demand, by using an annual production and a selected distribution dataset.

Capacities and efficiencies of the energy production units are defined as average values for each type of station in each of the three district heating groups. For group one (district heating boilers), only the efficiency needs to be stated, since the capacity of the boiler must always be sufficient. For groups two and three (CHP), capacities (MWe and MWth) and efficiencies are given for CHP units and boilers.

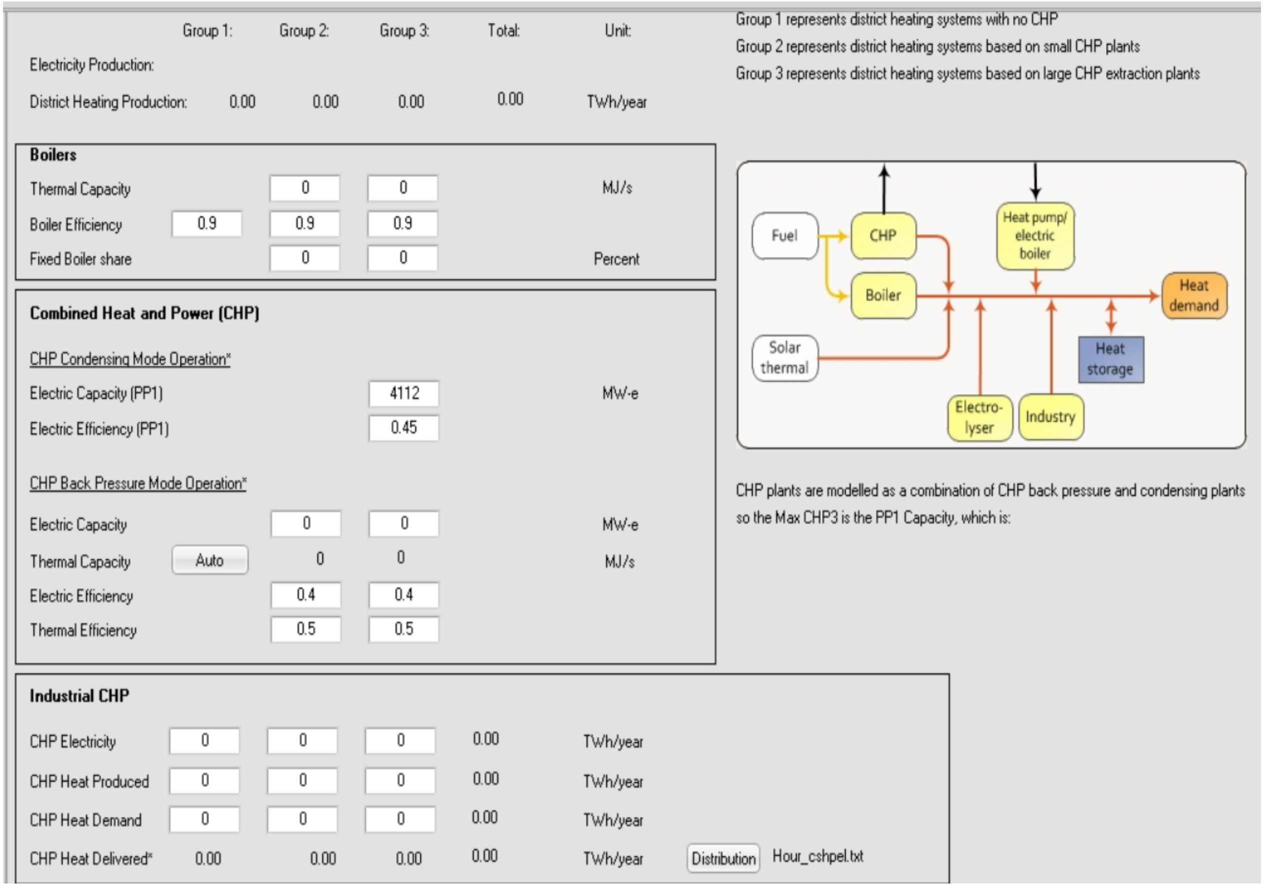

Figure 13 Electricity and heat supply tab in EnergyPlan

3.2.2.2 Power Plants

For power plants, the first parameter required is the total capacity installed. If necessary, it is possible to divide the power plants into two categories: condensing and PP2.

The PP2 category is usually used if there is a highly contrasting plant mix on the system, i.e. if there is one group of plants with a low efficiency and are expensive, but another group of plants, which have a high efficiency and are cheap.

In addition to the PP capacity, the total fuel consumed by the power plants is also required.

3.2.2.3 Variable Renewable Electricity

In order to define the energy available from a renewable energy resource in the system, the model will need values regarding the type of renewable energy, the capacity installed and the hourly distribution profile. The distribution profile is related to the quantity of sources available during on year. It is also possible to set the stabilisation share and the correction factor. The first one is the related to the installed capacity of the renewable resource that can contribute to grid stability (in percentage from 0 to 1). Nowadays, only hydro power is able to provide voltage and frequency regulation to the electric grid. The correction factor can adjusts the hourly distribution inputted for the renewable resource.

It can enhance the capacity factor related to the specific renewable energy source.

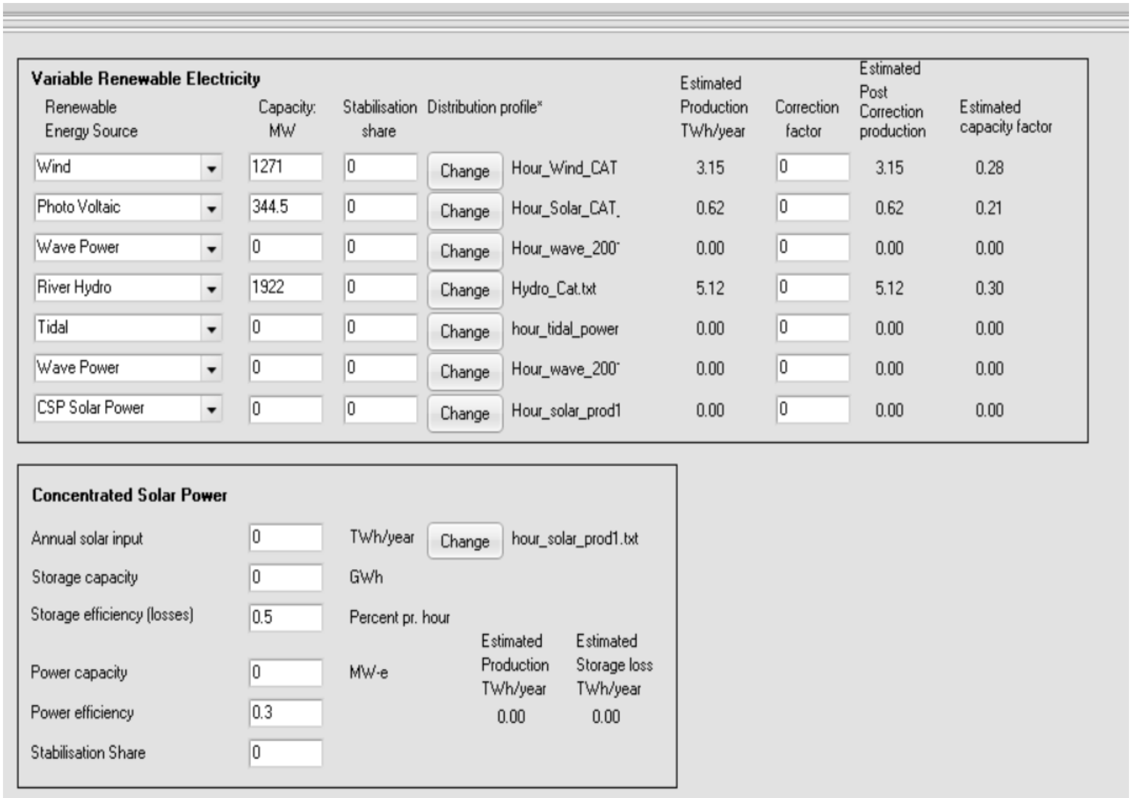

Figure 14 Variable renewable electricity tab in EnergyPlan

3.2.2.4 Fuel distribution

Once the power plants are fixed, the fuel distribution is needed to be analysed.

The amount of coal, oil, natural gas and biomass is asked for the CHP plants and PP of each district heating group.

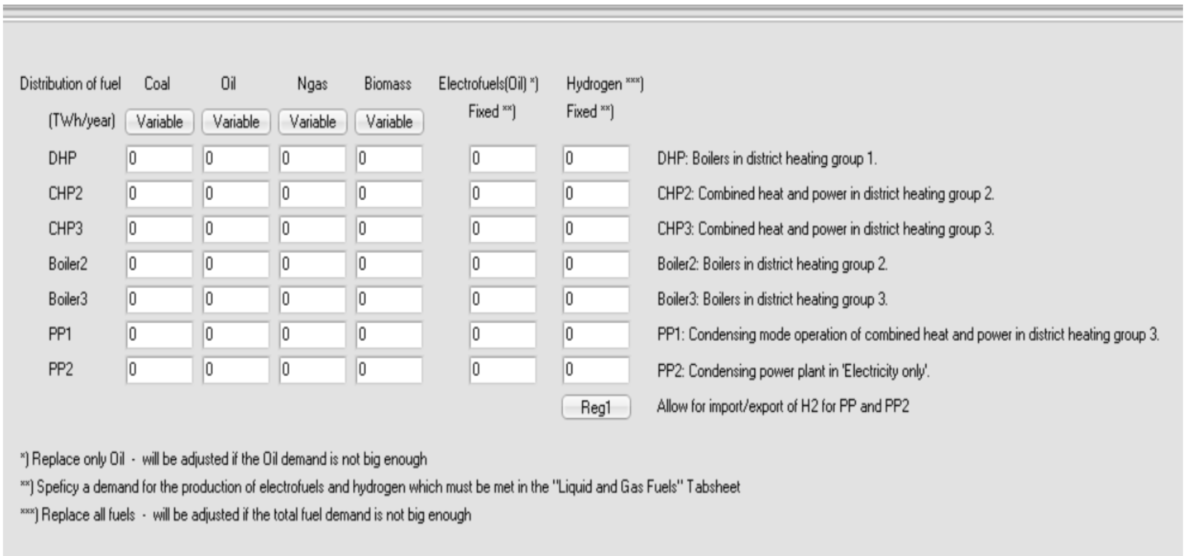

Figure 15 Fuel distribution tab in EnergyPlan

3.2.2.6 Carbon dioxide emissions

Since the emissions of CO2 are one of the output for a technical study of the system, a tab with information on the CO2 contents in the fuel is implemented in the software.

Carbon Capture and Storage or Recycling can be considered in the system.

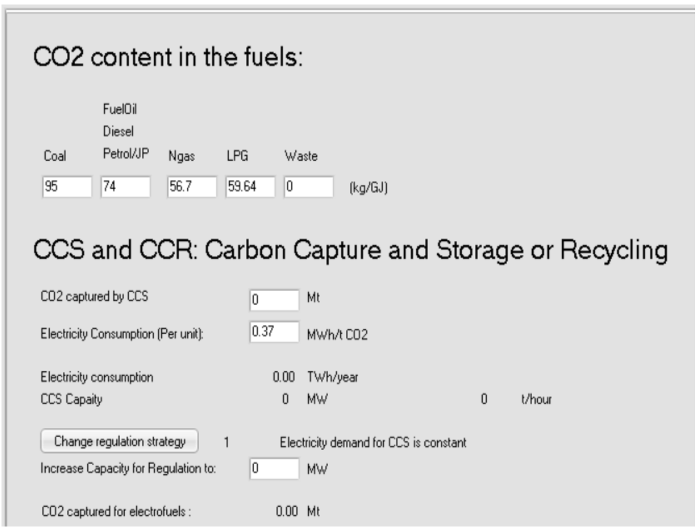

Figure 16 CO2 tab in EnergyPlan

3.2.3 Balancing and storage

For what concerns the sector of the model related to the different ways to store the energy, the model provides three different technology.

It can be found the electricity thermal and fuel storage.

For the electricity storage, battery, hydro and the rock bed technology can be used and it is possible to choose the priority of the kind of storage for the system.

For the thermal the input data are divided for the three main district heating groups and the capacity of storage in GWh is required.

Finally, the fuel storage is characterised by tha gas, oil and methanol storage in which the capacity in GWh is requested.

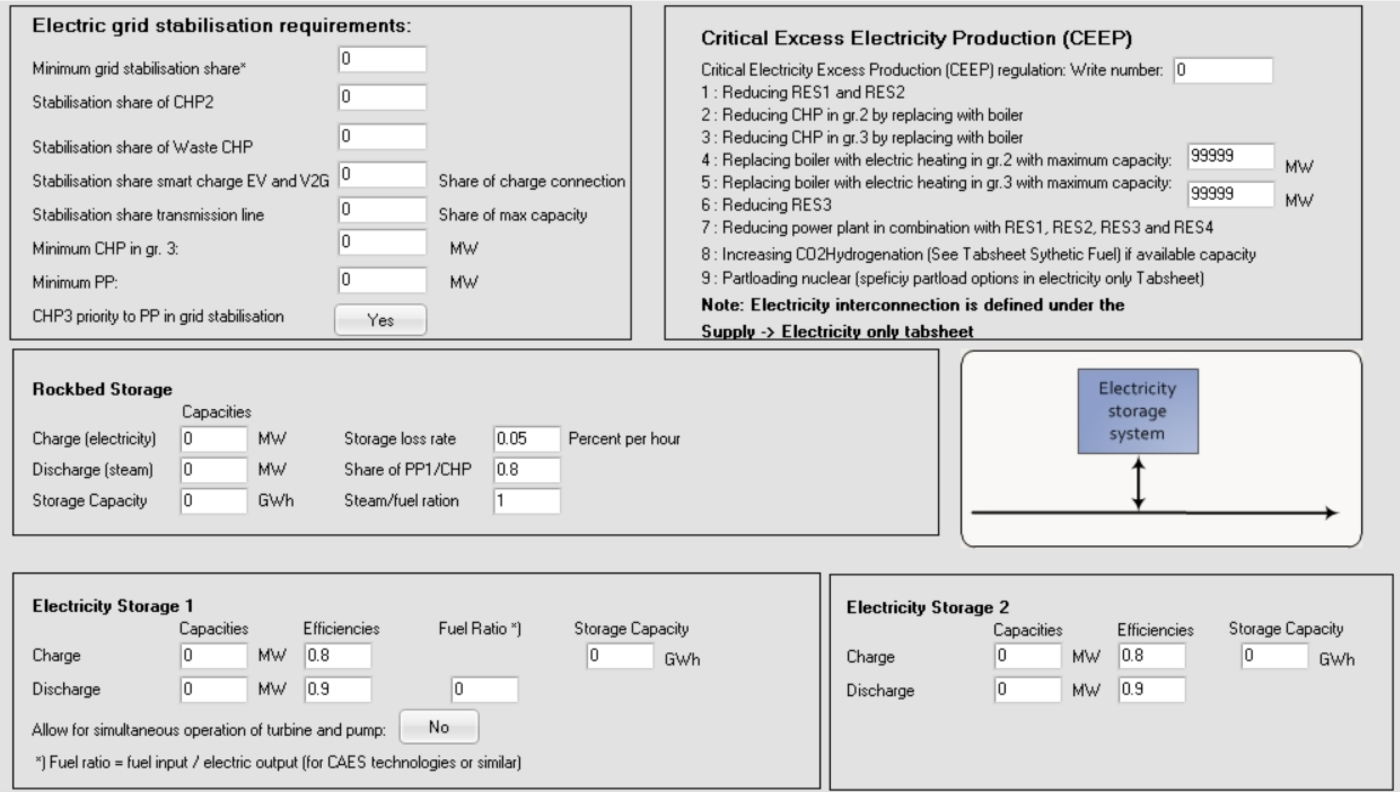

Figure 17 Balancing and storage tab in EnergyPlan

3.2.4 Simulation

As commented earlier, EnergyPLAN can be used for two kind of energy systems analysis. It can be performed a technical analysis, as in this study, where the input are the demands, capacities and efficiencies and the outputs are represented by fuel consumption, CO2 emissions and energy balance.

The other kind of analysis refers to the market exchange. It focus on the international market whit the purpose to identify the prices and the response in terms o change in import and export.

For this reason the software implements the possibility to choose a technical or a market economic simulation.

In the market-economic optimization, electricity production is determined on the basis of business economic marginal production costs of the different types of electricity-producing units.

For what concerns the technical simulation, there are the following two strategy [8]:

- Technical Regulation Strategy 1: Meeting heat demand. In this strategy, all units produce solely according to the heat demand.

- Technical Regulation Strategy 2: Meeting both heat and electricity demands with the introduction of CHP units.

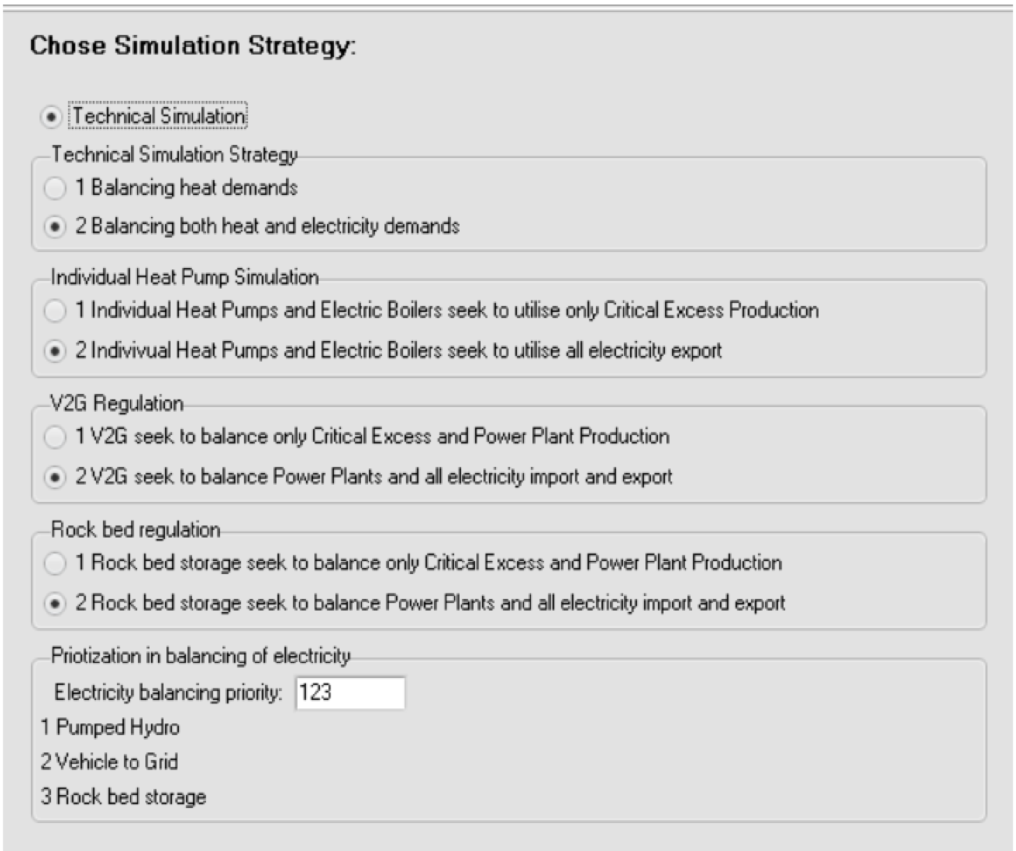

Figure 18 Simulation tab in EnergyPlan

4 The case study- Autonomous region of Catalunya

Catalunya is a Spanish autonomous community located at the north-eastern tip of the Iberian Peninsula, between the Pyrenees and the Mediterranean. It covers an area of 32,108.2 km² and has a population of 7,543,825.

Made up of four provinces, Barcelona, Gerona, Lleida and Tarragona, its capital is the city of Barcelona. It is bordered to the north by France and Andorra, to the west by Aragon, to the east by the Mediterranean Sea, and to the south by the Valencian Community.

Catalonia has a very marked geographical diversity. Its geography is conditioned by the 580 km of Mediterranean coastline and the Pyrenees mountains to the north.

It has an average altitude above sea level of close to 600 m, and the altitude ranges from 0 m to more than 3 000 m at some of the mountain peaks in the Pyrenees [11].

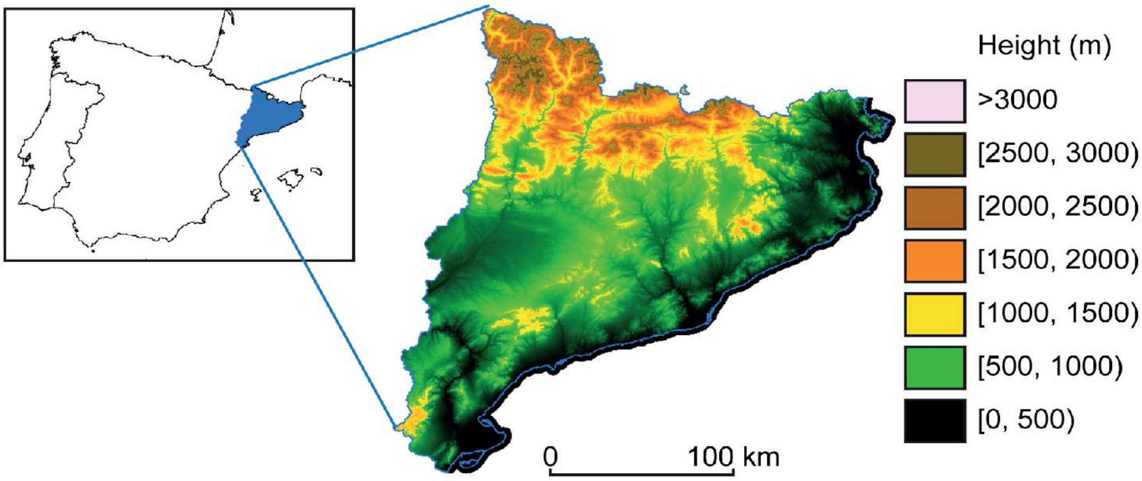

Figure 19 Altitude of different zones in Catalonia [11]

The hydrographic network can be divided in two sectors, an occidental slope or Ebro river slope and one oriental slope constituted by minor rivers that flow to the Mediterranean along the Catalan coast. The first slope provides an average of 18,700 cubic hectometres (4.5 cubic miles) per year, while the second only provides an average of 2,020 hm3 (0.48 cu mi)/year.

There is a climatic gradient going from the Pyrenean zones in the north, which have a temperate boreal climate, towards the southern zones, which have a more Mediterranean climate characterized by mild winters and dry summers. There is also a continental gradient running towards the west, where the climate is semiarid with very warm summers and colder winters.

4.1 Land use

In this study, a land use analysis will be not carried out in order to investigate the possibility to introduce more installations of renewable sources.

The information regarding the different uses of land are the following: approximately 28.7% of the land in Catalonia is devoted to crops; 15.7% is meadows and pastures, 1% is occupied by rivers, 43.4% by forests, 6.7% by urban or urbanisable areas, and 4.6% by other activities not specified in official statistics [11].

Table 2 Land use in Catalonia [12]

	Area (ha)					
	Barcelona	Girona	Lleida	Tarragona	Total	Total (%)
Road infrastructures	7543.3	2571.2	3038.2	4085.9	17238.7	0.5
Low-density urban areas	34897.7	17241.7	5080.6	13862.0	71082.0	2.2
High-density urban areas	21831.6	6103.3	5302.2	6509.3	39746.5	1.2
Industrial and commercial areas	21929.6	6360.7	8694.3	8723.0	45707.6	1.4
Rainfed herbaceous crops	130511.6	76797.8	198075.3	34971.7	440356.3	13.7
Irrigated herbaceous crops	14338.2	34502.9	98342.1	6723.5	153906.7	4.8
Rice fields	-	1030.5	64.5	21267.0	22362.1	0.7
Rainfed fruit trees	4828.5	3913.3	70315.2	108941.6	187998.7	5.9
Irrigated fruit trees	1276.1	4951.5	54392.6	25359.7	85979.8	2.7
Citrus plantations	10.8	0.1	0.9	9153.4	9165.2	0.3
Vineyards	28099.5	2478.4	4404.5	32648.3	67630.7	2.1
Sclerophyll forests	48837.9	107508.3	25319.7	16377.6	198043.4	6.2
Deciduous forests	61946.2	98892.8	116578.9	3077.9	280495.7	8.7
Needleleaf forests	221774.5	117476.3	203133.9	93530.5	635915.1	19.8
Shrublands	149477.7	75841.3	273001.3	220433.3	718753.6	22.4
Montane grasslands	3281.7	14313.9	73127.4	-	90723.0	2.8
Middle-altitude grasslands	6509.6	10095.3	24706.6	3737.8	45049.4	1.4
Lowland grasslands	2010.7	1072.2	10834.8	4785.2	18702.8	0.6
Wetland vegetation	323.9	811.8	432.1	3066.8	4634.5	0.1
Inland waters	1460.7	1596.7	8383.8	4260.1	15701.3	0.5
Permanent snowpacks	-	-	203.7	-	203.7	0.0
Burned areas	707.7	8.5	793.2	177.8	1687.0	0.1
Areas with little or no vegetation	11109.0	6380.0	32328.4	6234.8	56052.2	1.7
Sandy areas and beaches	374.6	289.5	-	2652.4	3316.5	0.1
Total	773080.9	590237.9	1216554.0	630579.6	3210452.3	100.0

4.2 Electricity demand and supply

In this research the data introduced into the model refer to the year 2019, in order to analyse a system not affected by Covid-19 pandemic.

However, the only available reference for the electricity production in Catalonia is that of Institut Català de energia in 2020.

The total electricity demand in Catalonia is 42,75 TWh considering services, residencial and domestic values.

The production of electricity in Catalonia in 2020 will be 45.315, 2 GWh, 19,8 of which will come from renewable energies, mainly hydroelectric (12%) and wind power (5,8).

More than half of the electricity produced will come from nuclear energy (54,9%).

As we see in figure below, the production of electricity from solar energy is only 1,1% of the total supply.In a region as Catalunya, where the solar irradiation can reach important values during the year, the use of solar panels shows a large potential for increase.

The remaining part of the production is carried out with combined cycle and CHP plants, respectively 12,2% and 10,9% with the use of natural gas as a fuel [3].

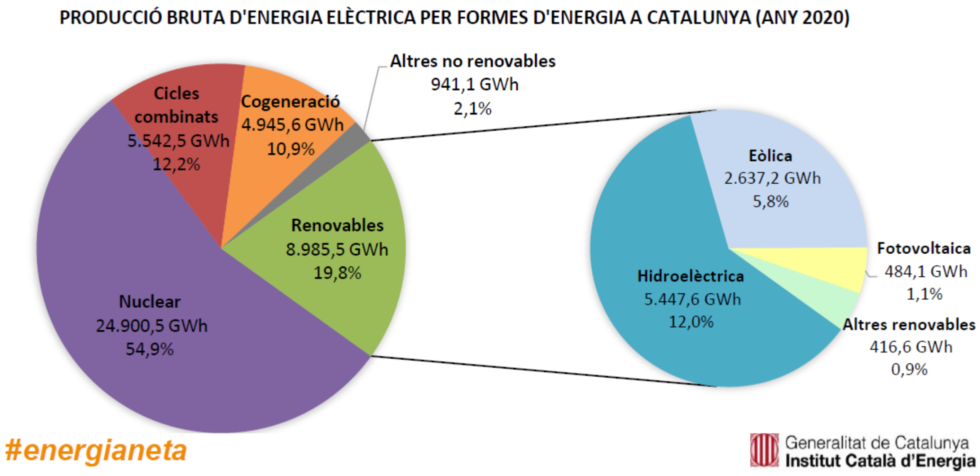

Figure 20 Electricity production in Catalonia [3]

4.2.1 Nuclear energy

As we seen in 2.2, Nuclear energy is the first source of electricity production in Catalunya with approximately 25 TWh in 2020.

There are two nuclear power plants in the region of Catalonia, located in Ascò and Vandellos with a respectively installed capacity of 1992 MW and 1045 MW. It has been introduced a capacity of nuclear equal to 3037 MW into the model; the corresponding annual production is estimated as 26.68 TWh/year, very close to the actual value explained before [13].

Table 3 Power and gross electricity production of electricity in Catalonia in 1990 and 2014 [13]

	1990			2014			Change 1990-2014	
	Power (MW)	Gross Produtcion (GWh)	% Gross Prodution	Power (MW)	Gross Produtcion (GWh)	% Gross Prodution	Power (MW)	Gross Produtcion (GWh)
Nuclear [1]	2.842,0	21.742,9	78,7%	3.146,9	23.737,1	54,1%	304,9	1994,2
Combined cycles	-	-	0,0%	4.112,0	5.223,6	11,9%	4.112,0	5.223,6
Fuel oil	2.377,6	1.405,1	5,1%	-	-	0,0%	-2.377,6	-1.405,1
Coal	160,0	837,2	3,0%	-	-	0,0%	-160,0	-837,2
Cogeneration	127.0	578.8	2.1%	876.3	5.110.9	11.7%	749.3	4.532.1

4.2.2 Combined Heat and Power plant and cogeneration

In table 3 the combined cycles (CHP) and the cogeneration power installed capacity are also illustrated [13].

In 2014 the reference value is 4112 MW for CHP plants and 876.3 MW for cogeneration with a percentage of gross production equal to 11.9% and 11.7%.

4.2.3 Renewable energy

This research wants to analyse the potential for increasing the share of renewable energy in Catalonia started from the current scenario with 19 almost 20% in the electricity sector.

The different renewable energy sources will be discussed separately.

In Catalonia the main sources are solar PV, onshore wind farms and hydroelectric plants.

Offshore wind is not currently employed, though it may be included in future scenarios.

The figure below shows the different installations of wind farm and solar panels with a visible concentration of installations in the south-west part of Catalonia.

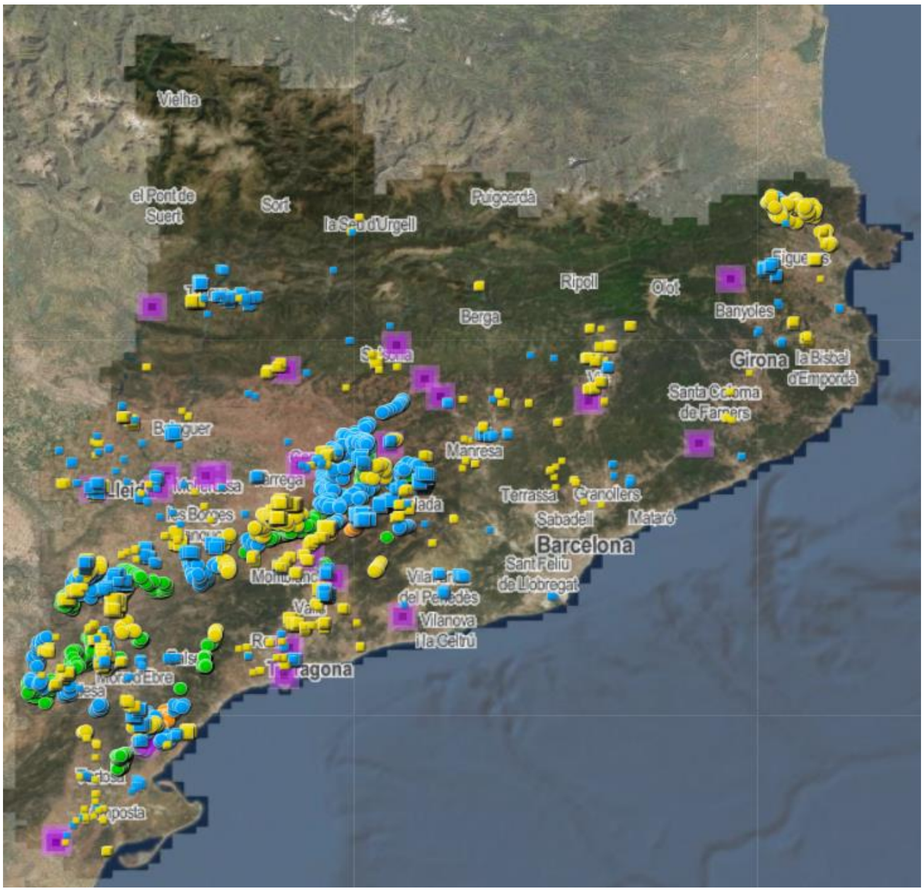

Figure 21 Renewable sources installation in Catalonia [3]

4.2.3.1 Wind energy

Wind is the second renewable source used in Catalonia with a production of electricity equal to 2 TWh in 2020.

Currently 1823 wind turbines are installed in the total area of Catalonia with an installed capacity of 1271 MW.

The following table includes the wind turbines installed for each region of Catalonia:

Table 4 Wind turbines installations in Catalonia [3]

COMARCA	EN SERVICIO	SOLICITADOS	NO VIABLES	TOTAL
Anoia	105	135	5	235
Terra Alta	148	107	61	194
Segrià	44	171	21	194
Baix Ebre	159	76	48	187
Segarra	18	153	0	171
Ribera d'Ebre	21	233	90	164
Alt Empordà	0	185	22	163
Garrigues	87	87	14	160
Conca de Barberà	78	93	38	133
Baix Camp	61	33	25	69
Urgell	26	52	10	68
Priorat	44	5	3	46
Solsonès	0	11	0	11
Bages	10	17	17	10
Alt Camp	10	0	0	10
Alt Penedès	0	21	13	8
Noguera	0	18	18	0
TOTAL	811	1397	385	1823

As we can appreciate in the following figure, hot spots for wind capturing are on the south-west part of the region with values of wind speed that can reach circa 10 m/s.

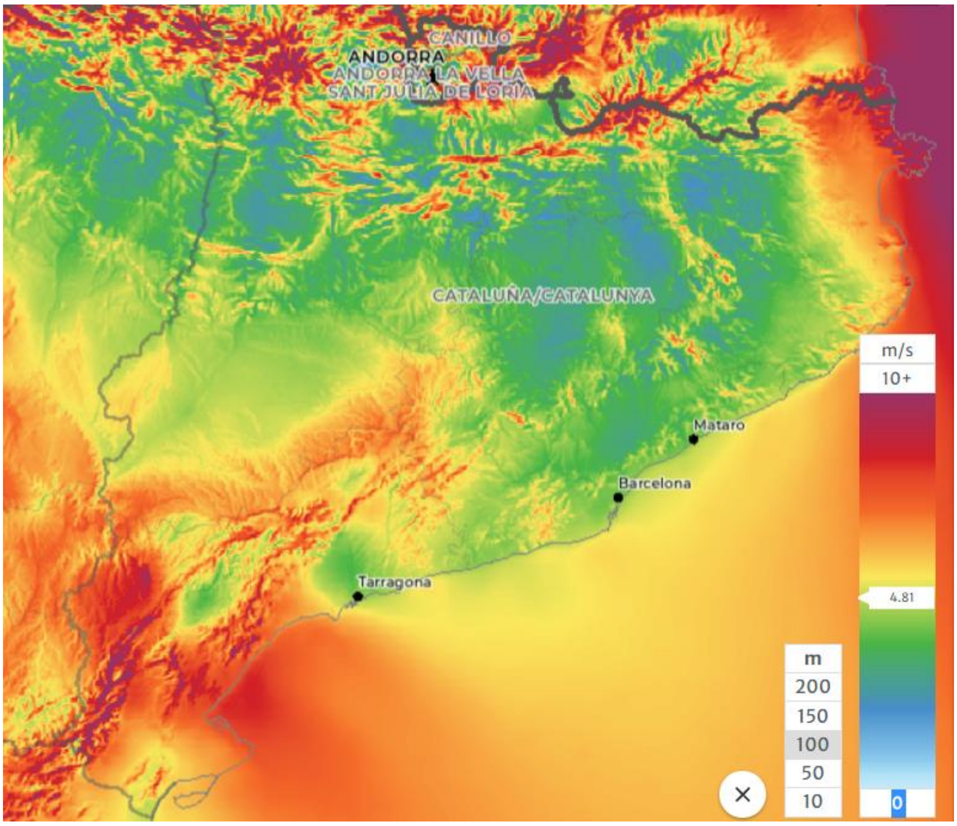

Figure 22 Wind speed in Catalonia [14]

A duration curve of wind speed in that location is the following:

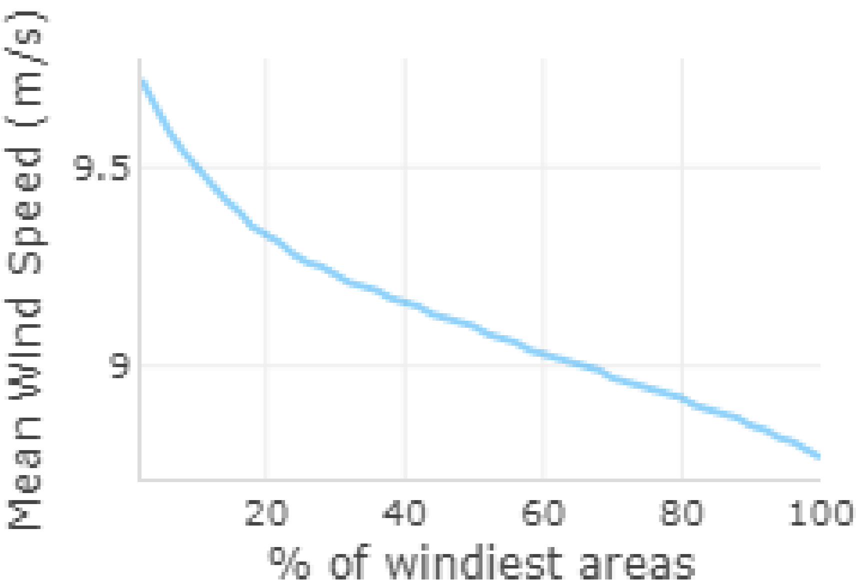

Figure 23 Duration curve of wind speed [14]

Despite of this spots, the average wind speed is around 5 m/s.

In order to reach a realistic distribution of the wind energy production during 2019 year in Catalonia, the Renewables.ninja.com website it was used [15]. Renewables.ninja.com is able to provide hourly data of production taking into account the location and the power installed.

EnergyPLAN is capable to work also with value greater than 1 and so it was possible to pass the values downloaded from [15] directly to the model.

Clearly, as it was shown in this chapter, the wind distribution and, following, the capacity to produce energy from it, is not homogeneous for the entire region.

For this reason, three different locations (Nord, South-West and South-Est) of Catalonia were analysed from the website and finally a mean of all the hourly values was performed.

The assumptions done related to these results are considering the same eight of hub and type of turbine for each wind farm.

In the figure below is it shown an example of result from the website (in this case of Lleida, Catalonia), where we can appreciate the monthly capacity factor during 2019.

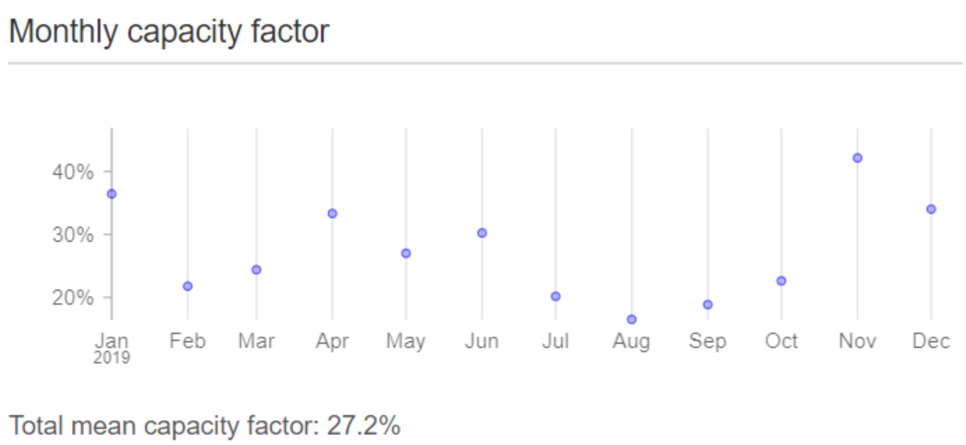

Figure 24 Monthly capacity factor of wind production in Lleida (Catalonia) [15]

4.2.3.2 Solar energy

As we have seen before, the solar energy production in Catalonia can be increased with a strategy that provides more solar panel installations in the entire area.

Despite this, the following figure shows the evolution of self-consumption PV per total power installed in kW.

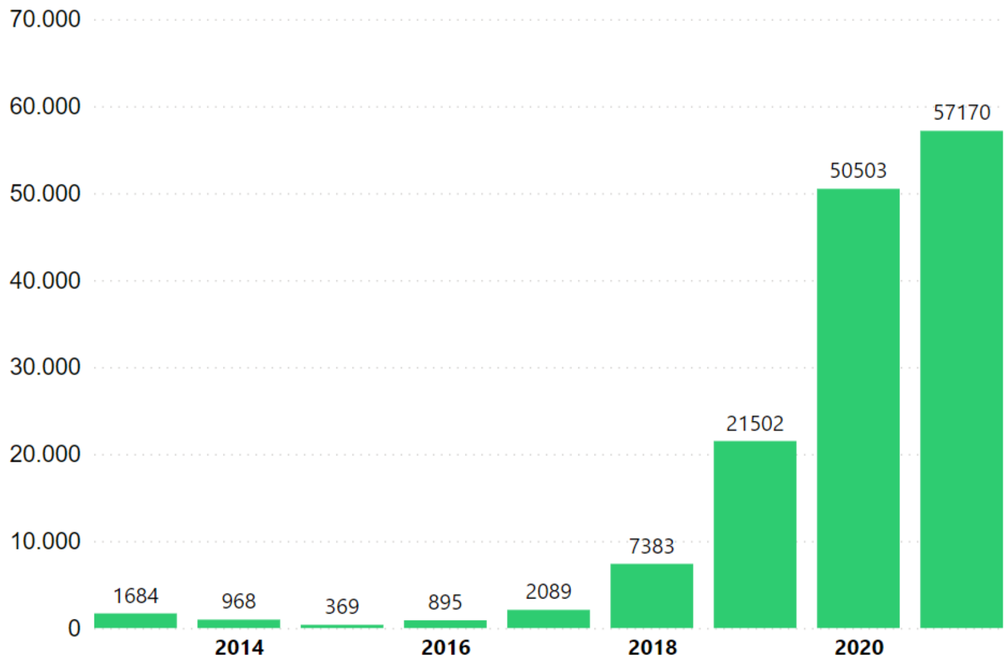

Figure 25 Evolution of self-consumption PV per total power installed in kW in Catalonia [15]

Currently the total of space used for solar panels installation is equal to 10.580 hectares with a total installed capacity of 344,5 MW.

The average annually data of solar irradiation in Catalunya has been collected in order to compare the availability of solar energy and what is actually captured from the European commission website [17]. The figure shows hourly values of power density in Catalunya in 2016.

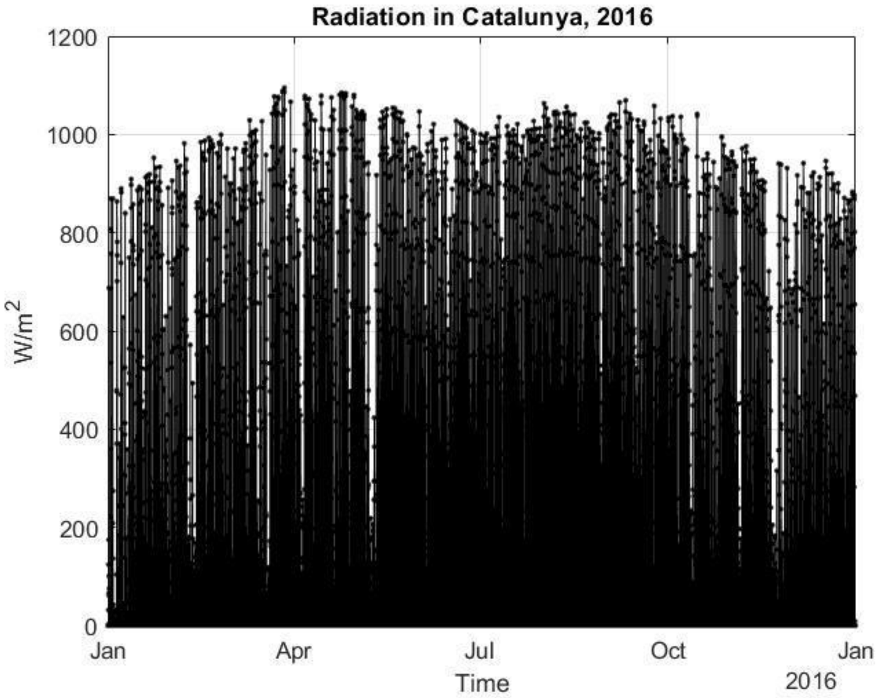

Figure 26 Radiation in Catalunya in 2016

Integrating the power in the time it is possible to reach the value of energy produced. It means to perform a cumulative sum in 365 days.

Using an assumption of 20% of efficiency for all the solar panels installed, it was possible to obtain the solar energy produced in one year.

A comparison of energy available per m^2 and electricity produced is carried out:

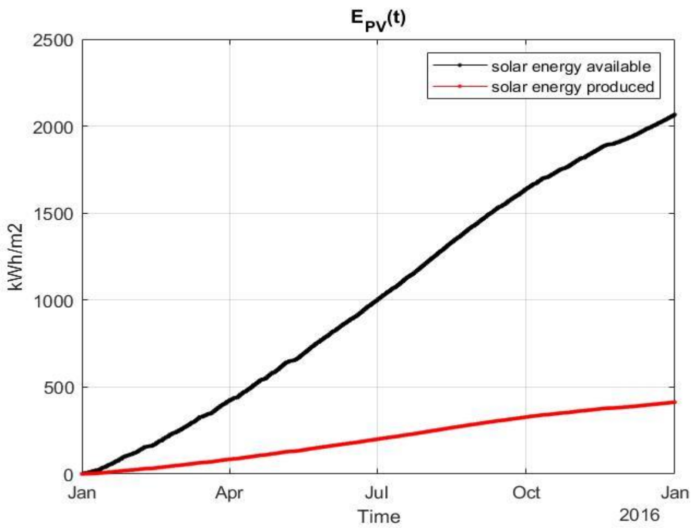

Figure 27 Comparison of energy available and electricity produced

After one year, 412 kWh/m^2 are produced.

As we seen in chapter 4.2.3.1, the same process was performed for the evaluation of the hourly distribution of energy generated by solar panels in Catalonia.

The following figure shows the different capacity factors for each month in 2019:

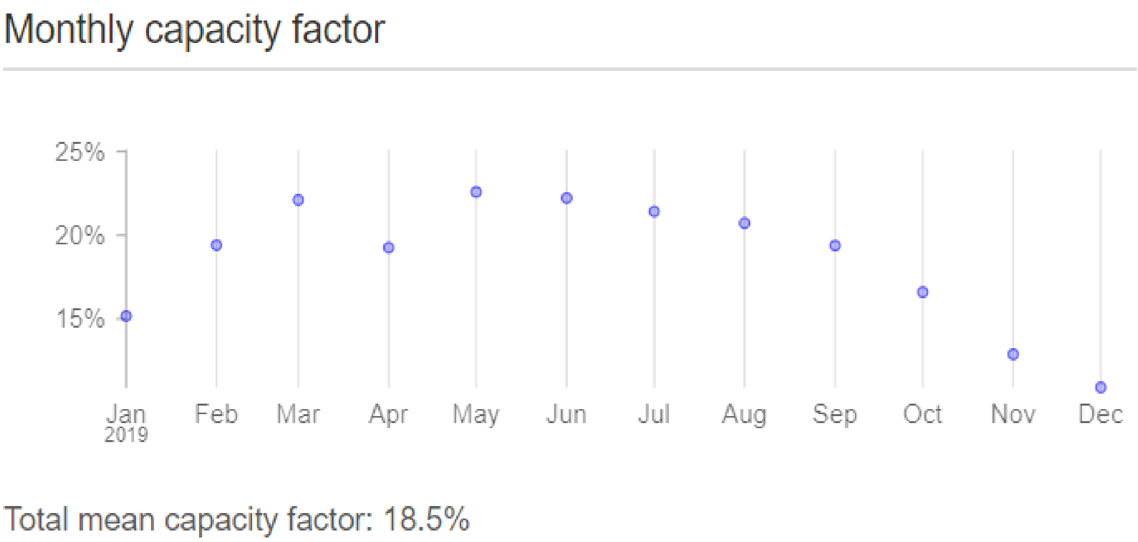

Figure 28 Monthly capacity factor of solar panels (PV) in Lleida (Catalonia) [15]

4.2.3.3 Hydro energy

Currently, hydropower leads the first place regarding the electricity production (8.5% of the electric production) from renewable sources with an installed capacity around 1922 MW [3].

The total production in Catalonia is splitted over these different plants:

38 plants > 10 MW

- Sallente (451 MW) – Lleida (PUMPED)
- Mequinensa (312 MW) - Baix Cinca (Aragó)
- Riba-roja (263 MW) - Tarragona
- Tavascan (152 MW) – Lleida (PUMPED)

Sallente and Tavascan plants are provided with a pumped hydro storage system.

In order to build up an hourly distribution for this kind of renewable energy, I assumed a constant value for each month considering the total production in Spain in 2019.

The lack of data for Catalunya leads to use in the model production values (0-100%) looking to the national production in 2019 shown in figure 29:

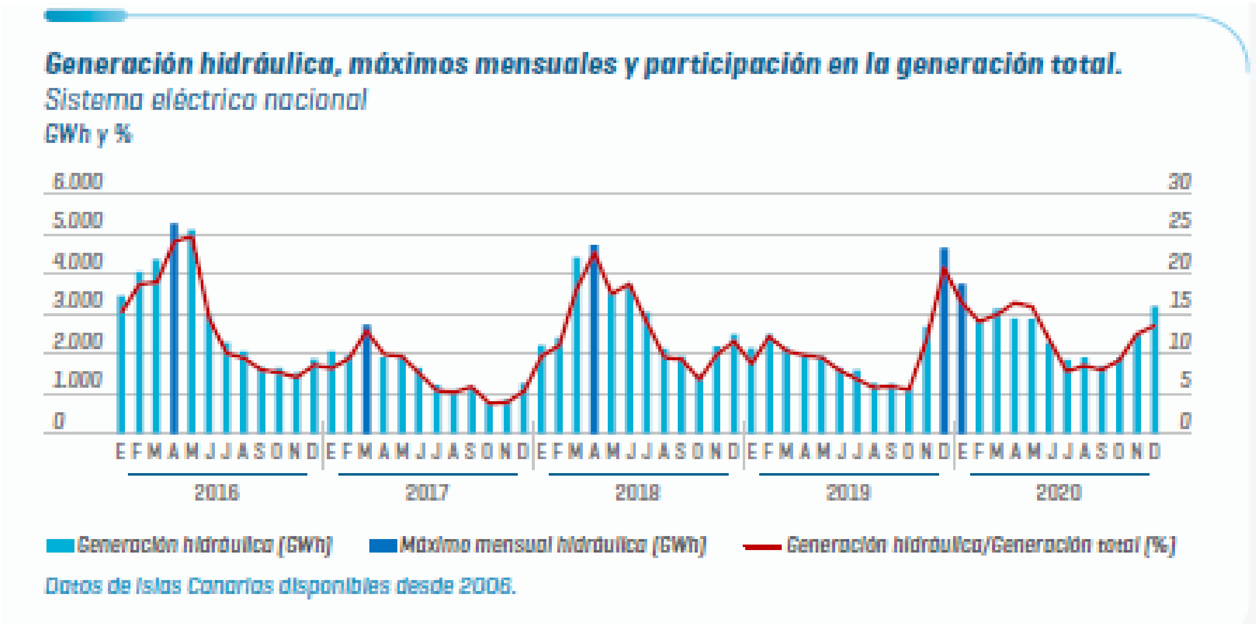

Figure 29 Monthly percentage of hydroelectric generation in Spain [18]

It has consisted into an iterative process, which could only be concluded once the output results (year production) from the model were similar to the reference value in 2019.

4.3 Heating sector

The heating sector is analysed, separately, as individual heating and district heating.

4.3.1 District heating

The region of Catalonia occupies first place for percentage of district heating distribution networks installed in Spain with 32.4% with a total installed capacity pf 490 MW [16].
All the district heating in Catalonia [19] use biomass as energy consumed and all of them are located in:

- Balaguer (LLeida)
- Ripoli (Girona)
- Planoles (Girona)
- Brull (Barcelona)
- Lles de Cerdanya (Lleida)
- Esterri de Aneu (Lleida)
- De Ger (Girona)
- Calders (Barcelona)
- Campdevanol (Girona)

Despite this, the contribution of district heating to the energy system is negligible and it will not take into account in this study.

4.3.2 Individual heating

Taking into consideration that district heating is negligible, the total heat demand of the model is related to the individual heating. The individual heating refers to the individual boilers used in the houses of Catalonia. So, the input required is the fuel demand in one year. In the figure below, it is shown the values of different fuels demand in in Catalonia in 2019.

Table 5 Fuel consumption for individual boilers [3]

Coal	0.0	0.0	0.0	0.0	0.0
Liquefied petroleum gasses	102.4	101.2	106.5	100.2	93.8
Kerosene	0.3	0.1	0.1	0.1	0.0
Gas-oil	204.3	205.7	203.0	224.0	233.3
Fuel-oil	0.0	0.0	0.0	0.0	0.0
Petroleum coke	0.2	0.1	0.1	0.1	0.0
Natural gas	802.2	756.3	780.5	885.9	832.2
Electric energy	838.7	842.0	856.6	877.5	866.1
Renewable energies (1)	90.2	87.1	90.3	90.6	97.6

4.4 Transport sector

Transport sector in Catalonia is dominated by the use of gas-oil with 42.58 TWh per year.

JP (jet fuel) is the second fuel for consumption with 16.6 TWh per year, gasoline, Natural Gas and LPG follow them with respectively 11, 0.36 and 0.18 TWh per year [3].Regarding biofuel consumption, in Spain most common diesel sold are with 7.5 and 10 percentage of biofuel. The Spain Biofuel Policy report [20] has recorded the increase of percentage of biofuel in Spain, from 4.3% in 2016 to 8.5% in 2020. As a result, in this paper 3.62 TWh/year of biofuel have been considered.

Table 6 Fuel consumption of transport sector [3]

Liquefied petroleum gasses	8.5	8.8	9.5	11.3	15.4
Kerosene	1,160.5	1,195.9	1,253.4	1,304.5	1,430.5
Gasoline	772.1	809.8	819.1	873.9	949.2
Gas-oil	3,385.3	3,506.1	3,536.7	3,591.2	3,661.2
Fuel-oil	49.0	63.0	61.3	67.0	65.3
Natural gas	25.0	25.6	26.6	28.4	31.3
Electric energy	86.4	86.8	89.7	89.8	89.7
Renewable energies (2)	160.4	177.4	206.3	267.3	273.3

4.5 Industry and fuel

Fuel consumption in industry sector is mainly composed by the Natural Gas with 19.71 TWh per year, followed by biomass, oil and coal with respectively 1.54, 0.9 and 0.25 TWh per year [3].

Table 7 Fuel consumption of industrial sector [3]

Coal	20.5	20.5	21.9	20.9	21.5
Liquefied petroleum gasses	9.6	9.3	9.8	9.8	7.8
Gas-oil	63.9	62.2	62.0	62.7	62.2
Fuel-oil	26.4	22.4	19.2	16.6	16.0
Petroleum coke	260.5	276.5	277.1	280.3	258.1
Natural gas	1,600.9	1,604.3	1,664.1	1,706.9	1,695.0
Electric energy	1,425.8	1,438.3	1,483.6	1,395.7	1,396.1
Non renewable waste	82.9	91.8	93.1	86.0	93.1
Renewable energies (1)	87.5	95.4	110.9	115.8	132.5
Solar thermal	0.5	0.5	0.5	0.5	0.5

5 Results

In this chapter, the future possibilities of Catalunya for sustainable energy management will be studied. Due to the lack of a study on the land availability for installation of new wind turbines, solar panels, etc., the Proencat study for 2050 [2] will be taken as a reference for the true possibilities of Catalonia

From [2] we can appreciate as by 2030, Catalunya is expected to have 1,000 MW of offshore wind energy, while by 2050 the need for this offshore energy source is estimated at 3,500 MW. Regarding the solar panels, the prospective energy scenario for Catalunya, photovoltaic power (344 MW) should increase 18-fold by 2030 (6,272 MW) and 68-fold by 2040 (23,885 MW), which gives an idea of the challenge posed or the difficulties in changing to a scenario without nuclear power. The capacity of combined cycle thermal plants would be reduced by 54% in 2030 and their presence would disappear by 2040.

These informations are crucial in order to analyse if it will be possible to reach the goal of 100% of renewables in 2050 scenario.

5.1 Catalunya 2019 scenario on EnergyPLAN

Once all the information are collected and each tab is fulfilled, the model must be validate. In order to validate the effectiveness of the model, the output values must be run from the software.

The following figure describes how the input and output are collected by EnergyPLAN:

Input Catalunya_2019.txt — The EnergyPLAN model 16.1

Electricity demand (TWh/year):		Flexible demand	0.00
Fixed demand	42.75	Fixed imp/exp.	0.00
Electric heating + HP	0.00	Transportation	0.00
Electric cooling	1.76	Total	44.51

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.00	0.00	0.00	0.00
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.00	0.00	0.00	0.00

Wind	1271	MW	3.15	TWh/year	0.00	Grid
Photo Voltaic	344	MW	0.62	TWh/year	0.00	stabili-
Wave Power	0	MW	0	TWh/year	0.00	sation
River Hydro	1922	MW	5.12	TWh/year	0.00	share
Hydro Power	0	MW	0	TWh/year		
Geothermal/Nuclear	3037	MW	26.68	TWh/year		

	Capacities		Efficiencies		
Group 2:	MW-e	MJ/s	elec.	Ther	COP
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Condensing	4112		0.45		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0.00	0.00
Gr.2:	0.00	0.00
Gr.3:	0.00	0.00

Regulation Strategy:	Technical regulation no. 2	
CEEP regulation	160000000	
Minimum Stabilisation share	0.00	
Stabilisation share of CHP	0.00	
Minimum CHP gr 3 load	0	MW
Minimum PP	0	MW
Heat Pump maximum share	1.00	
Maximum import/export	5000	MW
Distr. Name :	Hour_nordpool.txt	
Addition factor	0.00	DKK/MWh
Multiplication factor	2.00	
Dependency factor	0.00	DKK/MWh pr. MW
Average Market Price	227	DKK/MWh
Gas Storage	0	GWh
Syngas capacity	0	MW
Biogas max to grid	0	MW

Fuel Price level:

	Capacities	Storage	Efficiencies	
Elec. Storage	MW-e	GWh	Elec.	Ther.
Charge 1:	0	0	0.80	
Discharge 1:	0		0.90	
Charge 2:	0	0	0.80	
Discharge 2:	0		0.90	
Electrolysers:	0	0	0.80	0.00
Rockbed Storage:	0	0	1.00	
CAES fuel ratio:	0.000			

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	70.18	0.36	0.00
Household	0.00	2.71	9.78	1.13
Industry	0.25	0.90	19.71	1.54
Various	0.00	0.00	0.00	0.00

Output

	District Heating										Electricity																		Exchange	
	Demand	Production									Consumption						Production							Balance					Payment	
	Distr. heating MW	Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW	Elec. demand MW	Flex.& Transp. MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Imp Million DKK	Exp
January	0	0	0	0	0	0	0	0	0	0	5089	0	0	0	0	0	0	1415	0	3037	0	0	833	100	0	196	0	196	0	28
February	0	0	0	0	0	0	0	0	0	0	4972	0	0	0	0	0	0	642	0	3037	0	0	1331	100	0	38	0	38	0	5
March	0	0	0	0	0	0	0	0	0	0	4608	0	0	0	0	0	0	1017	0	3037	0	0	664	100	0	110	0	110	0	15
April	0	0	0	0	0	0	0	0	0	0	4503	0	0	0	0	0	0	1156	0	3037	0	0	545	100	0	235	0	235	0	34
May	0	0	0	0	0	0	0	0	0	0	4625	0	0	0	0	0	0	937	0	3037	0	0	737	100	0	86	0	86	0	12
June	0	0	0	0	0	0	0	0	0	0	4992	0	0	0	0	0	0	980	0	3037	0	0	1018	100	0	43	0	43	0	6
July	0	0	0	0	0	0	0	0	0	0	5676	0	0	0	0	0	0	867	0	3037	0	0	1781	100	0	9	0	9	0	1
August	0	0	0	0	0	0	0	0	0	0	5445	0	0	0	0	0	0	842	0	3037	0	0	1567	100	0	1	0	1	0	0
September	0	0	0	0	0	0	0	0	0	0	4993	0	0	0	0	0	0	978	0	3037	0	0	1052	100	0	74	0	74	0	13
October	0	0	0	0	0	0	0	0	0	0	4711	0	0	0	0	0	0	947	0	3037	0	0	806	100	0	78	0	78	0	13
November	0	0	0	0	0	0	0	0	0	0	6814	0	0	0	0	0	0	1238	0	3037	0	0	2547	100	1	9	0	9	0	1
December	0	0	0	0	0	0	0	0	0	0	4405	0	0	0	0	0	0	1119	0	3037	0	0	511	100	0	263	0	263	0	41
Average	0	0	0	0	0	0	0	0	0	0	5067	0	0	0	0	0	0	1013	0	3037	0	0	1113	100	0	96	0	96	Average price	
Maximum	0	0	0	0	0	0	0	0	0	0	8927	0	0	0	0	0	0	2403	0	3037	0	0	4985	100	294	2925	0	2925	(DKK/MWh)	
Minimum	0	0	0	0	0	0	0	0	0	0	1018	0	0	0	0	0	0	295	0	3037	0	0	0	100	0	0	0	0	256	202
TWh/year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	44.51	0.00	0.00	0.00	0.00	0.00	0.00	8.90	0.00	26.68	0.00	0.00	9.78		0.00	0.84	0.00	0.84	0	169

FUEL BALANCE (TWh/year):	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste/ HTL	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th.	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	-	5.43	-	-	-	-	-	-	-	-	-	-	-	-	-	0.25	5.68	0.00	5.68	1.94	1.94
Oil	-	-	-	-	-	5.43	-	-	-	-	-	-	-	-	-	-	-	70.18	2.71	0.90	79.22	0.00	79.22	21.10	21.10
N.Gas	-	-	-	-	-	5.43	-	-	-	-	-	-	-	-	-	-	-	0.54	9.78	19.71	35.46	0.00	35.46	7.24	7.28
Biomass	-	-	-	-	-	5.43	-	-	-	-	-	-	-	-	-	-	-	-	1.13	1.54	8.10	0.00	8.10	0.00	0.00
Renewable	-	-	-	-	-	-	-	-	-	-	-	-	3.15	0.62	-	5.12	-	-	-	-	8.90	0.00	8.90	0.00	0.00
H2 etc.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Biofuel	-	-	-	-	-	-	-	-	-	-	-3.62	-	-	-	-	-	-	3.62	-	-	0.00	0.00	0.00	0.00	0.00
Nuclear/CCS	-	-	-	-	-	-	76.22	-	-	-	-	-	-	-	-	-	-	-	-	-	76.22	0.00	76.22	0.00	0.00
Total	-	-	-	-	-	21.73	76.22	-	-	-	-3.62	-	3.15	0.62	-	5.12	-	74.34	13.62	22.40	213.58	-1.86	211.72	30.29	30.32

Figure 30 EnergyPlan results

Firstly, all the capacities, distributions and demands (heating, electricity, transport, household and industry) need to be checked. In the output table, instead, the consumption values must be verified, and the following production units need to produce the amount of required energy. Afterwards, the energy outputs from the model must be compared with those of the actual energy system.

To compare the model created and the actual management in Catalunya, two parameters were taken into account:

- <u>Renewables energy production</u>:

From [3] it is known that for the electricity production in Catalunya in 2019, the renewables sources used were photovoltaics, wind farms and hydroelectric plants.

The values recorded from solar, wind and hydro were respectively 0,416 TWh, 2,63 TWh and 5,4 TWh.

The following figure shows the output values from the model for each of these renewable sources:

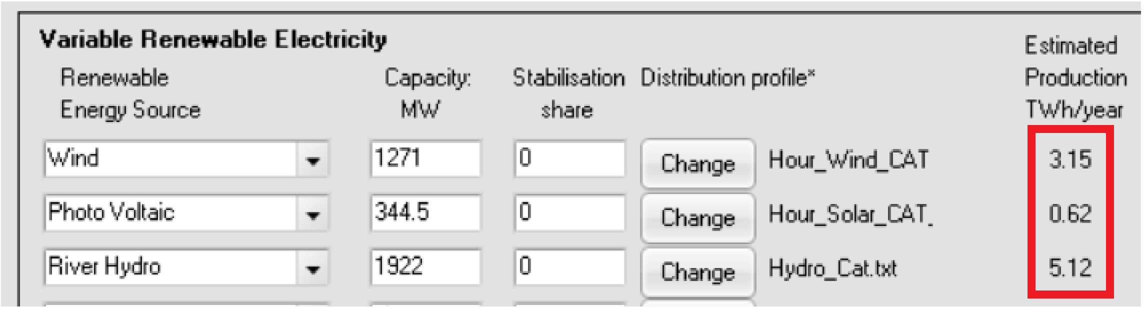

Figure 31 Renewable electricity in reference model

The estimated production values are extremely similar to that recorded by the "Institut Català d'energia".

- <u>CO_2 emissions</u>

One of the most important outputs that the software generates is the emissions of CO_2 produced by the system.

The value of emissions related to the model built is 30.29 million of tons, as it is shown in the following figure:

CO2 emission (Mt):

Total	Net
1.94	1.94
21.10	21.10
7.24	7.28
0.00	0.00
0.00	0.00
0.00	0.00
0.00	0.00
0.00	0.00
30.29	30.32

Figure 32 CO2 emissions in reference model

5.2 Current scenario without nuclear

It is well known that it is not feasible to shut down the nuclear plant in the current state, but as a first analysis on the model on enrgyPLAN it would be useful to observe how the software respond to such a change.

So, if hypothetically, Catalonia is no longer producing nuclear energy, by keeping the actual energy management in 2019, the results from the model will be as following:

- The renewable share increases, reaching a production of 16.86 TWh/year.

Table 8 Electricity share of RES with and without nuclear

SHARE OF RES (incl. Biomass):	Without nuclear	Ref scenario	
RES share of PES	16	8	percent
RES share of elec. prod.	39.4	26.5	percent
RES electricity prod.	16.86	11.33	TWh/year

- The total nuclear fuel consumption decreases, passing from 76 to 0 TWh, but coal, Ngas, biomass and oil have increased considerably, as it is shown in the following table:

Table 9 Fuel consumption outputs with and without nuclear

ANNUAL FUEL CONSUMPTIONS (TWh/year)	Without nuclear	Ref scenario	
Fuel Consumption (total)	191.95	213.58	TWh/year
CAES Fuel Consumption	0	0	TWh/year
Fuel(incl.Biomass excl.RES)	183.06	204.69	TWh/year
Fuel Consumption (incl. H2)	191.95	213.58	TWh/year
Fuel Consumption (corrected)	194.78	211.72	TWh/year
Coal Consumption	19.33	5.68	TWh/year
Oil Consumption	92.87	79.22	TWh/year
Ngas Consumption	49.11	35.46	TWh/year
Biomass Consumption	21.75	8.1	TWh/year
Nuclear Fuel Consumption	0	76.22	TWh/year

- Consequently, the fossil fuel power plant production has increased drastically.

Table 10 Power plants consumption with and without nuclear

TWh/year	Without nuclear	Ref scenario
Coal	19.08	5.43
Oil	19.08	5.43
N.Gas	19.08	5.43
Biomass	19.08	5.43
Renewable	0	0
H2 etc.	0	0
Biofuel	0	0
Nucl/CCS	0	0
Total	76.32	21.73

The final and more remarkable result from this analysis is related to the abrupt change of CO_2 emissions:

Table 11 CO2 emissions with and without nuclear

ANNUAL CO2 EMISSIONS (Mt):	Without nuclear	Actual scenario
CO2-emission (total)	41.378	30.288
CO2-emission (corrected)	41.414	30.325

As it is shown, shutting down the nuclear plant without any other change in the management of energy production will result to the increase of 10 million of tons per year of CO_2.

5.3 Scenario 2030

This scenario refers to the energy system envisaged by Catalonia for the year 2030. The idea behind this analysis is investigating the changes of the reference scenario installing the renewable source capacity wanted for 2030.

As it is known from chapter 1.1 of this study, the capacity required for solar and onshore wind energy is respectively 5 GW and 6.3 GW. In addition to the increase of the cited sources of energy, offshore wind is introduced in this scenario with a capacity of 1 GW installed.

With these new installations, the electricity generation from renewable sources undergoes a significant change. The estimated production from solar, onshore, and offshore wind are now respectively 11.33, 12.61, and 2.48 TWh/year. The overall electricity production is about 30 TWh per year with a RES share of electricity percentage equal to 71.6%.

The RES share of electricity percentage has passed from circa 20 (reference scenario) to 71.6, not only thanks to the new capacity of renewable introduce into the model, but also because of the reduction of 54% production of CHP plants and 40% of power plants. The CHP electric capacity in this scenario is equal to 2220 MW_e.

Considering the great difficulties of giving up nuclear power as early as 2030, the production of nuclear energy is considered as in the reference scenario.

Compression heat pumps are also introduced into the model with an electric capacity equal to a 20% of CHP capacity, equal to 822 MW-e. This is considered as an accurate initial value from [1] when performing a future analysis of heat pumps installations.

With all these changes brought to the system, a decrease in natural gas and coal consumption can be noticed with a value respectively of 32 and 2.85 TWh per year.

The annual CO_2 emissions has passed from 30 to 18 million tons.

In terms of costs of the system, a reduction of the annual value is noted. The value of the reference scenario, equal to 1 570 million of euros, is slightly reduced to 1 297 million of euros.

5.4 Scenario 2050

The 2050 scenario represents the model in which more changes can be introduced aiming to the smart energy system introduced in 1.2.2. With this scenario, it has been analysed the steps to do to shut down the nuclear, CHP and power plants in Catalonia.

As in the 2030model, the capacity of renewable sources expected by 2050 from [2] have been set into the system. Recalling that hydro energy is considered kept constant as in the reference scenario, the capacity of solar, onshore, and offshore wind will be now equal to, respectively, 24 GW,19 GW, and 3.5 GW.

The overall electricity production from renewable sources reaches now about 104 TWh per year, enough to satisfy the electricity demand of the system. The nuclear, CHP and power plants production are set to be zero.

Considering the changes introduced in 1.2.2 for the transition to a smart energy system, the scenario 2050 is characterized by the following innovation:

- District heating with 5 TWh of production.
- Solar thermal system with 2 TWh/year of production.
- Compression heat pumps with 2000 MW-e of electric capacity.
- Absorption heat pumps of 2 TWh/year.

- Waste incineration (considering a constant maximum hourly distribution of production) with:
    - 2 TWh/year of waste input.
    - 1.40 TWh/year of electricity production.
    - 1 TWh of biofuel production for transportation.

- Biofuel generation plants:
    - 20 TWh of biodiesel from 20.83 TWh/year of dry biomass.
    - 8 TWh of biopetrol from 22 TWh/year of biomass.
    - 10 TWh of bioJetPetrol from 27.65 TWh/year of biomass.

- Electrolysers with 4000 MW-e of capacity and 100 GWh of hydrogen storage that satisfy the hydrogen demand of:
    - 10 TWh for transport.
    - 0.89 TWh for hydrothermal liquefaction (HTL).

- Hydrothermal liquefaction (HTL) with input as hydrogen, waste, and biomass to produce:
    - 0.41 TWh of BioJetPetrol
    - 1.09 TWh of biodiesel
    - 0.58 TWh of methanol
    - 0.16 TWh of BioPetrol

- Electricity storage capacity (V2G) of 100 GWh.

- Thermal storage of 10 GWh.

With these innovations brought to the system: the transport sector is consuming only biofuel and electrofuel; the heating sector has been reduced oil (from 2.17 to 1.47 TWh/year) and natural gas (from 9.78 to 2.50 TWh/year) thanks to thermal energy storage; electricity has reached 117% of RES share.

The fuel consumption consists of biomass (55 TWh/year), waste (3 TWh/year), hydrogen (123 TWh/year), natural gas (20.76 TWh), oil (1.78 TWh) and coal (0.25 TWh) with a total of 225 TWh per year.

Despite the changes of the system, natural gas, oil, and coal are still being consumed in this scenario. The presence of oil is completely due to the individual heating (boilers). The consumption of natural gas, instead, is due to partially individual heating and partially to industry sector.

To completely replace the remaining fossil fuels, there would be a need for a large quantity of biomass and hydrogen consumption. This is considered unfeasible due to the space needed for biomass production and to the increase of annual costs of investments required for the hydrogen production. Since in this study the demand is considered constant for each scenario, these results highlight the reduction of the fuel demand as a crucial step for the transition to a smart energy system.

As a result, the emissions of CO2 have drastically reduced from 30 million of tons (2019) to 5 million of tons.

5.5 Comparison of results

A comparison of results for the three different scenarios is performed in this chapter.

In figure 32, the increase of capacity installed of renewable sources from scenario 2019 to 2030 is shown :

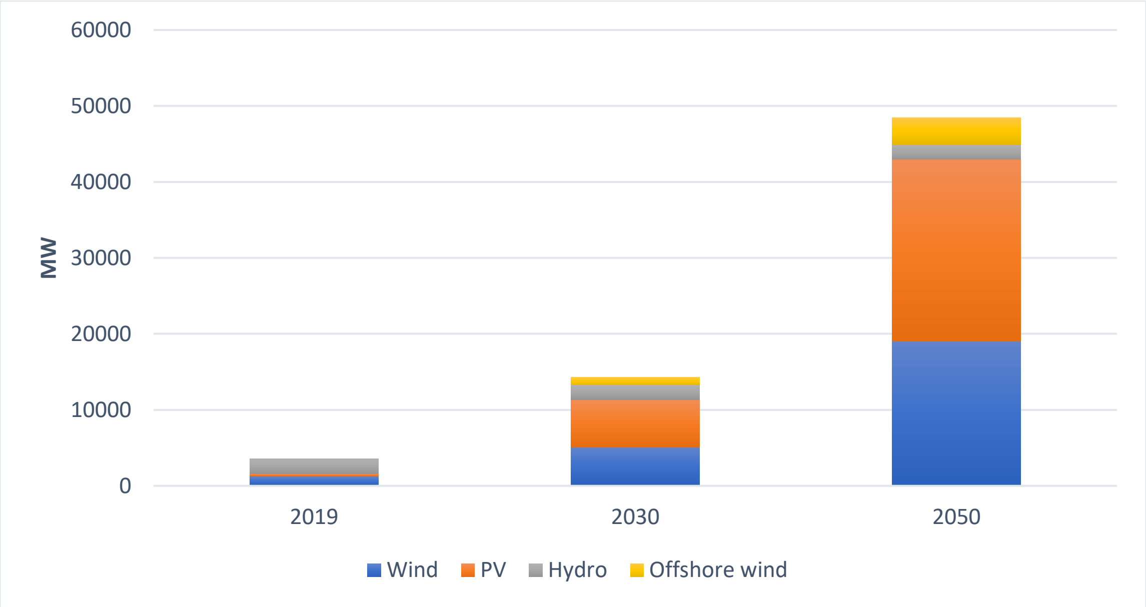

Figure 32 Capacity installed of renewable sources for each scenario

Thanks to the large increase of capacity installed, the electricity production is progressively raised as shown in the following figure:

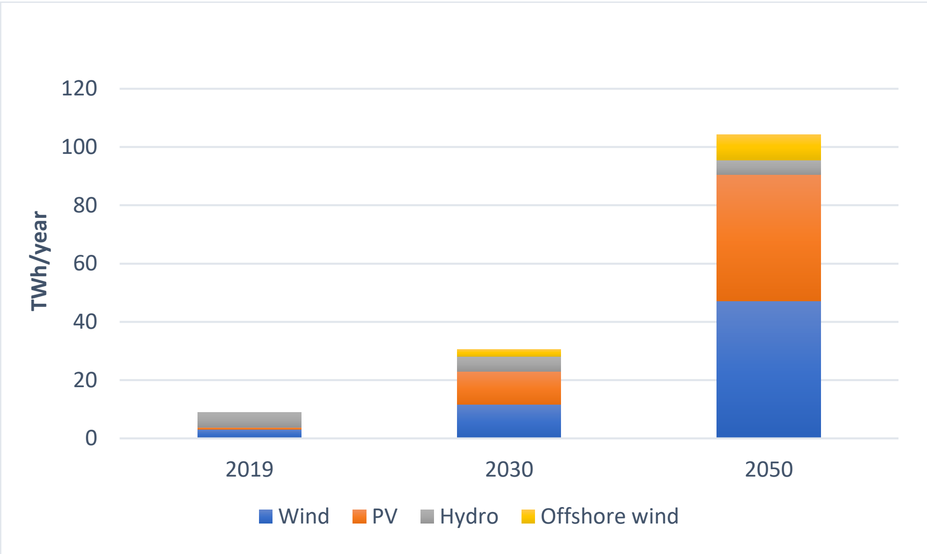

Figure 33 Renewable electricity production in different scenario

As it is shown in figure 32, in 2030 it can be appreciated a slight reduction of fuel consumption. In 2050 the overall consumption is increased almost reaching the total value of 2019. In 2050 the fuel used are primarily hydrogen and biomass, with the introduction of waste input in the system. As explained in 5.4, natural gas is still present in this scenario. Figure 33 shows the quantity of hydrogen and biomass needed to fully replace natural gas.

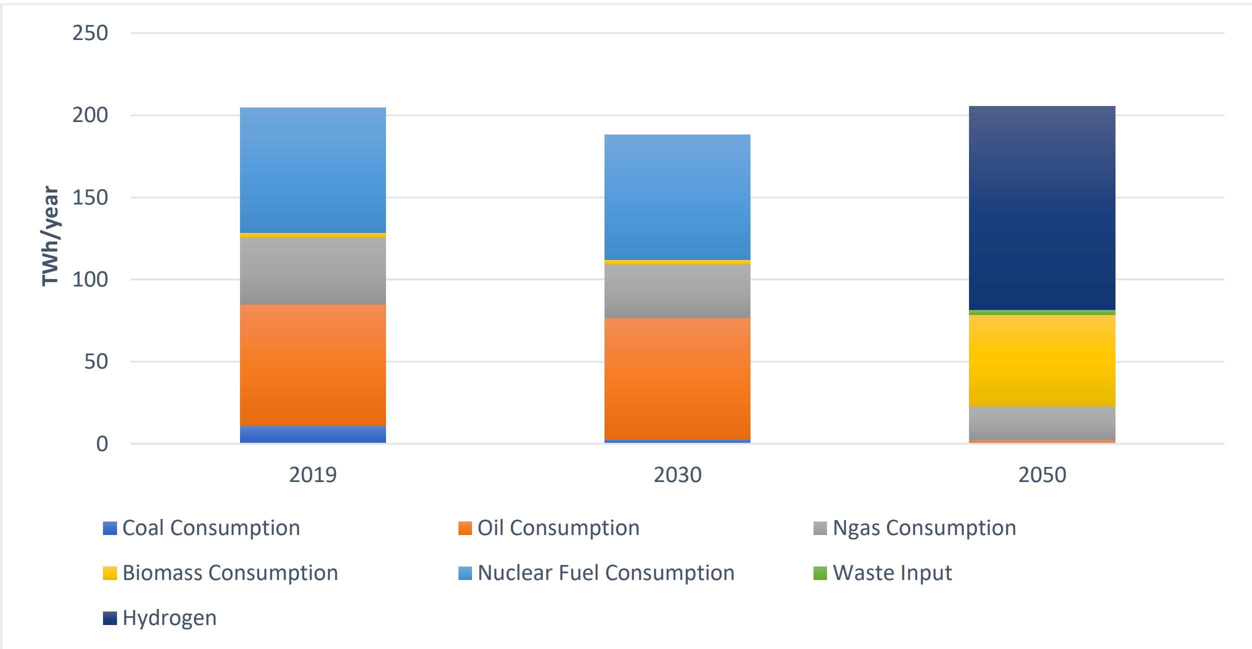

Figure 34 Fuel consumption of different scenarios

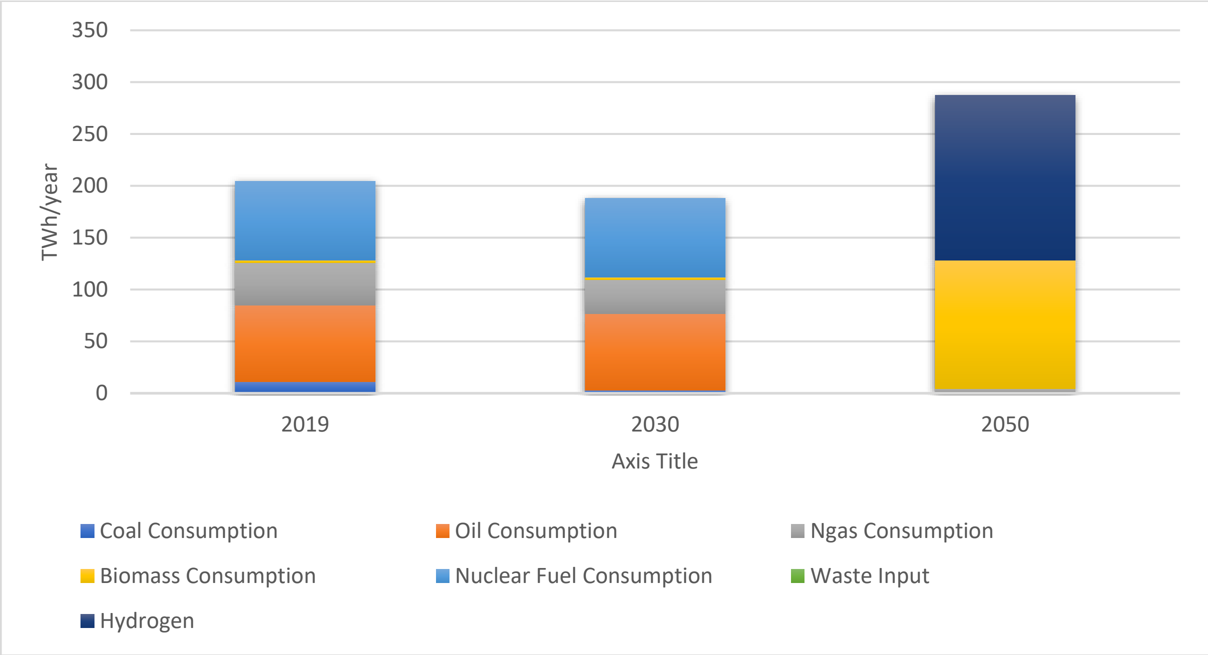

Figure 35 Fuel consumption required to fully replace natural gas

As it can be appreciated in figure 33, the quantity of biomass and hydrogen needed to replace natural gas reach values considered unfeasible in terms of land space and costs required.

For what concern the emissions of CO2, in 2030 scenario the value are almost halved and in 2050 reduced by 6 times:

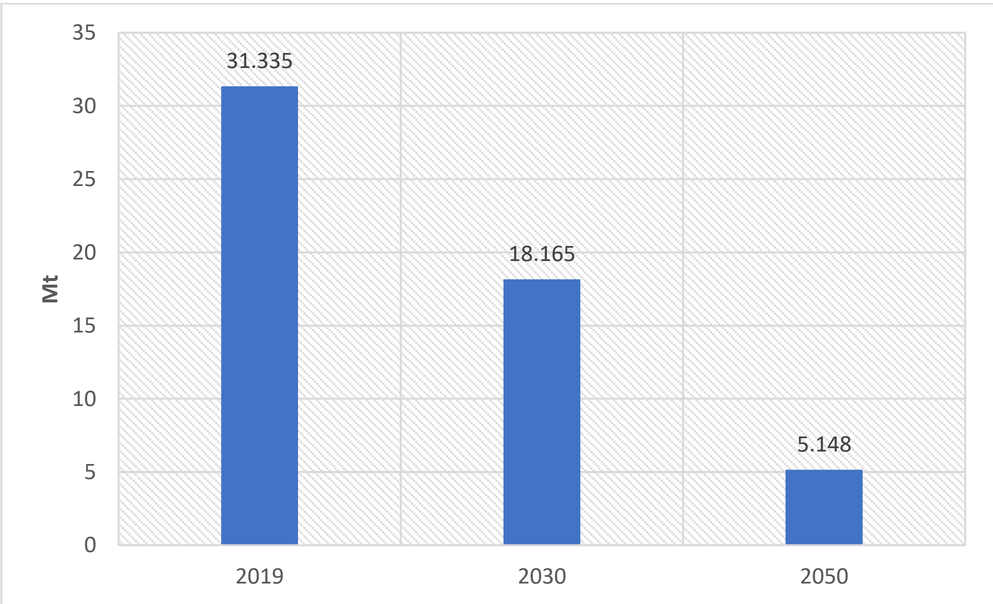

Figure 36 CO2 emissions of different scenario

Finally, a cost analysis for each scenario is performed on EnergyPlan considering different cost database implemented in the model and specific for each year:

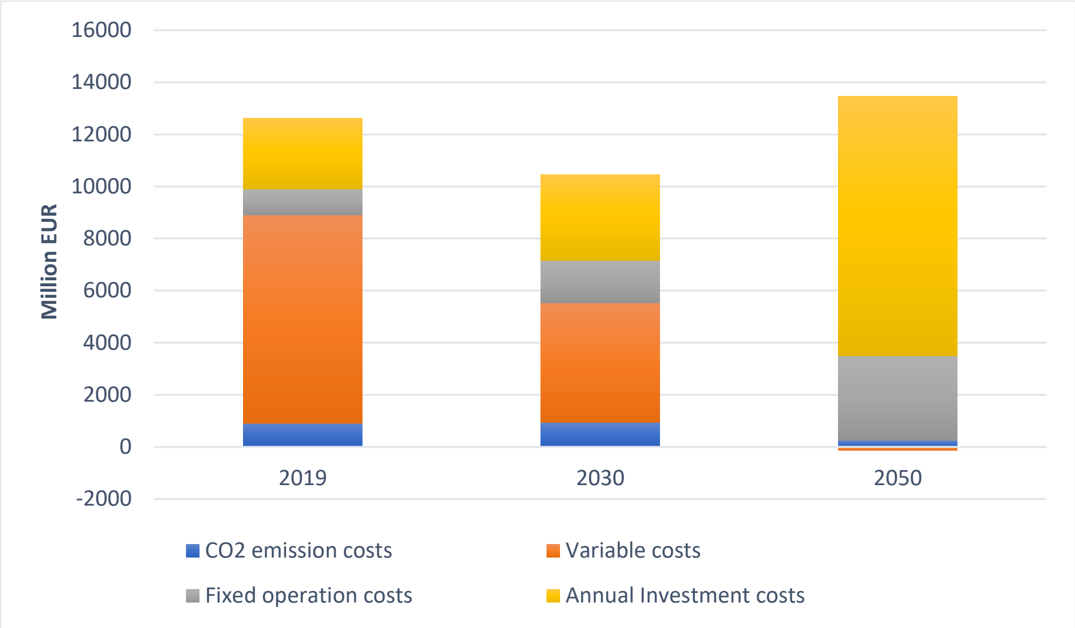

Figure 37 Annual costs of different scenarios

The annual investment costs are function of the total investment required for each input capacity for the production units in the system, the specific lifetime, and the percentage of interest (3%) used for socio-economic value.

For each of these units, the model calculates also the fixed and operation costs multiplying the total investment cost for the fixed annual operational cost in percentage of total investment.

It can be noticed how the total annual costs are reduced in 2030 scenario and increased in 2050 due to the annual investments of the different technologies implemented in the smart energy system.

6 Conclusions

This work provides a general prospect on the possibilities of Catalonia for the smart energy system transition by 2050. The support of EnergyPLan has been proved essential for this study. It was possible to analyse in detail the current system in each of its sectors and to provide possible future scenarios with the possibility to introduce into the model different technical alternatives and new technologies.

Initially, a reference scenario of the Catalonia energy system in 2019 has been assessed in the software. As a first step, it has been collected, and successively introduced into the model, the information related to the demand of electricity, heating, cooling, and transport. For the electricity, heating and cooling demand, the input requested referred to an hourly distribution of the demand for one year. For what concerns the heating sector, individual boilers consumption (coal, oil, natural gas, and biomass boiler) was also needed to differentiate the individual from the district heating demand. These kinds of data were found in administrative-institutional system for the Catalan government website. To assess the heating and cooling hourly demand distribution, it has been fed the values from the EnergyPlan model of Italy 2010, due to a lack of information, assuming them valid thanks to the similar weather of the countries. The last data needed to complete the total energy demand of Catalonia were the different fuel consumption related to industries and transport in one year. Once the demand has been set, the following step were referred to collecting the information of the supply system. Half of the total electricity production in Catalonia belonged to nuclear plants, followed by CHP plants, cogeneration, and renewable sources (almost 20%). Nuclear, CHP and power plants capacity were introduced into the system obtaining the expected values of production. The renewable energy in Catalonia referred to solar (1.1%), wind (5.8%) and hydroelectric (12%). Renewable.ninja website was used to evaluate the hourly distribution of solar and wind energy. Hydro energy distribution was built up manually setting the same percentage of production for each month considering the hydroelectric national production.

The validation of the reference scenario has been achieved comparing outputs from the model with the actual values, for instance, of emissions of carbon dioxide, electricity share of renewables, nuclear energy production and others. Once the reference model has been established and validated, it was possible to perform the simulations with the changes set of the system for the year 2030 and 2050.

In the scenario 2030, the RES electricity production triples the almost 9 TWh produced in 2019 producing 30 TWh/year. The main changes put into the system refers to installation of 1000 MW of offshore wind and 822 MW of heat pumps. The CO2 emissions has been reduced more than 10 Mt compared with the reference scenario. No major changes are detected in fuel consumption with a reduction only in natural gas and coal.

The renewable energy system was expected to be reached in the scenario 2050, where more assumptions were possible to introduce. The methodology followed for this scenario was related to the introduction of different kinds of storage (thermal, electric), electrolysers, absorbed heat pumps, bioenergy and waste incineration with the aim of 100% electrical share of RES and the replacement of fossil fuels.

The results in this scenario show satisfactory values emissions of carbon dioxide (5 million tons) and renewable energy production (75% of primary energy supply, 117% of electricity supply) thanks to the new values of capacity installed of solar, wind and offshore wind, respectively, equal to 24 GW, 19 GW and 3.5 GW. However, there is still a high value of natural gas consumed in the system (almost 20 TWh/year). The difficulties found for the full replacement of natural gas are considered related to the assumption of analysing future scenarios considering the same demand of 2019. It has been demonstrated the importance and the need to reduce the energy demand to achieve the goals set for the transition to smart energy system.

In future work, the model of Catalonia energy system could be subject of different analysis and simulations. The main advantage of using EnergyPlan is related to the possibility to have more then only one solution, building different scenarios and comparing the results obtained in different ways. So, possible improvement of this study concerns the knowledge of the feasibility of the 2050 scenario illustrated, since land use and advanced costs analysis are not part of the project.

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