# Strategy for energy storage in Spain for 2050

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# ABSTRACT

Nowadays, climate change has become one of the main problems faced by our society. To solve this problem, the EU, with its 2050 long-term strategy, has fixed the goal of decarbonising the countries of the European Union before 2050. To achieve this goal, it is necessary to have a 100% renewable system and carry out a storage strategy that helps in the integration of renewables.

The objective of this study is to contribute to the development of a national strategy for storage systems in Spain up to 2050. To do that, it is necessary to study the different storage technologies and make a comparison between them, to analyse which storage systems are more useful for large-scale energy storage in Spain, and to develop various models of the energy system of Spain until 2050, in order to consider different scenarios and technological options. To do that, the Energyplan modeling tool is used.

The results of this thesis demonstrate that the storage strategy in Spain must be based on the technologies of pumped hydro, batteries and deposits of molten salts as they are technologies that have features that allow them to work with large volumes of energy at a low economic cost. In addition, in the peninsula, due to orographic and climatic conditions, there is a great potential to use these technologies.

Further, it is considered that the existence of a high capacity interconnection, the use of biomass power plants, hydrogen production, and a balanced energy mix, are elements that must also play a relevant role in the development of storage strategy, as they contribute to the stability and safety of the electrical system.

**Key-words:** Energy storage, Energy planning, 100% Renewable systems, Energgplan

# RESUMO

Atualmente, as mudanças climáticas tornaram-se um dos principais problemas enfrentados pela nossa sociedade. Para resolver este problema, a EU, com a sua estratégia de longo prazo para 2050, fixou o objetivo de descarbonizar os países da União Europeia até 2050. Para atingir este objetivo, é necessário ter um sistema 100% renovável e implmentar uma estratégia de armazenamento que auxilie na integração de energias renováveis.

O objetivo deste estudo é contribuir para o desenvolvimento de uma estratégia nacional para sistemas de armazenamento em Espanha até 2050. Para isso, é necessário estudar as diferentes tecnologias de armazenamento e fazer uma comparação entre elas, para ientificar quais são os sistemas mais adequados para o armazenamento de energia em grande escala na Espanha, através da análise de vários modelos do sistema energético da Espanha até 2050, considerando diferentes cenários e opções tecnológicas. Para fazer isso, a ferramenta de modelação Energyplan é usada.

Os resultados desta tese demonstram que a estratégia de armazenamento em Espanha deve basear-se nas tecnologias de bombagem hídrica, baterias e depósitos de sais fundidos, pois são tecnologias que apresentam características que lhes permitem trabalhar com grandes volumes de energia a um baixo custo económico. Além disso, na península, devido às condições orográficas e climáticas, existe um grande potencial de utilização dessas tecnologias.

Considera-se que a existência de uma interconexão de alta capacidade, o uso de usinas de biomassa, a produção de hidrogênio e uma matriz energética equilibrada, são elementos adicionais que também devem desempenhar um papel relevante no desenvolvimento da estratégia de armazenamento, pois contribuem para a estabilidade e segurança do sistema elétrico.

**Palavras-chave:** Armazenamento de energia, Planejamento energético, Sistemas 100% renováveis, Energplan

# TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

# LIST OF ABBREVIATIONS

**AC** Alternating Current

**A-CAES** Adiabatic – Compressed Air Energy Storage

**ARENA** Australian Renewable Energy Agency

**CAES** Compressed Air Energy Storage

**CHP** Combined Heat and Power

**CNS** Climate Neutrality Scenario

**CSP** Concentrated Solar Power

**DC** Direct Current

**D-CAES** Diabatic – Compressed Air Energy Storage

**ELP** Estrategia Largo Plazo

**ENTSO** European Network of Transmission System Operators for Electricity

**ENTSO DG** ENTSO Distributed Generation Scenario

**ENTSO GCA** ENTSO Global Climate Action Scenario

**ENTSO ST** ENTSO Sustainable Transition Scenario

**ES** Energy Storage

**EU** European Union

**EV** Electric Vehicle

**FACTS** Flexible AC transmission

**FCEV** Fuel Cell Electric Vehicle

**FH2R** Fukushima Hydrogen Energy Research Field

**Fixed OM** Fixed Operation and Maintenance

**Li-Ion** Lithium-Ion

**MITECO** Ministerio para la Transición Ecológica y el Reto Demográfico

**NaS** Sodium-Sulfur

**NASA** National Aeronautics and Space Administration

**NiCd** Nickel-Cadmium

**P2G** Power-to-Gas

**P2L** Power-to-Liquid

**PCM** Phase Change Material

**PEM** Polymer Electrolyte Membrane

**PHES** Pumped Hydro Energy Storage

**PLCCTE** Proyecto de Ley de Cambio Climático y Transición Energética

**PNIEC** Plan Nacional Integrado de Energía y Clima

**PP** Power Plant

**PSB** Polysulfide Bromide redox flow Battery

**REE** Red Eléctrica Española

**RES** Renewable Energy sources

**RFB** Redox Flow Battery

**RNC2050** Roteiro para a Neutralidade Carbónica

**SMES** Superconducting Magnetic Energy Storage

**SMR** Steam Methane Reforming

**SOEC** Solid Oxide Electrolyser Cell

**TES** Thermal Energy Storage

**TRL** Technology Readiness Level

**TS ELP** Trend Scenario, Estrategia a Largo Plazo

**UPS** Uninterruptible Power Supply

**VRB** Vanadium Redox Battery

**ZnBr** Zinc-Bro

# 1 INTRODUCTION

## 1.1 Motivation

Nowadays, climate change has become one of the main problems our society faces. Climate change has a number of consequences, such as rising sea levels, rising temperatures, originating extreme climatic events like droughts and/or floods. In short, climate change can change the world as we know it, to unknown limits.

To solve this problem, in 2015 the Paris Agreements was established between almost all countries in the world (197) as the first universal and legally binding agreement on climate change. The Paris Agreement establishes a global framework to prevent the temperature rise from exceeding 2 ° C. As a consequence, the EU has established its long-term strategy for 2050, fixing the goal of decarbonising the countries of the European Union by 2050.

Achieving these goals requires a 100% renewable electrical system that works in conjunction with storage systems to achieve a safe, stable and $CO_2$ free electrical system.

One of the motivations of the author of the work is to gain a greater understanding of the operation of one of the tools that are part of the solution to climate change: storage systems. Other motivation points for the elaboration of the work are: to know situation of the systems of storage in Spain, to learn to use programs of simulation of national energetic systems (EnergyPlan) and to try to contribute in the elaboration of the strategy of storage of the Spanish state.

## 1.2 Objectives

The main objective of the work is to contribute to the development of a national strategy for storage systems in Spain up to 2050. To do that, it is necessary to develop the following specific tasks:

- To know which storage systems are more useful for large-scale energy storage in Spain;
- To estimate the electricity demand of Spain until 2050;
- To develop various models of the Spanish energy system until 2050, in order to consider different scenarios and technological options;

## 1.3 Contributions

Once the work has been completed, this document contributions are:

- Updated summary of the different storage technologies and comparison between them;
- Updated map of the infrastructure installed in Spain of storage systems;
- Analysis of the operating behaviours of storage systems;

## 1.4 Structure of the thesis

The development of this thesis is structured in three main parts.

First, a literature review is done, explaining the different types of storage systems available. For each type of system, the following characteristics are explained: advantages and disadvantages, areas of application, technical and economic characteristics, maturity of the technology and the operating principle. In addition, a general summary is made, where is explained which technologies are more suitable for each specific situation.

Then, an “X-ray” of the storage infrastructure installed in Spain is performed. The strengths of the Iberian Peninsula and the potential of the main technologies are explained.

Finally, the Spanish energy models for the years of 2030, 2040, and 2050 are developed. To do this, the evolution of Spanish electricity demand is estimated (taking into account the directives and strategies planned by the Spanish state) and conclusions are made regarding the best storage strategies that should be implemented in Spain over the next decades.

# 2 Literature review

This section aims to show basic knowledge of different storage technologies. For each technology it is explained: its operation, the fields of application, the economic and technical characteristics, the level of maturity and the advantages and disadvantages that they have.

Storage technologies can be classified in several ways (storage capacity, discharge time, mechanical and electrical…), in the present study the technologies will be divided into two groups: Non electrochemical systems and electrochemical systems.

## 2.1 Types of energy storage systems

### 2.1.1 Non electrochemical

### *Pump Hydro (PHES)*

**Storage type**

PHES (pumped hydro energy storage) technology is considered a large-scale energy storage system. This type of plants tends to have hight rated power and are usually located in mountainous areas to harness water resources and store potential energy.

**Operating principle**

PHES technology store potential energy by pumping water to a high-level using electricity. To store energy, the water is pumped from the lower to the upper reservoir, which increases the water potential energy level. To generate energy, the water is turbined from the upper to the lower reservoir.

Figure 1 shows how a PHES plant works:

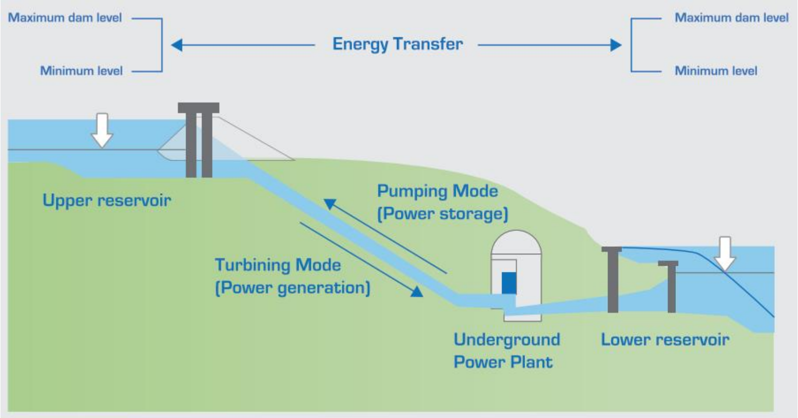

**Figure 1. PHES operating principle. (Source: EASE)**

**Application areas**

The PHES is used when the electricity is high as an energy generator and it stores energy when the electricity price is low. Due to the intermittency of renewables, the combination of PHES and renewables generation plants are becoming frequent.

Today it is the most widely used storage system in the world and in Spain. In Figure 2, can be seen La Muela PHES plant, which is the largest PHES in Spain.

**Figure 2. La Muela pumped hydroelectric energy storage power plant. (Source: www.nsenergybusiness.com)**

## Technical characteristics

**Table 1. Technical characteristics of PHES**.[1][2][3][4][5][6]

| **Power Range** [MW] | **Energy Range** [MWh] | **Energy Density** [Wh/kg] | **Energy Density** [Wh/L] | **Total Efficiency** [%] | **Discharge Duration** [t] | **Response time** [t] |
|---|---|---|---|---|---|---|
| 100 – 5000 | 100-100000 | 0.5 – 3 | 0.5 - 1.5 | 70 - 87 | 1h - days | s - min |

## Economic characteristics

**Table 2. Economic characteristics of PHES.** [1] [3][7]

| **Power Investment Cost** [€/kW] | **Energy Investment Cost** [€/kWh] | **Maintenance Cost** [€/kW/year] | **Lifetime** [years] |
|---|---|---|---|
| 500-4600 | 70-350 | 13 | 50 - 100 |

## Technology Readiness Level

The technology used PHES dates to the 1890's[8]. Due to the uninterrupted use of PHES for many years, the TRL of this technology is considered to be level 9 [1][9].

## Technology analysis

The advantages and disadvantages of this technology are summarized below:

Advantages

- High efficiency and big capacity.
- Mature Technology.
- High Lifetime of the structure.
- Growth perspectives.

Disadvantages

- High installation costs.
- Dependence on local geography.
- High environmental impact.
- Dependence on climatology.

- Conversion of existing hydroelectric power stations.

## *Compressed Air (CAES)*

### Storage type

Large scale, mechanical potential energy.

### Operating principle

An electrical compressor converts electric energy into potential energy pressurizing air into compresses air systems (CAS) like occurring aquifers, solution-mined salt caverns, and mechanically formed reservoirs in rock formations [10]. Then, the air is expanded through an air turbine to generate electrical energy when is needed.

This technology is mainly classified between adiabatic CAES and diabatic CAES. The main difference is that A-CAES (Adiabatic Compressed Air Energy Storage) store the heat generated in the air compression, whereas D-CAES (Diabatic Compressed Air Energy Storage) does not. It is considered that the A-CAES efficiency can be greater than 70%, while the efficiency of D-CAES technology is around 55% [2].

### Application areas

The CAES technology can help with the integration of renewables, like wind [11]. Also, it can be used as a power reserve to deal with voltage drops or power demand peaks.

Presently, there are only 2 commercial CAES plants in operation in the world (McIntosh and Huntorf), but there are some planned projects and others under construction for the future [11].

Below you can see the McIntosh CAES plant:

**Figure 3. The McIntosh CAES Plant (Source: DOE Global Energy Storage Database)**

## Technical characteristics

**Table 3. Technical characteristics of CAES.** [1][2][4][5][6][11][12]

| **Power Range** [MW] | **Energy Range** [MWh] | **Energy Density** [Wh/kg] | **Energy Density** [Wh/L] | **Total Efficiency** [%] | **Discharge Duration** [t] | **Response time** [t] |
|---|---|---|---|---|---|---|
| 10 - 2700 | 10 - 10000 | 30 - 60 | 2-15 | 55-70 | h - days | min |

## Economic characteristics

**Table 4. Economic characteristics of CAES.** [1][2][3][4][5][6]

| **Power Investment Cost** [€/kW] | **Energy Investment Cost** [€/kWh] | **Maintenance Cost** [€/kW/year] | **Lifetime** [years] |
|---|---|---|---|
| 400 - 1200 | 95 - 230 | 17 | 20 – 40 |

## Technology Readiness Level

CAES technology has been in use for decades [12]. Nowadays, there are 2 CAES plants that have been working for more than 25 years and some more under construction and planification [11]. The TRL of this technology depends on the type. D_CAES technology is considered to be level 9 [9] because it has been used for a long time, although, it only has 2 plants presently in operation. A-CAES technology, at the moment it has no operating plants and it is considered TRL level 5-6 [9].

## Technology analysis

The advantages and disadvantages of this technology are summarized below:

Advantages

- Large energy and power capacity.
- Durable and highly sustainable.
- No degradation of capacity over time.
- Competitive and more cost effective.

Disadvantages

- High Investment costs.
- Emissions of $CO_2$, when use natural gas.
- Security issues related to pressurized storage.
- Lower cycle efficiency than PHES and batteries.

## *Flywheels*

## Storage type

Small scale, kinetic energy.

## Operating principle

This technology is based on a rotating massive cylinder which levitates inside a vacuum chamber to reduce friction. The energy charge and discharge is done through an electric generator/motor. To store energy, the electric machine works as a motor (consuming electricity) and increasing the speed of the flywheel. On the other hand, the electric machine (working as a generator) uses the speed of the flywheel to generate electricity. The main limitation of this technology is that the energy cannot be discharged for periods longer than minutes.

### Application areas

As flywheels can provide almost instantaneous power, they are very useful for frequency and voltage regulation and also for working as an uninterruptible power supply (UPS) system operation for short periods of time [13]. It is also a useful technology for the integration of renewables and as a fast charge storage system.

**Figure 4. Beacon Power's flywheel energy storage plant in Stephentown, New York. (Source: Beacon Power)**

### Technical characteristics

**Table 5. Technical characteristics of flywheels.** [1][3][4][5][6][7][14]

| **Power Range** [MW] | **Energy Range** [MWh] | **Energy Density** [Wh/kg] | **Energy Density** [Wh/kg] | **Total Efficiency** [%] | **Discharge Duration** [t] | **Response time** [t] |
|---|---|---|---|---|---|---|
| 0.002 – 20 | 0.005-5 | 5 – 130 | 20-80 | 90 - 95 | s - min | ms - s |

### Economic characteristics

**Table 6. Economic characteristics of flywheels.** [1][3][15]

| **Power Investment Cost** [€/kW] | **Energy Investment Cost** [€/kWh] | **Maintenance Cost** [€/kW/year] | **Lifetime** [years] |
|---|---|---|---|
| 100 - 300 | 1000 - 3500 | 1 | 15 - 20 |

### Technology Readiness Level

The TRL of this technology is considered level 9 in some commercial products. However, there are prototypes experimenting with new materials that are at a TRL level of 7 or lower [9].

### Technology analysis

The advantages and disadvantages of this technology are summarized below:

Advantages

- Low maintenance.
- Long cycle life without degradation.
- Fast response.
- High power density.
- High efficiency for short periods.
- Can work at high temperatures.

Disadvantages

- High Investment cost.
- Difficult/expensive replacement of bearings as cost of materials production is high.
- Safety issues related to the high speed of operation

## *Thermochemical*

### Storage type

Small scale, chemical energy.

### Operating principle

The thermochemical storage system is, generally, based on the following reversible chemical reaction[16]:

$$C + heat \leftrightarrows A + B$$

The charging process is an endothermic process where the heat energy from an external energy source is absorbed and results in components A and B. Once the charging process has been completed, components A and B can be stored separately without energy losses[17][18].

The discharging process is an exothermic process where the components A and B are combined, and they release the previously stored energy. At this stage component C is regenerated.

### Application areas

This technology is still under development. Could be useful for building applications [19] such as water heating and space heating [16]. Also, it could be applied for thermal storage in solar thermal power plants [17].

### Technical & economic characteristics

Thermochemical energy storage is a very immature technology and there are still no reliable technical and economic values of its characteristics.

### Technology Readiness Level

This technology is in a primary research and development phase. For the moment, there haven’t been commercial applications so far [18]. The TRL of this technology is considered level 3-4.

### Technology analysis

Based on references [17] the advantages and disadvantages of this technology are summarized below:

Advantages

- High storage density.
- Long storage period.
- Low heat losses.
- Wide range and characteristics.
- Long distance transport possibility.

Disadvantages

- High capital costs.
- Technically complex.
- Low maturity.

## *Magnetic superconductors (SMES)*

### Storage type

Small scale, magnetic energy

### Operating principle

This technology stores energy in a magnetic field generated by the flow of direct current (DC) electricity into a super-conducting coil. In order to avoid energy dissipation, the super-conducting coil is cryogenically cooled to a temperature below its superconducting critical temperature.

The following Figure 5 shows SMES technology scheme:

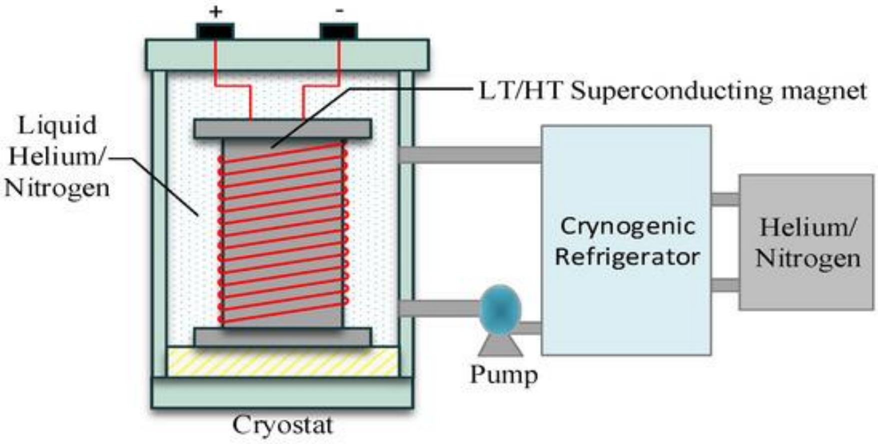

**Figure 5. SMES technology operating principle. (Source:**[20]**)**

### Application areas

SMES technology, due to its fast response time, is currently used as FACTS (Flexible Alternating Current Transmission System) and UPS (Uninterruptible Power Supplies) [21]. It is also used to smooth wind power plants output power and to reduce fluctuation [22].

### Technical characteristics

**Table 7. Technical characteristics of SMES.** [7][1][4][5][6]

| **Power Range** [MW] | **Energy Range** [MWh] | **Energy Density** [Wh/kg] | **Energy Density** [Wh/L] | **Total Efficiency** [%] | **Discharge Duration** [t] | **Response time** [t] |
|---|---|---|---|---|---|---|
| 0.01 - 10 | 0.001-0.01 | 10 - 75 | 6 | 95 - 98 | ms - min | ms |

## Economic characteristics

**Table 8. Economic characteristics of SMES.** [1][2][4]

| **Power Investment Cost** [€/kW] | **Energy Investment Cost** [€/kWh] | **Maintenance Cost** [€/kW/year] | **Lifetime** [years] |
|---|---|---|---|
| 100 - 400 | 700 - 10000 | 18.5 | 20 - 30 |

## Technology Readiness Level

The superconducting magnetic energy storage technology can be divided into those that operate with high critical temperature superconductors and those that operate with low critical temperature superconductors. Low critical temperature SMES technology has some projects already made and tested on the network , and it is considered TRL level 9 [9]. On the other hand, high critical temperature SMES is in an earlier stage development, its TRL level is 5 [9].

## Technology analysis

Based on references [6][17][21], the advantages and disadvantages of this technology are summarized below:

| Advantages | Disadvantages |
|---|---|
| - High power density. | - High capital costs. |
| - High lifetime system. | - Technically complex. |
| - High efficiency. | - Needs a Cooling System. |
| - Quick response and charging time | - Primary research phase. |

## *Thermal storage (TES)*

## Storage type

Small and long scale, thermal energy.

## Operating principle

TES technology consist in storing thermal energy at high or low temperature by heating or cooling the storage medium which is in an isolated containment. This thermal energy is stored during a period of time until it is used for generating electrical energy or for a thermal use. TES technology has specific technologies that work very different. It can be classified in several ways, one of them is into low-temperature (<10ºC), medium-temperature (10ºC to 250ºC) and high-temperature (>250ºC)[23][7].

In this work, special emphasis will be placed on molten salts technology, as it is a technology widely used as a large-scale system. Its operation consists of storing the thermal energy produced during the day, by the solar concentrators, and using it to generate energy in the hours of less sun. It is a very efficient system but over time it has thermal losses due to heat dissipation. Hereunder, the scheme of a solar thermal power plant using TES at high temperature is shown:

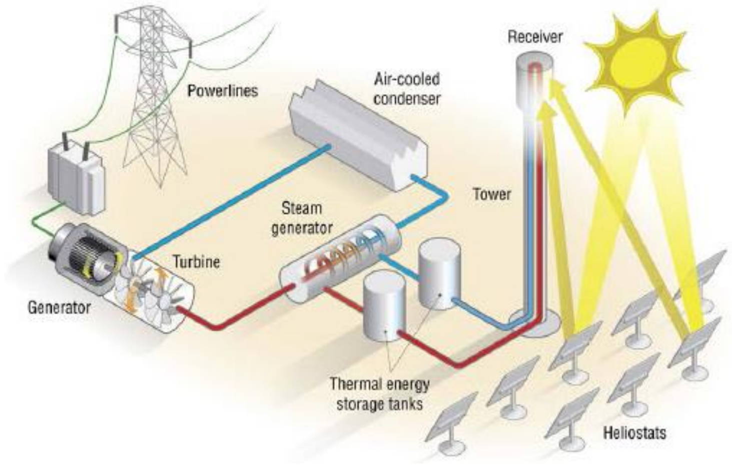

Figure 6. Solar thermal power plant scheme. (Source: https://cleanleap.com/)

## Application areas

TES technology has a wide variety of applications like buildings, combined heat-and-power (CHP), district heating and industrial sector.

In Spain, hybrid energy systems of CSP (Concentrated Solar Power) plants and thermal storage with molten salts are common. Below you can see the deposits that contain the molten salts of one of these plants.

Figure 7. Manchasol & Extresol Solar Thermal Complex (Source: CSP focus)

## Technical characteristics

**Table 9. Technical characteristics of molten salts deposits.** [5][24][25]

| **Power Range** [MW] | **Energy Range** [MWh] | **Energy Density** [Wh/kg] | **Total Efficiency** [%] | **Discharge Duration** [t] | **Response time** [t] |
|---|---|---|---|---|---|
| 1 - 300 | MWh – 5GWh | - | 90-99[1] | min - h | min |

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[1] In this case, the efficiency value of the molten salt deposits decreases over time, so the value shown refers to very short storage times.

## Economic characteristics

**Table 10. Economic characteristics of molten salts deposits.** [5][24]

| Power Investment Cost [€/kW] | Energy Investment Cost [€/kWh] | Maintenance Cost [€/kW/year] | Lifetime [years] |
|---|---|---|---|
| 100-300 | 27-70[2] | - | 30 |

## Technology Readiness Level

Depending on the specific TES technology used, the level of maturity varies. For example, molten salt deposits for thermal solar plants is TRL level 9, PCM (phase change material) for solar thermal plant or buildings is TRL level 7 [26].

## Technology analysis

The advantages and disadvantages of molten salts technology are summarized below:

| Advantages | Disadvantages |
|---|---|
| - Good heat transfer capability. | - Molten salts can be corrosive. |
| - High efficiency. | - Limited to CSP technology for power applications. |
| - Integration with CSP. | - If melted salts are frozen, can cause serious damage to the installation. |
| - Low cost system. | |

### *Hydrogen production*

## Storage type

Large scale, chemical energy.

## Operating principle

This technology consists of transforming electrical energy into chemical energy in the form of hydrogen. The hydrogen can be extracted from water, fossil fuels, biomass or from a mix of both. Depending on the primary source, different types of technologies can be used.

One of the technologies used is electrolysis, which produces pure hydrogen from splitting water molecules into hydrogen ($H_2$) and oxygen($O_2$) by applying an electric current. Another commonly used technology used is called SMR (steam methane reforming), which extracts hydrogen from natural gas.

Once the hydrogen has been produced, it is stored in different forms (pressurized gas, liquid) and containers. Finally, it is used as a fuel (for example, injecting it into the gas network) or converted back into electrical energy by a fuel cell. Fuel cell technology is explained in the *Fuel Cells section*.

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[2] Eur/kWh thermic

## Application areas

Hydrogen is considered an energy vector and its area of application is very wide. Its areas of application include the integration of renewables, transport, buildings (methane gas replacement) and industrial heat generation.[27]

## Technical & economic characteristics

Table 11 shows just the efficiency of the $H_2$ generation.

**Table 11. Technical and economic characteristics of hydrogen production.** [28][29]

| Technology Type | Power Range [MW] | Total Efficiency [%] | Power Investment Cost [€/kW] |
|---|---|---|---|
| **Alkaline electrolyser** | 0.1 - 100 | 62 - 82 | 500 - 1000 |
| **PEM electrolyser** | 0.1 - 100 | 67 - 84 | 1100 - 1800 |
| **SOEC electrolyser** | - | 75 - 90 | 2800 - 5600 |
| **SRM** | - | 60 - 85 | - |

## Technology Readiness Level

The degree of maturity depends heavily on the technology used to produce hydrogen. Below is a table with the TRL level depending on the type of technology used:

**Table 12. Hydrogen production TRL levels.** [28]

| Technology Type | TRL |
|---|---|
| **Alkaline electrolyser** | 9 |
| **PEM electrolyser** | 7 - 9 |
| **SOEC electrolyser** | 3 - 5 |
| **SRM** | 9 |

## Technology analysis

Based on references [30][7] some advantages and disadvantages of this technology are summarized below:

| Advantages | Disadvantages |
|---|---|
| - High energy conversion efficiencies. | - High investment costs. |
| - Production from water with no emissions. | - Low overall efficiencies. |
| - Abundance. | - Safety issues. |
| - Different forms of storage (liquid, gas). | - Low energy density at ambient conditions. |
| - Higher HHV and LHV than other fuels. | - Lack of existing infrastructure. |

**Figure 8. FH2R 10 MW hydrogen production plant in Fukushima. (Source https://fuelcellsworks.com/)**

## *Power to Gas (P2G)*

### Storage type

Large scale, chemical energy.

### Operating principle

This technology consists of producing gas fuel from electricity and storing it in the gas grid or in existing natural gas infrastructures (salt caverns, existing natural gas storage sites…)[31]. Then, the gas is converted into electricity (using generators or gas turbines) or burned to produce heat.

The most used gases by P2G technology are hydrogen and methane. In the case of hydrogen, as mentioned above, the main ways to produce hydrogen are electrolysis and SRM. In the case of methane, the production takes several stages. Hydrogen is first produced from electrical energy by electrolysis or SRM. Once the hydrogen has been obtained, it goes through a process called methanization which uses a $CO_2$ supply to finally obtain the methane.

Gas fuels can have a similar function to storage systems as they can be stored and used when needed. It is considered a viable technology and can offer a wide storage capacity [32] of the order of TWh [27].

### Application areas

P2G technology has a wide range of applications like in the industry, mobility, heating sectors and also for electricity generation.

### Technical & economic characteristics

**Table 13. Technical and economic characteristics of P2G.** [1][5][33][34]

| **Technology Type** | **Energy Range** [MWh] | **Total Efficiency** [%] | **Response time** [t] | **Power Investment Cost** [€/kW] |
|---|---|---|---|---|
| **P2G ($H_2$)** | GWh-TWh | 34-44 | - | - |
| **P2G ($CH_4$)** | GWh-TWh | 30-38 | 10min | 1000-2000 |

#### Technology Readiness Level
It is a technology that is in the advanced demonstration phase with several prototypes in operation. The TRL of this technology is considered level 6-8 [9].

#### Technology analysis
The advantages and disadvantages of this technology are summarized below:

Advantages

- Can use an existing structure.
- High energy and power capacity.
- High time of energy storage (ex: Summer to winter).

Disadvantages

- Low overall efficiency.
- Low level of maturity.
- High capital costs.

## 2.1.2 Electrochemical

### *Primary batteries*
A primary cell is any type of electrochemical cell in which the electrochemical reaction occurs in a single direction, so it can only be discharged. It is mainly used for small applications such as sensors, toys or medical applications. So, it is discarded as a suitable energy storage system for the purpose of this work.

### *Secondary batteries*
Secondary batteries refer to those batteries that are rechargeable. The main types are: Lead-Acid, Li-ion, NaS, NiCd.

#### Storage type
Small and long scale, electrochemical energy.

#### Operating principle
Rechargeable batteries are an energy storage system that stores electrochemical energy from an electric current through a reversible reaction. The batteries are composed of a cathode and an anode that are separated by a porous material which allows electron and ion flow between the two parts.

When the battery is charging, the cathode material is oxidized, and the electrons are conducted to the negative electrode. When discharging the chemical reaction occurs in with the opposite way.

In this project we are going to analyse the characteristics of 4 types of batteries: Lead-Acid, Li-ion, NaS, NiCd, as they are the most used for energy storage [7].

#### Application areas
Rechargeable batteries are used in different environments. Due to its high-density energy it is a useful technology in the automobile sector, in electric vehicles. Moreover, since secondary batteries have a high scalability and flexibility, they are very used for the integration of renewables, for residential and commercial buildings, and for the regulation of voltage and frequency of the electrical network. Also, they are used for electronic devices and as UPS systems.

**Figure 9. The world's largest 100 MW/129 MWh lithium-ion battery in Hornsdale, South Australia.** [35]**(Source: Tesla)**

## Technical characteristics

**Table 14. Technical characteristics of secondary batteries.** [1][2][3][4]

| Technology Type | Power Range [MW] | Energy Range [MWh] | Energy Density [Wh/kg] | Energy Density [Wh/L] | Total Efficiency [%] | Discharge Duration [t] | Response time [t] |
|---|---|---|---|---|---|---|---|
| **Lead-Acid** | 0.001-50 | 0 - 40 | 30 - 50 | 50 - 90 | 75 - 95 | min - h | ms |
| **Li–ion** | 0.001-100 | <200 | 75 - 250 | 200-500 | 90 - 98 | min - h | ms |
| **NaS** | 0.5-50 | >350 | 150 - 240 | 150-300 | 75-90 | min - h | ms |
| **NiCd** | 0 - 40 | - | 45 - 80 | 15 - 150 | 60 - 91 | min - h | ms |

## Economic characteristics

**Table 15. Economic characteristics of secondary batteries.** [1][2][3][4][5][36]

| Technology Type | Power Investment Cost [€/kW] | Energy Investment Cost [€/kWh] | Maintenance Cost [€/kW/year] | Lifetime [years] |
|---|---|---|---|---|
| **Lead-Acid** | 100-500 | 200-400 | 7-15 | 15-20 |
| **Li–ion** | 150-1300 | 180-1000 | 6-20 | 10-20 |
| **NaS** | 300-3000 | 275-350 | 7-15 | 10-20 |
| **NiCd** | 500-1500 | 400-700 | 20 | 15-20 |

### Technology Readiness Level

The TRL level varies depending on the specific type of batteries. Table 16 shows the TRL level depending on the type of technology used:

**Table 16. Secondary batteries TRL levels.** [2][4][9]

| Technology Type | TRL |
|---|---|
| **Lead-Acid** | 9 |
| **Li–ion** | 8 |
| **NaS** | 9 |
| **NiCd** | 8 |

### Technology analysis

The advantages and disadvantages of this technology are summarized below:

| Advantages | Disadvantages |
|---|---|
| - High efficiency. | - Suffers from aging effect. |
| - High energy density. | - Safety issues (overheating). |
| - Mobile storage system. | - Limited material resources. |
| - Very useful for automobile sector. | - Composed by materials that are difficult to recycle. |

## *Redox flow cells (RFB)*

There are different types of RFB, the main ones are VRB, ZnBr and PSB.

### Storage type

Large scale, electrochemical energy.

### Operating principle

The RFB transforms electrical energy into electrochemical energy from a reversible chemical reaction. This technology consists of 2 tanks that store electrolytic liquids, one with a positive charge and the other with a negative charge. The solutions of the tanks are pumped to a cell stack that is composed of 2 electrodes and two compartments which are separated by a selective ion membrane.

When the battery is charging, the discharged positive electrolyte detaches an electron that travels from the positive electrode to the negative electrode and jump into the negative electrolyte by varying its charge. Meanwhile the membrane allows the passage of ions to complete the reaction. When the battery is discharged  the electrochemical energy contained in the electrolyte it is released in the reverse reaction and the electrical energy is extracted [36][38].

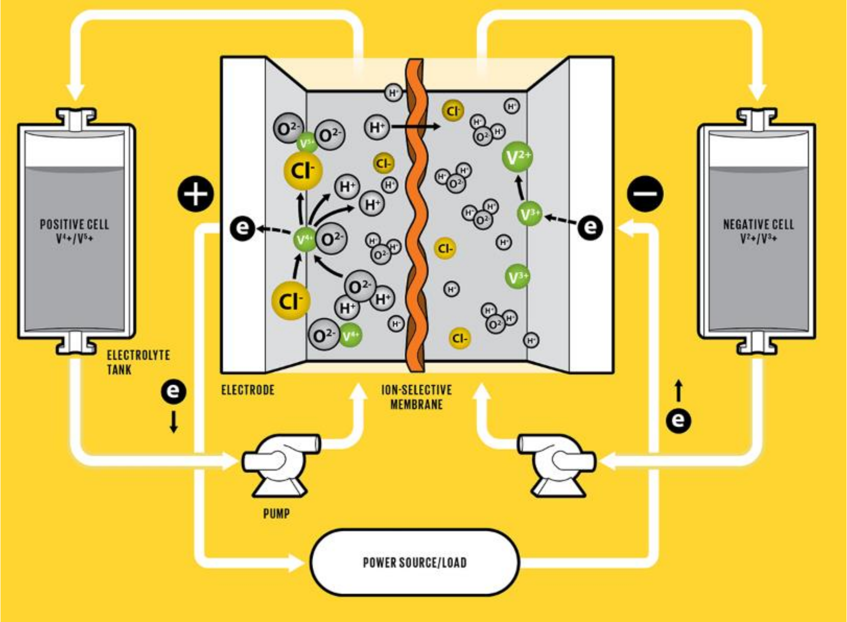

**Figure 10. Operation of a redox flow battery during the charging process. Illustration: James Provost**

## Application areas

Due to their great flexibility and scalability, their main fields of application are related to large-scale non-mobile energy storage systems. For example, the integration of renewables or frequency and voltage control.

In 2016, the largest redox flow batteries plant was implemented. Its main uses are to work during peak network demand and as auxiliary power supply for black start[3].[39]

**Figure 11. The world's largest VRF battery: 200MW/800MWh in Dalian, China. (Source: Rongkepower)**

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[3] It is the process in which the power supply of the electrical network is reactivated after a partial or general shutdown

## Technical characteristics

**Table 17. Technical characteristics of redox flow cells.** [1][2][4][5][10][36]

| Technology Type | Power Range [MW] | Energy Range [MWh] | Energy Density [Wh/kg] | Total Efficiency [%] | Discharge Duration [t] | Response time [t] |
|---|---|---|---|---|---|---|
| **VRB** | 0,5-100 | <100 | 10-30 | 75-85 | s - h | ms |
| **ZnBR** | 1-10 | <100 | 80 | 66-80 | s - h | ms |
| **PSB** | 1-15 | - | 15-30 | 75 | s - h | ms |

## Economic characteristics

**Table 18. Economic characteristics of redox flow cells.** [1][2][4][36]

| Technology Type | Power Investment Cost [€/kW] | Energy Investment Cost [€/kWh] | Maintenance Cost [€/kW/year] | Lifetime [years] |
|---|---|---|---|---|
| **VRB** | 5-20 | 150-1500 | 100-1000 | 17-47 |
| **ZnBR** | 5-15 | 550-1800 | 100-700 | 11-34 |
| **PSB** | 10-15 | 150-1000 | 700-2500 | - |

## Technology Readiness Level

The first flow batteries were made by NASA in the 1970 [40], however, RFB are not widely commercialized [38]. Next there is a table with the TRL level depending on the type of technology used:

**Table 19. Redox flow batteries TRL levels.** [9]

| Technology Type | TRL |
|---|---|
| **VRB** | 7 |
| **ZnBR** | 5-6 |

## Technology analysis

Based on references [6][37][38][40], the advantages and disadvantages of this technology are summarized below:

Advantages

- Modular design.
- Good scalability.
- Flexible operation.
- Low degradation.
- Fast charge.
- Decoupled energy storage and power generation.

Disadvantages

- Low energy density [Wh/L]
- High investment costs.
- Low maturity.
- More complex than conventional batteries.
- Toxicity of some electrolytes used.

## *Supercapacitors*

### Storage type

Small scale, static electricity.

### Operating principle

This technology stores static electricity into 2 electrodes separated by an ion-permeable membrane and an electrolyte which connect the 2 electrodes ionically. When a current is applied to the electrodes, a positive charge builds up on one electrode and a negative charge builds up on the other one.

### Application areas

The main applications are the ones that require energy to be delivered at high power or velocity. The field of electronics or electric vehicles are some examples.

### Technical characteristics

**Table 20. Technical characteristics of supercapacitors.** [1][3][4][5][41]

| **Power Range** [MW] | **Energy Range** [MWh] | **Energy Density** [Wh/kg] | **Energy Density** [Wh/L] | **Total Efficiency** [%] | **Discharge Duration** [t] | **Response time** [t] |
|---|---|---|---|---|---|---|
| 0.01-5 | 0.001-0.005 | 10 - 104 | 10 - 30 | 94 - 98 | s - min | ms |

### Economic characteristics

**Table 21. Economic characteristics of supercapacitors.** [1][3]

| **Power Investment Cost** [€/kW] | **Energy Investment Cost** [€/kWh] | **Maintenance Cost** [€/kW/year] | **Lifetime** [years] |
|---|---|---|---|
| 10 - 400 | 300 – 20 000 | - | 16 - 40 |

### Technology Readiness Level

This technology has been used in a wide range of projects, so it is in the commercialisation stage with a TRL of 8. [3]

### Technology analysis

Based on references [6][41][42][43][44] the advantages and disadvantages of this technology are summarized below:

Advantages

- High cycle life and efficiency.
- High safety rating.
- High charge/discharge velocity.
- High power density [W/kg].

Disadvantages

- Low energy density [Wh/kg].
- Low energy density [Wh/L].
- High investment costs.
- Require power conditioning to deliver steady output power.

## *Fuel Cells*

### Storage type

Electrochemical energy.

### Operating principle

The fuel cell consists of transforming chemical energy into electrical energy. It is generally composed by a hydrogen inlet, an oxygen inlet, an $H_2O$ outlet and an electrolyte that separates 2 electrodes (cathode and anode).

For the generation of electricity, oxygen passes through the cathode side at the same time that hydrogen passes through the anode site and it is dissociated into electrons and protons. Then, the protons pass through the electrolyte membrane and the electrons are forced to travel on an external circuit, generating an electric current and excess heat. Finally, protons, electrons, and oxygen combine on the cathode side to produce water molecules.

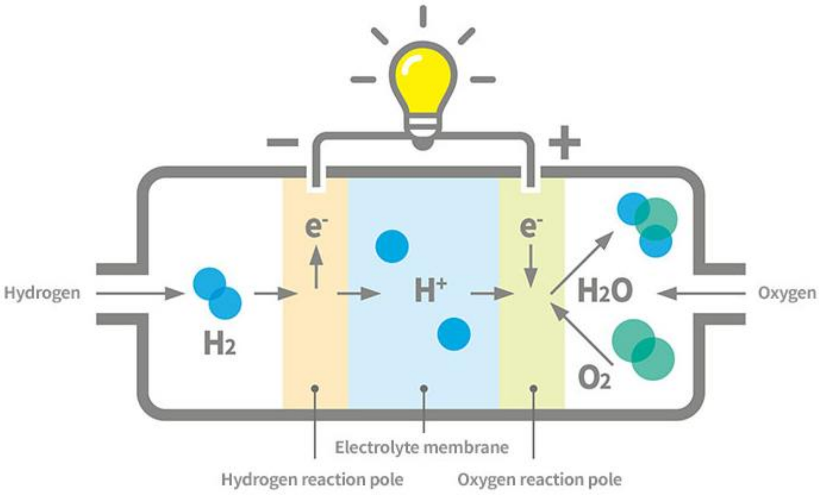

**Figure 12. Simplified operating principle of a PEM fuel cell. (Source: Doosan mobility)**

## Application areas

The fuel cell is a relatively new technology. At present, its main uses are for the generation of electricity and the automobile sector.

## Technical characteristics

**Table 22. Technical characteristics of Fuel cells.** [1][4][45][46]

| **Power Range** [MW] | **Energy Range** [MWh] | **Energy Density** [Wh/kg] | **Energy Density** [Wh/L] | **Total Efficiency** [%] | **Discharge Duration** [t] | **Response time** [t] |
|---|---|---|---|---|---|---|
| 0.01-58.8 | - | 800 - 10000 | - | >60 | s-h | s |

## Economic characteristics

**Table 23. Economic characteristics of Fuel cells.** [1][2][46]

| **Power Investment Cost** [€/kW] | **Energy Investment Cost** [€/kWh] | **Maintenance Cost** [€/kW/year] | **Lifetime** [years] |
|---|---|---|---|
| 550 – 2000 | 1 – 15 | - | 5-25 |

## Technology Readiness Level

The TRL level varies depending on the specific type of technology. Generally, their TRL level is in the range of 4 to 9 [9].

## Technology analysis

The advantages and disadvantages of molten salts technology are summarized below:

Advantages

- High efficiency in cogeneration.
- Silent during operation.
- Low size.
- Efficiency remains constant with its use.

Disadvantages

- Expensive technology.
- Low overall efficiency.
- Low level of maturity of some technologies.
- Lack of infrastructure.

## 2.2 Comparative of energy storage systems

Once the different energy storage technologies have been explained, a comparative analysis is carried out to determine which storage systems are most suitable for each of the possible situations.

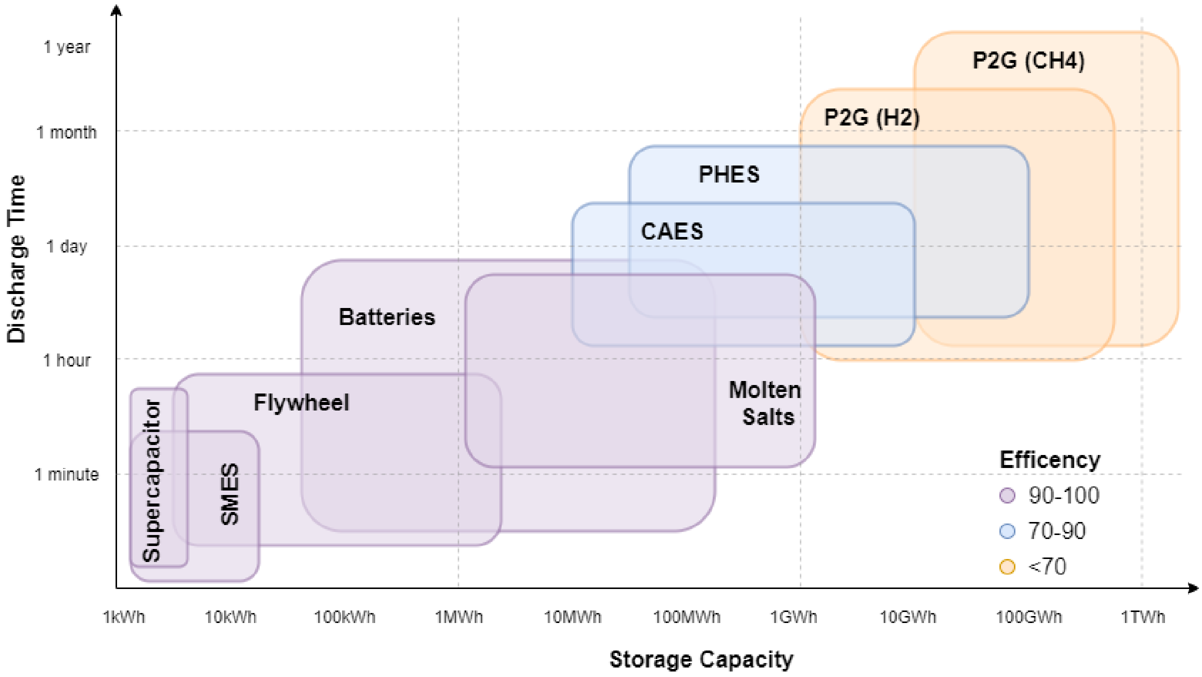

**Figure 13. Comparative of ES technologies in a Discharge Time - Storage Capacity graphic.**

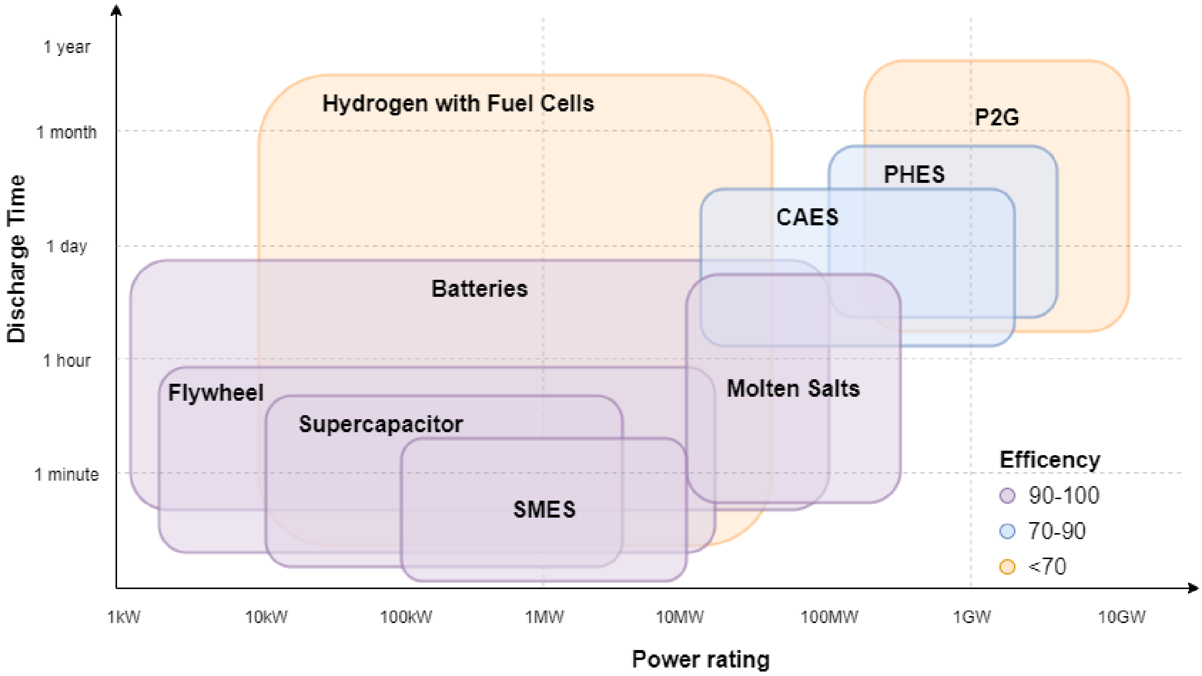

**Figure 14. Comparative of ES technologies in a Discharge Time - Power Rating graphic.**

Figure 13 and Figure 14 presents a comparison between different storage technologies taking into account the discharging time, the storage capacity and the power rating. Regarding this, CAES, P2G, PHES, molten salts and battery technologies are the most suitable systems to be used on a large scale. For example, these systems are very useful for storing surplus energy from renewable energies or for generating energy and decreasing the peak of energy demand.

On the other hand, flywheels, supercapacitors and SMES are a very suitable system to act quickly and for short periods of time. For example, they can be applied in frequency regulation and voltage control of an electrical network.

Following there is a table from the World Energy Council that indicates which storage systems are up to date for different situations.

**Table 24. Possible applications by technology.** [6]

| | Electrical | | Mechanical | | | Electrochemical | | Chemical | Thermal |
|---|---|---|---|---|---|---|---|---|---|
| | Super-capacitors | SMES | PHES | CAES | Flywheels | Second. batteries | Redox flow | $H_2$ | Molten salts |
| **Power quality** | ✓ | ✓ | | | ✓ | ✓ | ⌛ | | |
| **Energy arbitrage** | | | ✓ | ✓ | | ✓ | ✓ | ⌛ | ✓ |
| **RES integration** | | ✓ | | | ✓ | ✓ | ✓ | ✓ | |
| **Emergency back-up** | | | | | ✓ | ✓ | ✓ | ⌛ | ⌛ |
| **Peak shaving** | | | ✓ | ✓ | | ✓ | ⌛ | ⌛ | ⌛ |
| **Time shifting** | | | ✓ | ✓ | | ✓ | ⌛ | ⌛ | ⌛ |
| **Load levelling** | | | ✓ | ✓ | | ✓ | ⌛ | ⌛ | ⌛ |
| **Black start** | | | | | | ✓ | ✓ | ⌛ | ⌛ |
| **Seasonal storage** | | | ⌛ | ☆ | | | | ⌛ | ⌛ |
| **Spinning reserve** | | ⌛ | | | ⌛ | ✓ | ⌛ | ⌛ | |
| **Network expansion** | | | ✓ | ⌛ | | ✓ | ⌛ | ⌛ | ⌛ |
| **Network stabilisation** | ⌛ | ✓ | | | ⌛ | ✓ | ⌛ | | |
| **Voltage regulation** | ⌛ | ⌛ | | | ⌛ | ✓ | ✓ | | |
| **End-user services** | ⌛ | ⌛ | | | ⌛ | ✓ | ⌛ | | |

✓ for proven ⌛ for promising ☆ possible

Finally, the following tables summarize the characteristics of the storage systems explained in the previous point.

**Table 25. Technical characteristics comparation of non-electrochemical energy storage systems.**

| Technology Type | Power Range [MW] | Energy Range [MWh] | Energy Density [Wh/kg] | Energy Density [Wh/L] | Total Efficiency [%] | Discharge Duration [t] | Response time [t] |
|---|---|---|---|---|---|---|---|
| **PHES** | 100-5000 | 100-100000 | 0.5 – 3 | 0.5-1.5 | 70 - 87 | h - days | s - min |
| **CAES** | 10 - 2700 | 10 - 10000 | 30 - 60 | 2-15 | 55 - 70 | h - days | min |
| **Flywheel** | 0.002-20 | 0.005-5 | 5 – 130 | 20-80 | 90 - 95 | s - min | ms-s |
| **SMES** | 0.01 – 10 | 0.001-0.01 | 10 - 75 | 6 | 95 - 98 | ms - min | ms |
| **Molten Salts** | 1 - 300 | MWh – 5GWh | - | - | 90 – 99 | min - h | min |
| **Alkaline electrolyser** | 0.1 – 100 | - | - | - | 62 - 82 | - | - |
| **PEM electrolyser** | 0.1 - 100 | - | - | - | 67 - 84 | - | - |
| **SOEC electrolyser** | - | - | - | - | 75 - 90 | - | - |
| **SRM** | - | - | - | - | 62 - 82 | - | - |
| **P2G ($H_2$)** | - | GWh - TWh | - | - | 34 - 44 | - | - |
| **P2G ($CH_4$)** | - | GWh - TWh | - | - | 30 - 38 | - | 10min |

**Table 26. Technical characteristics comparation of electrochemical energy storage systems.**

| Technology Type | Power Range [MW] | Energy Range [MWh] | Energy Density [Wh/kg] | Energy Density [Wh/L] | Total Efficiency [%] | Discharge Duration [t] | Response time [t] |
|---|---|---|---|---|---|---|---|
| **Lead-Acid** | 0.001-50 | 0 -40 | 30 - 50 | 50 - 90 | 75 - 95 | min - h | ms |
| **Li–ion** | 0.001-100 | <200 | 75 - 250 | 200-500 | 90 - 98 | min - h | ms |
| **NaS** | 0.5-50 | >350 | 150 - 240 | 150-300 | 75-90 | min - h | ms |
| **NiCd** | 0 - 40 | - | 45 - 80 | 15 - 150 | 60 - 91 | min - h | ms |
| **VRB** | 0.5-100 | <100 | 10-30 | - | 75-85 | s - h | ms |
| **ZnBR** | 1-10 | <100 | 80 | - | 66-80 | s - h | ms |
| **PSB** | 1-15 | - | 15-30 | - | 75 | s - h | ms |
| **Supercapacitor** | 0.01-5 | 0.001-0.005 | 10 - 104 | 10 - 30 | 94 - 98 | s - min | ms |
| **Fuel cell** | 0.01-58.8 | - | 800 - 10000 | 500-3000 | >60 | s-h | s |

**Table 27. Economic characteristics comparation of non-electrochemical energy storage systems.**

| Technology Type | Power Investment Cost [€/kW] | Energy Investment Cost [€/kWh] | Maintenance Cost [€/kW/year] | Lifetime [years] |
|---|---|---|---|---|
| **PHES** | 500-4600 | 70-350 | 5-40 | 50-100 |
| **CAES** | 400-1200 | 95-230 | 17 | 20-40 |
| **Flywheel** | 100 - 300 | 1000 - 3500 | 1 | 15 - 20 |
| **SMES** | 100-400 | 700-7000 | 18.5 | 20-30 |
| **Molten Salts** | 100 – 300 | 25 – 70 | - | 30 |
| **Alkaline electrolyser** | 500-1000 | - | - | - |
| **PEM electrolyser** | 1100-1800 | - | - | - |
| **SOEC electrolyser** | 2800-5600 | - | - | - |
| **SRM** | - | - | - | - |
| **P2G ($H_2$)** | - | - | - | - |
| **P2G ($CH_4$)** | 1000-2000 | - | - | - |
| | - | - | - | - |

**Table 28. Economic characteristics comparation of electrochemical energy storage systems.**

| Technology Type | Power Investment Cost [€/kW] | Energy Investment Cost [€/kWh] | Maintenance Cost [€/kW/year] | Lifetime [years] |
|---|---|---|---|---|
| **Lead-Acid** | 100-500 | 200-400 | 7-15 | 15-20 |
| **Li–ion** | 150-1300 | 180-1000 | 6-20 | 10-20 |
| **NaS** | 300-3000 | 275-350 | 7-15 | 10-20 |
| **NiCd** | 500-1500 | 400-700 | 20 | 15-20 |
| **VRB** | 150-1500 | 100-1000 | 17-47 | 5-20 |
| **ZnBR** | 550-1800 | 100-700 | 11-34 | 5-15 |
| **PSB** | 150-1000 | 700-2500 | - | 10-15 |
| **Supercapacitor** | 10-400 | 300-20000 | - | 16-40 |
| **Fuel cell** | 550-2000 | 1-15 | - | 5 -25 |

# 3 Storage infrastructure installed in Spain

Regarding the *Global Energy Storage Database*[47], in 2020, the Spanish energy storage system is based primarily on PHES technology, and to a lesser extent, on molten salt deposits.

The installed power of PHES technology accounts for 88% of the entire Spanish system, while molten salts technology has an installed power of 12% of the total. In addition, with less than 1% incidence, there are other energy storage systems such as flywheels, electrochemical batteries and capacitors. The current mix of the Spanish energy storage system is described in Figure 15.

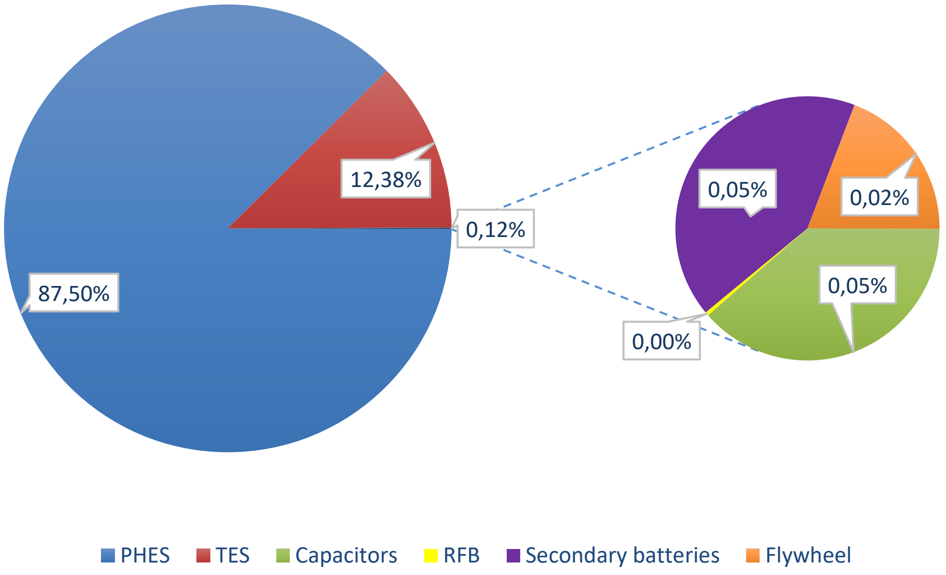

**Figure 15. Installed Power mix of energy storage technologies in Spain.**

### 3.1.1 PHES technology

The Spanish potential for PHES technology is enormous, and Spain is considered to be the second country in Europe with the most theoretical potential after Turkey [48]. At present, Spain is the 4th country in the world and the first in Europe with more PHES installed power with 8GW [49]. In addition, in the coming years it will be the country of Europe where the installed power will grow more [50]. The following graphic shows the PHES installed power from different countries around the world.

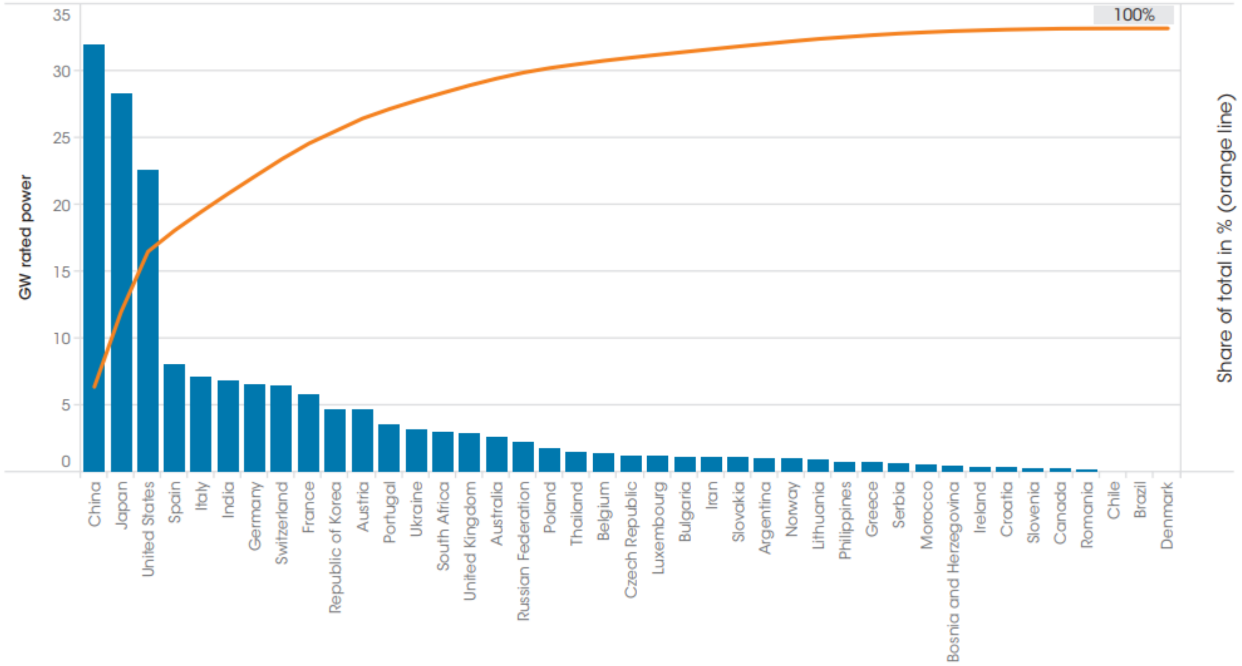

**Figure 16. Global operational pumped hydro storage power capacity by country, mid-2017.** [49]

In Spain there are about twenty PHES plants. The main uses are the integration of renewables, electric supply capacity and demand time shift.

Table 29 presents the details of the power, location and name of each of the PHES plants in Spain.

**Table 29. PHES infrastructure installed in Spain.** [47]

| Name | Technology | Rated Power [MW] | Ubication |
|---|---|---|---|
| **Gobantes** | PHES | 3.6 | Gobantes |
| **Urdiceto** | PHES | 7.2 | Bielsa |
| **El Hierro** | PHES | 11.3 | El Hierro |
| **Pintado** | PHES | 14 | Cazalla Sierra |
| **Guijo de Grandadilla** | PHES | 54 | Guijo de Grandadilla |
| **CH de Ip** | PHES | 88.5 | Huesca |
| **Montamara** | PHES | 90 | Tavascan |
| **Gabriel y Galan** | PHES | 111 | Guijo De Granadilla |
| **Torrejon** | PHES | 132 | Torrejon |
| **Tanes** | PHES | 133 | Redes National Park |

| | | | |
|---|---|---|---|
| **Guillena** | PHES | 215 | Guillena |
| **Moralets-Llauset** | PHES | 219.1 | Huesca |
| **Valdencanas** | PHES | 225 | Valdecanas |
| **Conso** | PHES | 228 | Villarino Conso |
| **Puente Bibey** | PHES | 315 | Manzaneda |
| **Aguayo I** | PHES | 360 | Bárcena de Pie de Concha |
| **Tajo de la Encantada** | PHES | 360 | Ardales Y Alora |
| **Estany de Sallent** | PHES | 468 | Capdella |
| **Villarino** | PHES | 810 | Villarino |
| **Aguayo II** | PHES | 1014 | Bárcena de Pie de Concha |
| **Aldeadávila II** | PHES | 1139 | Duero |
| **La Muela** | PHES | 2000 | Cortes-La Muela |

### 3.1.2 Molten Salt technology

Spain is the country with the most installed power CSP plants [51]. Many of these solar plants have molten salts deposits to store surplus heat energy to produce electricity at peak times or when there is no solar radiation. These systems cannot store electricity coming from the grid, but despite this drawback, it increases the flexibility of the system, so it is as useful as any other storage technology. Table 30 presents list of solar thermal power plants that have molten salt deposits in Spain, in the total of 1.13 GW.

**Table 30. TES infrastructure installed in Spain.** [47][52][53]

| Name | Technology | Type | Rated Power [MW] | Energy Range [MWh] | Ubication |
|---|---|---|---|---|---|
| **Puerto Errado 1** | TES | Molten Salt | 1,4 | 0,7 | Calasparra |
| **PS10** | TES | Water-Steam | 11 | 10 | Sanlúcar La Mayor |
| **PS20** | TES | Water-Steam | 20 | 20 | Sanlúcar La Mayor |
| **Gemasolar Plant** | TES | Molten Salt | 20 | 300 | Fuentes de Andalucía |
| **Puerto Errado 2** | TES | Molten Salt | 30 | 15 | Calasparra |
| **Andasol 1** | TES | Molten Salt | 50 | 375 | Aldiere |

| | | | | | |
|---|---|---|---|---|---|
| **Andasol 2** | TES | Molten Salt | 50 | 375 | Aldeire y la Calahorra |
| **Andasol 3** | TES | Molten Salt | 50 | 375 | Aldeire |
| **Arcosol 50** | TES | Molten Salt | 50 | 375 | San José del Valle |
| **Arenales** | TES | Molten Salt | 50 | 350 | Morón de la Frontera |
| **Aste 1B** | TES | Molten Salt | 50 | 400 | Alcázar de San Juan |
| **Aste 1A** | TES | Molten Salt | 50 | 400 | Alcázar de San Juan |
| **Astexol II** | TES | Molten Salt | 50 | 400 | Olivenza |
| **Caceres** | TES | Molten Salt | 50 | 375 | Valdeobispo |
| **Casablanca** | TES | Molten Salt | 50 | 375 | Talarrubias |
| **Extresol 1** | TES | Molten Salt | 50 | 375 | Torre de Miguel Sesmero |
| **Extresol 2** | TES | Molten Salt | 50 | 375 | Torre de Miguel Sesmero |
| **Extresol 3** | TES | Molten Salt | 50 | 375 | Torre de Miguel Sesmero |
| **La Africana** | TES | Molten Salt | 50 | 375 | Posadas |
| **La Dehesa** | TES | Molten Salt | 50 | 375 | La Garrovilla |
| **La Florida** | TES | Molten Salt | 50 | 375 | Alvarado |
| **Manchasol 1** | TES | Molten Salt | 50 | 375 | Alcazar de San Juan |
| **Manchasol 2** | TES | Molten Salt | 50 | 375 | Alcazar de San Juan |
| **Termesol 50** | TES | Molten Salt | 50 | 375 | San José del Valle |
| **Termosol 1** | TES | Molten Salt | 50 | 450 | Navalvillar de Pela |
| **Termosol 2** | TES | Molten Salt | 50 | 450 | Navalvillar de Pela |
| **TOTAL** | | | **1131.4** | **8420.7** | **SPAIN** |

### 3.1.3 Supercapacitor energy storage technology

There are currently two active projects that use supercapacitors as a storage system, one in Madrid and the other in La Palma.

The supercapacitors located in La Palma are integrated into a conventional power plant and are able to respond to fast events and to maintain island frequency in an acceptable range.

The plant in Madrid is a hybrid system between a bank of batteries and supercapacitors, that is responsible for recovering and storing the energy generated by the action of the braking of a train.

Supercapacitors can charge and discharge faster and more efficiently than batteries, so, this hybrid system allows to recover more energy and extend the battery life by 20 to 25 percent [54].

**Table 31. Supercapacitors infrastructure installed in Spain.**

| Name | Technology | Rated Power [kW] | Ubication |
|---|---|---|---|
| **Ferrolinera WESS: Ultracapacitors - Win Inertia** | Electro-chemical Capacitor | 300 | Madrid |
| **Endesa STORE: La Palma** | Electro-chemical Capacitor | 4000 | La Palma |

### 3.1.4 Flywheel

Nowadays in Spain there are 2 flywheels projects located in the Canary Islands, specifically in Lanzarote and La Gomera. These two islands have very small and isolated systems with imbalances in frequency and voltage between generation and demand.

Flywheel plants allow a more stable and balanced electrical system as they can supply or consume large amounts of energy in a short time [55]. So, the main function of these two projects is to regulate the frequency and voltage of the system.

Below are the main features of these two plants.

**Table 32. Flywheel infrastructure installed in Spain.** [47]

| Name | Technology | Rated Power [kW] | Ubication |
|---|---|---|---|
| **Endesa STORE: La Gomera** | Flywheel | 500 | La Gomera |
| **Subestación de Mácher** | Flywheel | 1650 | Tias, Lanzarote |

In Spain there is between 3 and 4 MW of installed capacity of electrochemical batteries, without counting electric cars batteries. 3 different types of battery installations can be found: Lithium-Ion battery, Vanadium Redox Flow battery and Lead-Acid battery. The principal uses of these plants are the integration of renewables into electrical and mobility system, frequency and voltage regulation, energy recovery from the braking of a train, to reduce peak demand charge, and development and demonstration of rapid charging of electric vehicles.

Table 33 describes with the characteristics of electrochemical battery plants in Spain.

**Table 33. Electro-chemical batteries infrastructure installed in Spain.** [47]

| Name | Technology | Rated Power [kW] | Ubication |
|---|---|---|---|
| **CENER VRB** | Flow Battery | 50 | Sarriguren |
| **Dutt Power Electronics BESS** | Lead-acid Battery | 40 | Albiztur |
| **FerroSmartGrid - Regulation Node** | Lead-acid Battery | 50 | Antequera |
| **Endesa HQ B2G** | Lithium-ion Battery | 20 | Barcelona |
| **IREC B2G** | Lithium-ion Battery | 23 | Barcelona |
| **Endesa: CRAVE** | Lithium-ion Battery | 47 | Zaragoza |
| **Endesa: V2G** | Lithium-ion Battery | 80 | Malaga |
| **Smart City Malaga** | Lithium-ion Battery | 106 | Malaga |
| **Ferrolinera WESS: Li-Ion Batteries - Win Inertia** | Lithium-ion Battery | 300 | Madrid |
| **Abengoa Li-ion project** | Lithium-ion Battery | 1000 | Seville |
| **Almacena Li-ion** | Lithium-ion Battery | 1000 | Carmona |
| **Endesa STORE: Gran Canaria** | Lithium-ion Battery | 1000 | Gran Canaria |
| **Acciona-ILIS project** | Lithium-ion Battery | 1000 | Tudela |

# 4 Storage needs assessment of the national electric system

This section provides a study of the energy storage needs of the Spanish electricity system in the future. A total of 6 possible energy scenarios have been developed for the study, which follow a deterministic model. The following is a brief explanation of each of them:

- **Scenario 2018:** Real scenario of the Spanish electricity system in 2018;
- **Scenario 2030:** Forecast of the Spanish electricity system for 2030;
- **Scenario 2040:** Forecast of the Spanish electricity system in 2040, it is assumed that hydrogen has practically no incidence on the industrial and transport sectors;
- **Scenario H2040:** Forecast of the Spanish electricity system in 2040, it is assumed that hydrogen has incidence on the industrial and transport sectors;
- **Scenario 2050:** Forecast of the Spanish electricity system in 2050, it is assumed that hydrogen has practically no incidence on the industrial and transport sectors;
- **Scenario H2050:** Forecast of the Spanish electricity system in 2050, it is assumed that hydrogen has incidence on the industrial and transport sectors;

The models used for the simulation have been constructed taking into account other studies and trying to achieve the objectives indicated in the official documents PNIEC[56] and PLCCTE[57], which are included in the 2050 long-term climate strategy to pursuit an economy with net-zero greenhouse gas emissions for 2050.

In the documents previously mentioned the following goals can be emphasized:

1. Spain must achieve climate neutrality no later than 2050;

2. Before 2050, the electricity system in Spain has to be 100% renewable;

3. The renewable presence in 2030 must be at least 70% for electricity demand;

4. The mobility sector will drastically reduce its emissions in 2050;

5. The electrical system should be the main vector of decarbonization.

## 4.1 Modeling future scenarios

### 4.1.1 2018 Scenario

#### *Final electric energy demand*

The value of the demand for electricity has been obtained from the 2018 annual report prepared by *Red Eléctrica Española* [58]. The document considers an electricity demand of 243.7 TWh consumed throughout 2018.

This value includes the demand for electricity from the peninsula, plus the demand for the link that connects Spain with the Balearic Islands. As mentioned above, the demand for the Canary Islands has not been taken into account, as it has its own electrical system and it is not part of the study.

### *Installed power*

As with electricity demand, the balance of the installed electric power has been obtained from the 2018 annual report prepared by *Red Eléctrica Española* [58], except for the value of *River Hydro* installed power, which has been obtained from the *Excel Inventory of generation 2015-2018* from [59]. Table 34 indicates the installed power of each type of technology and the percentage of its total representation within the system.

**Table 34. Spanish installed power by technology in 2018.**

| Technology | MW | % |
|---|---|---|
| On-shore wind power | 23091 | 23.0% |
| River Hydro | 1740 | 1.7% |
| Hydroelectric without pumping | 17047 | 17.0% |
| Hydroelectric with pumping | 3329 | 3.3% |
| Solar PV | 4466 | 4.4% |
| Solar thermal | 2304 | 2.3% |
| Renewable waste | 123 | 0.1% |
| Other renewable | 859 | 0.9% |
| Coal | 9562 | 9.5% |
| Combined cycle | 24562 | 24.5% |
| Cogeneration | 5730 | 5.7% |
| Nuclear | 7117 | 7.1% |
| Other no renewable | 452 | 0.5% |
| TOTAL | 100382 | |

### *Storage capacity*

Regarding energy storage, for the year 2018, two technologies are considered: hydro pumping with 3329 MW of installed power according to [58] and deposits of molten salts in solar thermal plants with 8,4 GWh according to [47][52][53].

### *International electric energy exchanges capacity*

The value of the Spanish capacity interconnection in 2018 has been obtained from the PNIEC and REE. In 2018 Spain, the interconnection capacity (with Portugal, France and Morocco) is 5200 MW, three times below the European directive [60] which requires to have installed a capacity of at least 15% of the rated power of the system by 2030.

## 4.1.2 2030 Scenario

### *Final electric energy demand*

For the 2030 scenario, the value of the electricity demand provided by the PNIEC has been taken into account. The document considers that the annual electricity demand will increase by about 20 TWh in 12 years, in other words, it will grow from 243.7 TWh to 262.7 TWh.

### *Installed power*

Regarding the installed power, it is considered that the architecture of the Spanish electrical system in 2030 will be the one indicated in the PNIEC, except for the value of the *River Hydro* technology. In 2018 the ENTSO body defined 3 possible scenarios (ST, DG, EUCO) on the Spanish electricity system, and in all three scenarios the value of the installed capacity of *River Hydro* was 3850 MW [61].

As the value of river hydro provided by the PNIEC is considered insufficient, it has been decided to take the value provided by the ENTSO as the reference for 2030. Table 35 presents the estimate installed power of each type of technology and the percentage of its total representation within the system.

**Table 35. Forecast of the installed power in the 2030 scenario.**

| Technology | MW | % |
|---|---|---|
| Onn-shore wind power | 48550 | 31.2% |
| River Hydro | 3850 | 2.5% |
| Hydroelectric without pumping | 16250 | 10.4% |
| Hydroelectric with pumping | 7890 | 5.1% |
| Solar PV | 38404 | 24.7% |
| Solar thermal | 7300 | 4.7% |
| Others renewable | 1730 | 1.1% |
| Combined cycle | 24560 | 15.8% |
| Cogeneration | 3980 | 2.6% |
| Nuclear | 3050 | 2.0% |
| TOTAL | 155564 | 100% |

### *Storage capacity*

In 2030 scenario, 3 energy storage technologies are planned: hydro pumping with 7890 MW, deposits of molten salts in solar thermal plants and batteries.

The installed capacity of batteries considered in PNIEC is 2500 MW, but in the present study, an installed capacity of 0 MW and 5000 MW is also considered. In addition, the PNIEC considers that the batteries will have a storage capacity of 2 hours at nominal power, therefore, the storage capacity will be 0 GWh, 5GWh and 10 GWh, respectively.

Regarding the storage capacity of molten salt deposits, the PNIEC indicates that solar thermal plants will have a storage capacity equal to 9 hours of operation at rated power of the plant. It is considered difficult for all solar thermal plants to achieve this condition, so this rule will apply to only 80% of the plants. Then, the storage capacity of molten salt deposits is:

$$7.3\ GW \cdot 9\ h \cdot 0.8 = 52.6\ GWh$$

### *International electric energy exchanges capacity*

By 2030, the PNIEC expects an interconnection capacity of 13100 MW. This represents 8.4% of the total installed power, still less than the 15% required by the directive of the European Union [60]. The interconnection capacity forecast provided by the PNIEC for each country is described in Table 36.

**Table 36. Interconnection capacity forecast in 2030 according to PNIEC.**

| Interconnections | MW |
|---|---|
| ESP-FR | 8000 |
| ESP-PT | 4200 |
| ESP-MOR | 900 |
| Total | 13100 |

### *Electric vehicle*

Regarding the electrification of transport for the future, different projections made by different entities or authors have been considered [61][62][56] and are described in Table 37.

**Table 37. Forecasts of electric car incidence in Spain at 2030 scenario.**

| Document | Scenario | Nº of vehicles |
|---|---|---|
| PNIEC | - | 5000000 |
| Article [62] | Low Penetration | 2600000 |
| Article [62] | Medium Penetration | 4000000 |
| Article [62] | High Penetration | 6000000 |
| ENTSO | EUCO | 5717299 |
| THESIS | | 5000000 |

To obtain the number of cars, the average between the medium and high penetration scenario of the paper [62] has been made. This value is the same that PNIEC proposes and it is similar to ENTSO value.

Load efficiency, battery capacity and charging power values have been obtained from [63]. In the following table you can see the car models and their characteristics:

**Table 38. Characteristics of car models.**

| Model | Battery capacity [kWh] | Power of on-board charger [kW] |
|---|---|---|
| Nissan leaf II | 40 | 6.6 |
| Renault zoe | 41 | 22 |

For the calculations of total storage capacity and total charging power, the values of the *Renault ZOE* model have been chosen and multiplied by the total number of cars. Regarding annual consumption, the value 18.08 TWh has been obtained from PNIEC. The results are presented in Table 39.

**Table 39. Global characteristics of the electric cars network in 2030 scenario**

| Characteristics | Value |
|---|---|
| Battery capacity [GWh] | 205 |
| Charge power [MW] | 110000 |
| Efficiency | 0.9 [64] |
| Annual consumption [TWh] | 18.08 |

### 4.1.3 2040 Scenario

#### *Final electric energy demand*

Even though EU governance regulation required member states to submit their first national long-term strategies to the Commission by 1 January 2020 [65], at the time this study has been done, the Spanish state has not yet made the definitive document. On May 19 of this year, the PLCCTE bill was presented to the Spanish courts. Unfortunately, this is a very generic document and lacks specific technical content.

To be able to carry out the work, forecasts of future scenarios done by different agencies and authors have been compiled. As Portugal has similar climatic conditions to Spain, the scenarios proposed in document RNC250 [66] have also been extrapolated to the Spanish electricity system.

Table 40 presents the different forecasts for electricity demand in Spain for 2040:

**Table 40. Forecasts of Spanish electricity demand for 2040.**

| Document | Year | Scenario | Demand [TWh] |
|---|---|---|---|
| AEE [67] | 2017 | - | 345.0 |
| Article [68] | 2018 | 1,36% | 374.8 |
| Article [68] | 2018 | 1,73% | 413.6 |
| ENTSO | 2018 | ST | 282.7 |
| ENTSO | 2018 | DG | 317.3 |
| ENTSO | 2018 | EU/GCA | 290.3 |
| Extrapolation RNC | 2019 | A | 397.8 |
| Extrapolation RNC | 2019 | B | 405.2 |
| Article [69] | 2019 | 1,36% | 346.0 |
| Article [69] | 2019 | 1,73% | 376.8 |

Articles [68] and [69] consider two possible scenarios for the growth of electricity demand (1.36% and 1.73% per year), based on the results of the *Global Calculator Tool* [70]. Due to the crisis of the COVID19 and considering that the PLCCTE is clearly committed to a more sustainable future and a high incidence of RES, the most optimistic scenario has been chosen (1.36% ) and this value has been applied on the forecast made by PNIEC of 2030 electricity demand.

Then the evolution of demand until 2040 is considered to be:

**Table 41. Electricity demand evolution until 2040.**

|  | 2018 | 2030 | 2040 |
|---|---|---|---|
| Electric Demand [TWh] | 243.69 | 262.66 | 301.04 |

#### *Installed power*

As in the case of electricity demand, different scenarios have been compiled in order to create the mix of installed power that best suits the goals of the PNIEC and PLCCTE documents. The following table shows the values chosen for this study:

**Table 42. Compilation of installed power forecast for 2040 scenario.**

| Installed power [MW] | AEE | ENTSO-GCA | Article [69] | Article [69] | THESIS |
|---|---|---|---|---|---|
| On-shore wind power | 50000 | 47590 | 32100 | 39800 | 47590 |
| Off-shore wind power | | 3408 | | | 3408 |
| Hydroelectric | 20400 | 24920 | 24700 | 25900 | 24920 |
| Hydro pump | - | 10150 | - | - | 10150 |
| Solar PV | 45000 | 77000 | 24600 | 27300 | 77000 |
| Solar thermal | - | 3363 | - | - | 12300 |
| Others renewable | 2550 | 2550 | - | - | 2550 |
| Combined cycle | - | 24560 | 24948 | 24948 | 12280 |
| Cogeneration | - | - | 10800 | 13200 | - |
| Nuclear | 3200 | 3050 | - | - | 3050 |
| Others no renewable | - | - | 3800 | 3500 | - |
| TOTAL | 121150 | 196591 | 120948 | 134648 | 193248 |

The installed power mix considered in this study is a modification of the GCA 2040 scenario developed by ENTSO. The only modified values of installed power are those of solar thermal and combined cycle technologies.

The installed power of thermal solar is considered 12300 MW, so that it increases about 5000 MW, a similar value between the scenarios 2018 and 2030. In addition, it should be noted that the value proposed by ENTSO is lower than the power provided by the PNIEC for 2030, therefore, it has been discarded.

Regarding the installed power of combined cycle plants, it is reduced by half in order to reach the goal of PLCCTE to be 100% renewable in the electrical system by 2050.

### Storage capacity

Compared to 2030 scenario hydro pumping storage installed power is increased to 10150 MW.

In 2040 scenario, the installed power of batteries it will be assumed between 5000 MW and 9000 MW. As in the 2030 scenario the batteries will have a storage capacity of 2 hours at nominal power, therefore, the storage capacity will be between 10 GWh and 18 GWh.

Regarding molten salt deposits, is considered that the storage capacity is equal to 9 hours of operation at rated power of the plant. It is considered difficult for all solar thermal plants to achieve this condition, so this rule will apply to only 90% of the plants. Then, the storage capacity of molten salt deposits is:

$$12.3\ GW \cdot 9\ h \cdot 0.9 = 99.63\ GWh$$

### International electric energy exchanges capacity

It is assumed that, in 2040, there will be at least an interconnection capacity equal to or greater than 15% of the rated power of the system, as it is indicated by the PLCCTE and the European directive [60].

Then the interconnection capacity is considered to be 28987 MW.

### *Electric vehicle*

To obtain the number of electric cars for the 2040 scenario, the same methodology has been followed as with the 2030 scenario. The average between the medium and high penetration scenario of the paper [62] has been made. The estimated values are presented in Table 43.

**Table 43. Forecasts of electric car incidence in Spain at 2040 scenario.**

| Document | Scenario | Nº of vehicles |
|---|---|---|
| Article [62] | Low Penetration | 6500000 |
| Article [62] | Medium Penetration | 8500000 |
| Article [62] | High Penetration | 13500000 |
| ENTSO | EUCO | 10427246 |
| THESIS | | 11000000 |

The total storage capacity and total charge power have been calculated in the same way that scenario 2030. For 2040 scenario, the increase in annual consumption is directly proportional to the increase in the number of cars. Table 44 summarizes the results.

**Table 44. Global characteristics of the electric cars network in 2040 scenario.**

| Characteristics | Value |
|---|---|
| Battery capacity [GWh] | 451 |
| Charge power [MW] | 242000 |
| Efficiency | 0.9 |
| Annual consumption [TWh] | 39.78 |

## 4.1.4 H2040 Scenario

### *Final electric energy demand*

As discussed before, in scenario H2040 it is hypothesized that green hydrogen will replace some of the fossil fuels used in the industrial and transportation sectors. So, the electricity demand of the H2040 scenario is the sum between the demand of the 2040 scenario and the electricity used for hydrogen production.

For the calculation of hydrogen consumption, an extrapolation of the forecast made by the Portuguese document RNC2050 to the Spanish system has been made. The following table shows the data indicated in RNC2050, as can be seen, considering two possibilities on hydrogen consumption:

**Table 45. Forecast of hydrogen consumption in Portugal according to RNC2050.** [66]

| RNC 2050 | 2040 | |
|---|---|---|
| Electricity consumption [TWh] | 264.74 | 269.7 |
| Average [TWh] | 267.22 | |
| Hydrogen consumption [TWh] | 4.61 | 13.71 |
| Hydrogen % on demand | 1.7% | 5.1% |

For the Spanish scenario, first the percentage of hydrogen has been applied in relation to the total demand for electricity. Then, the average of the two values has been made. Finally, the electricity required for produce hydrogen has been calculated by applying the efficiency mentioned in the article [71]. The values are shown below:

**Table 46. First calculation of hydrogen consumption in Spain at H2040 scenario.**

| SPAIN | 2040 | |
|---|---|---|
| Electricity Demand [TWh] | 301 | |
| Hydrogen consumption [TWh] | 5.19 | 15.44 |
| AVERAGE [TWh] | 10.32 | |
| Electricity demand for Hydrogen Production [TWh] | 13.76 | |

Then the value of the electricity demand is recalculated:

$$301 + 13.76 = 314.76\,TWh$$

The above procedures are repeated until the results converge, and in the Table 47 the final results can be seen:

**Table 47. Hydrogen Spanish consumption at H2040 scenario.**

| SPAIN | 2040 | |
|---|---|---|
| Electricity Demand [TWh] | 315.42 | |
| Hydrogen consumption [TWh] | 5.44 | 16,19 |
| AVERAGE [TWh] | 10.81 | |
| Electricity demand for Hydrogen Production [TWh] | 14.42 | |

Therefore, the electricity demand considered by the H2040 scenario is 315.42 TWh.

### *Installed power*

The H2040 scenario has more installed power than the 2040 scenario. The increase in installed power is proportional to the increase in electricity demand due to hydrogen production.

It has been considered that the production of green hydrogen will be done from photovoltaic plants, therefore, the increase in installed power with respect to the 2040 scenario will be made in photovoltaic solar energy. Below, there is the installed power mix for the H2040 scenario:

**Table 48. Installed power mix in the H2040 scenario.**

| Technology | MW | % |
|---|---|---|
| Onn-shore wind power | 47590 | 23.5% |
| Off-shore wind power | 3408 | 1.7% |
| River Hydro | 3850 | 1.9% |
| Hydroelectric without pumping | 21070 | 10.4% |
| Hydroelectric with pumping | 10150 | 5.0% |
| Solar PV | 77000 | 38.0% |

| | | |
|---|---|---|
| $H_2$ Solar PV | 9255 | 4.6% |
| Solar thermal | 12300 | 6.1% |
| Others renewable | 2550 | 1.3% |
| Combined cycle | 12280 | 6.1% |
| Nuclear | 3050 | 1.5% |
| TOTAL | 202503 | 100% |

### *Storage capacity*

The H2040 scenario has the same storage capacity as the 2040 scenario.

Photovoltaic plants that produce hydrogen can also be used to regulate the system by producing hydrogen and storing it, when there is a surplus of energy and using photovoltaic plants at times of low production of other renewables (as long as solar irradiance is available).

### *International electric energy exchanges capacity*

Then the interconnection capacity it is assumed to be a 15% of the rated power of the system. So, the interconnection capacity of H2040 scenario will be 30376 MW.

### *EV and FCEV*

In the H2040 scenario, the sum of EVs and FCEV (Fuel Cell Electric Vehicle) will be equal to the number of EVs in the 2040 scenario. The FCEVs will have a 10% penetration as indicated in the article [72]. Table 49 and Table 50 shows the number of cars of each type and the characteristics:

**Table 49. Global characteristics of electric cars network in H2040 scenario.**

| H2040 scenario | Value |
|---|---|
| Number of EV Vehicles | 9900000 |
| Battery capacity [GWh] | 405.90 |
| Charge power [MW] | 217800 |
| Efficiency | 0.90 |
| Annual consumption EV | 35.80 |

**Table 50. Global characteristics of FCEV network in H2040 scenario**

| H2040 scenario | Value |
|---|---|
| Number of FCEV Vehicles | 1100000 |
| Annual consumption FCEV | 3.98 |

## 4.1.5 2050 Scenario

### *Final electric energy demand*

As in the 2040 scenario, the value of electricity demand has been obtained by applying an annual increase of 1.36%. The evolution of electric demand is:

**Table 51. Evolution of electricity demand in Spain until 2050 scenario**

| | 2018 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Electric Demand [TWh] | 243.69 | 262.66 | 301.04 | 344.6 |

### *Installed power*

The year 2050 must be 100% renewable as it is one of the goals of the PLCCTE. Because no 100% renewable scenario has been found, the 2050 scenario has been build following the next steps:

1. Installed power grows with the same proportion as demand.

**Table 52. Total installed power at 2050 scenario.**

| | 2040 | 2050 |
|---|---|---|
| Installed power [GW] | 193.2 | 221.2 |
| Demand [TWh] | 301.0 | 344.6 |

2. The hydroelectric installed power maintains the same value as in the 2040 scenario. It is considered that the best places for the use of this energy will have already been built. In addition, large hydroelectric power plants are a type of construction that have a big environmental impact.

3. The installed Biomass power is 5000 MW. An extrapolation of the Portuguese system to Spanish has been made, and the value of biomass is near 5000 MW. The results of the extrapolation are shown below:

**Table 53. Spanish installed power [GW] mix extrapolation from RNC2050.**

| SPAIN | 2050 | 2050 |
|---|---|---|
| Natural Gas | 0.6 | 0.6 |
| Hydroelectric | 15.8 | 14.1 |
| Hydroelectric with pumping | 10.5 | 9.4 |
| On-shore wind power | 37.1 | 36.1 |
| Off-shore wind power | 0.6 | 3.6 |
| Centralized Solar PV | 40.1 | 40.0 |
| Decentralized Solar PV | 37.1 | 36.1 |
| Biomass/Biogas/Waste | **4.3** | **5.0** |
| Batteries | 12.7 | 38.8 |
| Hydrogen | 40.1 | 59.6 |
| Installed power [GW] | 198.9 | 243.3 |
| Demand [TWh] | 344.6 | 344.6 |

4. The rest of installed power is going to be divided following the same proportion than the year 2040.

**Table 54. Increase of the installed power of wind, solar PV and solar thermal technologies.**

| Technology | 2040 | | 2050 | |
|---|---|---|---|---|
| On-shore wind power | 47590 | 34% | 61440 | 34% |
| Off-shore wind power | 3408 | 2% | 4400 | 2% |
| Solar PV | 77000 | 55% | 99409 | 55% |
| Solar thermal | 12300 | 9% | 15880 | 9% |
| TOTAL | 140298 | 100% | 181128 | 100% |

The following table show the installed power mix for the 2050 scenario:

**Table 55. Installed power mix of 2050 scenario.**

| Technology | MW |
|---|---|
| On-shore wind power | 61440 |
| Off-shore wind power | 4400 |
| Hydroelectric | 24920 |
| Hydro pumping | 10150 |
| Solar PV | 99409 |
| Solar thermal | 15880 |
| Biomass | 5000 |
| TOTAL | 221198 |

### *Storage capacity*

As in the previous scenarios, energy storage is mainly based on 3 technologies: hydro pumping, batteries, molten salt deposits. As mentioned in the previous section, the installed power of hydro pumping storage remains constant.

In 2050 scenario, the installed power of batteries it will be assumed between 10000 MW and 14000 MW. As in the 2040 scenario the batteries will have a storage capacity of 2 hours at nominal power, therefore, the storage capacity will be between 20 GWh and 28 GWh.

About molten salt deposits storage capacity, is calculated in the same way as in the 2040 scenario. So, the storage capacity of molten salt deposits is:

$$15.88\ GW \cdot 9\ h \cdot 0.9 = 128.6\ GWh$$

### *International electric energy exchanges capacity*

As in the 2040 scenario, the interconnection capacity of the Spanish Electric System will be 15% of the rated power of the system.

Then the interconnection capacity is 33180 MW.

### *Electric vehicle*

For the calculation of the number of electric cars in 2050, the same calculations have been made as in the 2030 and 2040 scenarios. The following table shows the number of electric cars expected for the 2050 scenario.

**Table 56. Forecasts of number of electric cars in Spain at 2050 scenario.**

| Document | Scenario | 2050 |
|---|---|---|
| Article [62] | Low Penetration | 10000000 |
| Article [62] | Medium Penetration | 14000000 |
| Article [62] | High Penetration | 20000000 |
| THESIS | | 17000000 |

The following table shows the values of charge and discharge efficiency, total storage capacity, total charge power and annual consumption. These values have been obtained in the same way as the 2040 scenario.

**Table 57. Global characteristics of electric cars networks in 2050 scenario.**

| Characteristics | Value |
|---|---|
| Battery capacity [GWh] | 451 |
| Charge power [MW] | 242000 |
| Efficiency | 0.9 |
| Annual consumption [TWh] | 39.78 |

### 4.1.6 H2050 Scenario

#### *Final electric energy demand*

As in the H2040 scenario, the electricity demand of the H2050 scenario is the sum between the demand of the 2050 scenario and the electricity used for hydrogen production.

The calculation of hydrogen production has been done in the same way as in scenario H2040, that is, by performing an extrapolation of the forecast made by the Portuguese document RNC2050 to the Spanish system.

In the following table, we can see the values of electricity demand and hydrogen consumption, among other values:

**Table 58. Hydrogen Spanish consumption at H2050 scenario.**

| SPAIN | 2040 | |
|---|---|---|
| Electricity Demand [TWh] | 370.80 | |
| Hydrogen consumption [TWh] | 15.43 | 25.53 |
| AVERAGE [TWh] | 20.48 | |
| Electricity demand for Hydrogen Production [TWh] | 26.26 | |

#### *Installed power*

Due to the increase in electricity demand, the total installed power of the H2050 scenario will increase in the same proportion as the demand.

As in the H2040 scenario and for the same reasons, the increase in the installed power, with respect to the 2050 scenario, will be made in photovoltaic solar energy. The following table shows the installed power mix for the H2050 scenario:

**Table 59. Installed power mix of H2050 scenario.**

| Technology | 2050 | % |
|---|---|---|
| Onn-shore wind power | 61440 | 25.8% |
| Off-shore wind power | 4400 | 1.8% |
| River Hydro | 3850 | 1.6% |
| Hydroelectric without pumping | 21070 | 8.9% |
| Hydroelectric with pumping | 10150 | 4.3% |
| Solar PV | 99408 | 41.8% |
| $H_2$ Solar PV | 16855 | 7.1% |
| Solar thermal | 15880 | 6.7% |
| Biomass | 5000 | 2.1% |
| TOTAL | 238053 | 100% |

### *Storage capacity*

The H2050 scenario has the same storage capacity as the 2050 scenario.

### *International electric energy exchanges capacity*

The interconnection capacity it is assumed to be a 15% of the rated power of the system. So, the interconnection capacity of H2050 scenario will be 35708 MW.

### *EV and FCEV*

In the H2050 scenario, the sum of EVs and FCEVs will be equal to the number of EVs in the 2050 scenario. The FCEVs will have a 10% penetration as indicated in the article [72]. The following tables shows the number of cars of each type and the characteristics:

**Table 60. Global characteristics of electric cars network in H2050 scenario.**

| H2050 scenario | Value |
|---|---|
| Number of EV Vehicles | 9900000 |
| Battery capacity [GWh] | 557.6 |
| Charge power [MW] | 299200 |
| Efficiency | 0.9 |
| Annual consumption EV | 49.18 |

**Table 61. Global characteristics of FCEV network in H2050 scenario.**

| H2050 scenario | Value |
|---|---|
| Number of FCEV Vehicles | 3400000 |
| Annual consumption FCEV | 12.29 |

## 4.2 EnergyPlan Simulation

The EnergyPlan program has been used to simulate the different scenarios. Energyplan is a program developed by Henrik Lund in 1999 to conduct macro-energetic studies of countries or regions, although small-scale studies can also be done. The program makes an hourly annual energy simulation on the electricity, heating, cooling, industry, and transportation sectors, although, in the present study, it has only been used to study the electrical system.

EnergyPlan can perform the following two types of simulations:

- **Technical simulation**: Optimizes the operation of the given system considering only technical parameters.
- **Economic Simulation:** The simulation optimises the operation of each plant in accordance with business-economic profits, including any taxes and $CO_2$ emissions costs.

### 4.2.1 Methodology

For the simulation, a series of data must first be introduced, such as demand, system installed power mix, technology costs, annual distributions, and other parameters. In addition, the program allows you to choose different simulation strategies, which are mainly related to imports/exports and excess energy production. Once the inputs of the program have been defined, it carries out an annual study of the system introduced, giving as outputs annual values and hourly evolutions of energy production, costs, $CO_2$ emissions, among others.

In summary, the steps to follow for the simulation of the scenarios are simplified in the following list:

1. Input of electricity demand;
2. Input of energy supply and energy storage systems;
3. Input of annual distributions and parameters that characterize the demand;
4. Simulation and output of the results.

For this study, the program has been first calibrated by performing the simulation of the year 2018. The year 2018 was chosen as a reference, as it is the year closest to the present with the updated values. For the calibration, specific values of the program have been adjusted until the results are close to the real values of the year 2018.

Once the program has been calibrated, the models of the years 2030, 2040 and 2050 have been simulated.

### 4.2.2 Simulation parameters

As mentioned in the methodology section, to perform the simulation with EnergyPlan, it is necessary to enter initial parameters, among other things, as discussed in the previous section. The most important program parameters are specified below

#### *Fuel distribution*

In our case study, fuel distribution refers to the consumption of fuels that power plants have used to generate electricity.

Fuel consumption has been divided between cogeneration power plants (PP1) and non-cogeneration thermal power plants (PP2). The following 4 tables show the distribution of fuel consumption for the years simulated in the study:

**Table 62. 2018 distribution of fuel consumption.**

| 2018 [TWh] | Coal | Oil | Ngas | Biomass |
|---|---|---|---|---|
| PP1 | 2 | 7.6 | 78.6 | 9 |
| PP2 | 101.8 | 24.8 | 68.1 | 14.8 |

**Table 63. 2030 distribution of fuel consumption.**

| 2030 [TWh] | Coal | Oil | Ngas | Biomass |
|---|---|---|---|---|
| PP1 | 1.4 | 5.3 | 54.6 | 6.3 |
| PP2 | 0 | 0 | 68.1 | 29.8 |

**Table 64. 2040 distribution of fuel consumption.**

| 2040 [TWh] | Coal | Oil | Ngas | Biomass |
|---|---|---|---|---|
| PP1 | 0 | 0 | 0 | 0 |
| PP2 | 0 | 0 | 34.1 | 43.9 |

**Table 65. 2050 distribution of fuel consumption.**

| 2050 [TWh] | Coal | Oil | Ngas | Biomass |
|---|---|---|---|---|
| PP1 | 0 | 0 | 0 | 0 |
| PP2 | 0 | 0 | 0 | 86.1 |

The values for 2018 have been obtained from “Ministerio para la Transición Ecológica y el Reto Demográfico” website [73].

For the rest of the years, the consumption of each type of fuel has increased or decreased in proportion to the installed power of each type of plant and what they consume.

### *$CO_2$ price*

$CO_2$ price is way to promote the reduction of greenhouse gas emissions. It is based on applying a cost to each ton of $CO_2$ emitted so that it has an economic cost for pollutants, thus the reduction of emissions results also in economic savings.

The value of the $CO_2$ price for 2018 has been obtained from the website [74]. For the years 2030 and 2040 the value has been obtained from the ENTSO-DT scenarios. Finally, the price in 2050 has been taken arbitrarily, taking into account the values of previous years. Below is the summary table:

**Table 66. $CO_2$ price evolution.**

| | 2018 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Price $CO_2$ [Eur/ton] | 15.9 | 50.0 | 80.0 | 110.0 |

It should be noted that in 2050 renewables and storage systems will be quite mature technologies and with competitive costs, so it is very possible that it will not be necessary to increase the price of $CO_2$ so much.

## *Technology Costs*

As Henrik Lund explains in[75], it is very difficult to predict the cost of technologies for the future. For this reason, it has been decided to use the data provided by EnergyPlan on its website. Table 67, Table 68, Table 69 summarize the considered values.

**Table 67. Technology Costs of 2018 and 2030.**

| | 2018 | | | 2030 | | |
|---|---|---|---|---|---|---|
| Technology | Investment (M€/unit) | Lifetime (years) | Fixed OM (% of inv.) | Investment (M€/unit) | Lifetime (years) | Fixed OM (% of inv.) |
| Large Power plants | 1.32 | 31 | 2.43 | 1.26 | 31 | 2.45 |
| Nuclear plants | 4,5 | 60 | 2 | 4.12 | 60 | 1.9 |
| Pump hydro | 0.6 | 50 | 1.5 | 0.6 | 50 | 1.5 |
| Pumped storage | 7.5 | 50 | 1.5 | 7.50 | 50 | 1.5 |
| Onshore wind power | 1.02 | 26 | 3.20 | 0.91 | 30 | 3.27 |
| Offshore wind power | 2.19 | 26 | 2.02 | 1.75 | 30 | 1.94 |
| Photo Voltaic | 1.14 | 33 | 1 | 0.85 | 40 | 1 |
| CSP solar power | 4.94 | 30 | 4 | 3.80 | 30 | 4 |
| River hydro | 5.56 | 60 | 1.5 | 5.62 | 60 | 1.5 |
| Dammed Hydro power | 2.48 | 60 | 1.25 | 2.55 | 60 | 1.25 |
| Dammed Hydro Storage | 7.5 | 50 | 1.5 | 7.5 | 50 | 1.5 |
| Hydro pump | 0.6 | 50 | 1.5 | 0.60 | 50 | 1.5 |
| Geothermal Electricity | 5.19 | 30 | 1.52 | 4.47 | 30 | 1.8 |
| Electrolyser | 0.78 | 25 | 5 | 0.55 | 25 | 5 |
| Interconnection | 1.2 | 40 | 1 | 1.2 | 40 | 1 |
| Hydrogen storage | - | - | - | 7.60 | 25 | 2.5 |
| Batteries | - | - | - | 0.05 | 20 | 1.5 |
| Storage batteries | - | - | - | 0.20 | 20 | 0.5 |
| Tidal | - | - | - | 3.4 | 20 | 3.8 |

**Table 68. Technology Costs of 2040 and 2050.**

| | 2040 | | | 2050 | | |
|---|---|---|---|---|---|---|
| Technology | Investment (M€/unit) | Lifetime (years) | Fixed OM (% of inv.) | Investment (M€/unit) | Lifetime (years) | Fixed OM (% of inv.) |
| Large Power plants | 1.23 | 31 | 2.46 | 1.20 | 31 | 2.48 |
| Nuclear plants | 3.93 | 60 | 1.75 | 3.76 | 60 | 1.6 |
| Pump hydro | 0.6 | 50 | 1.5 | 0.6 | 50 | 1.5 |
| Pumped storage | 7.5 | 50 | 1.5 | 7.50 | 50 | 1.5 |
| Onshore wind power | 0.92 | 30 | 3.33 | 0.93 | 30 | 3.4 |
| Offshore wind power | 1.62 | 30 | 1.93 | 1.50 | 30 | 1.93 |
| Photo Voltaic | 0.78 | 40 | 1 | 0.72 | 40 | 1 |
| CSP solar power | 3.6 | 30 | 4 | 3.40 | 30 | 4 |
| River hydro | 5.62 | 60 | 1.5 | 5.62 | 60 | 1.5 |
| Dammed Hydro power | 2.55 | 60 | 1.25 | 2.55 | 60 | 1.25 |
| Dammed Hydro Storage | 7.5 | 50 | 1.5 | 7.5 | 50 | 1.5 |
| Hydro pump | 0.6 | 50 | 1.5 | 0.60 | 50 | 1.5 |
| Geothermal Electricity | 4.04 | 30 | 2 | 3.61 | 30 | 2.2 |
| Electrolyser | 0.52 | 25 | 5 | 0.50 | 25 | 5 |
| Interconnection | 1.2 | 40 | 1 | 1.2 | 40 | 1 |
| Hydrogen storage | 6.4 | 25 | 2.03 | 6.40 | 25 | 2.03 |
| Batteries | 0.05 | 20 | 1.5 | 0.05 | 20 | 1.5 |
| Storage batteries | 0.2 | 20 | 0.5 | 0.20 | 20 | 0.5 |
| Tidal | 1.9 | 20 | 4.9 | 1.9 | 20 | 4.9 |

**Table 69. Fuel price evolution.**

| Fuel Price [EUR/GJ] | 2018 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Coal | 2.4 | 3.2 | 3.8 | 4.5 |
| Fuel Oil | 7.7 | 14.3 | 19.7 | 25.2 |
| Diesel/Gasoil | 12.5 | 18.4 | 23.4 | 28.3 |
| Petrol/JP | 13.2 | 18.6 | 23.0 | 27.5 |
| Ngas | 6.9 | 9.4 | 11.4 | 13.5 |
| Biomass | 5.0 | 6.6 | 8.0 | 9.3 |
| Dry mass | 10.3 | 11.4 | 12.4 | 13.3 |
| Wet Biomass | 0.0 | 0.0 | 0.0 | 0.0 |
| Nuclear/Uranium | 1.5 | 1.5 | 1.5 | 1.5 |

### *Distributions*

One of the most important data to be introduced into the program are the distributions files. The distributions are archives of 8784 hours values (all the hours of a leap year) that allow to establish, together with an annual value, the distributions of the evolution of prices, electricity demand or energy generation for each energy source.

All values have been obtained from the *esios* database [76] provided by the REE. The main distributions used are explained below.

### Energy Generation

The distributions values of energy generation are relative (between 0 and 1) and have been obtained by dividing the generating power of each hour by the total installed power for each type of technology. All values have been obtained from 2018 year except for the Dry hydro distribution.

Dry hydro is a distribution that has been used in the work to simulate the generation of hydraulic energy in dry years. The value of the dry hydro distribution has been obtained from 2017 year, because according to the report [77] of the REE, it has been the driest year of the last decade. Below you can see the graphics of hydraulic generation of recent years:

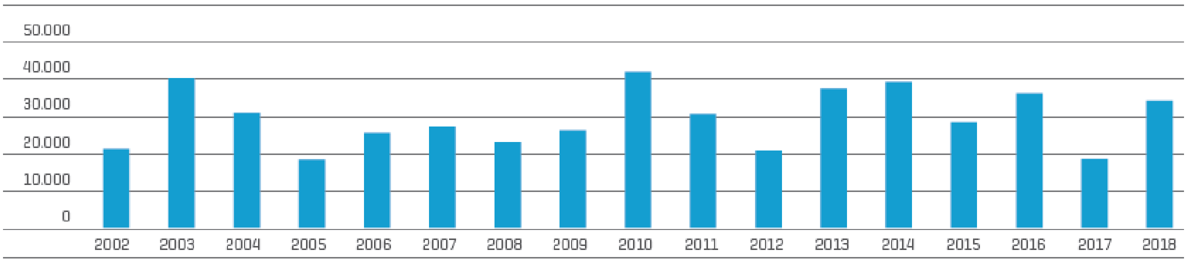

**Figure 17. Evolution of electricity generation [GWh] by hydraulic plants in Spain.**

The other electricity generation technologies that have also needed distribution for the simulation of the program are: Nuclear, PV, Solar thermal, Wet hydro and Eolic. The following graphs show the hourly capacity factor and the monthly capacity factor of each of the technologies.

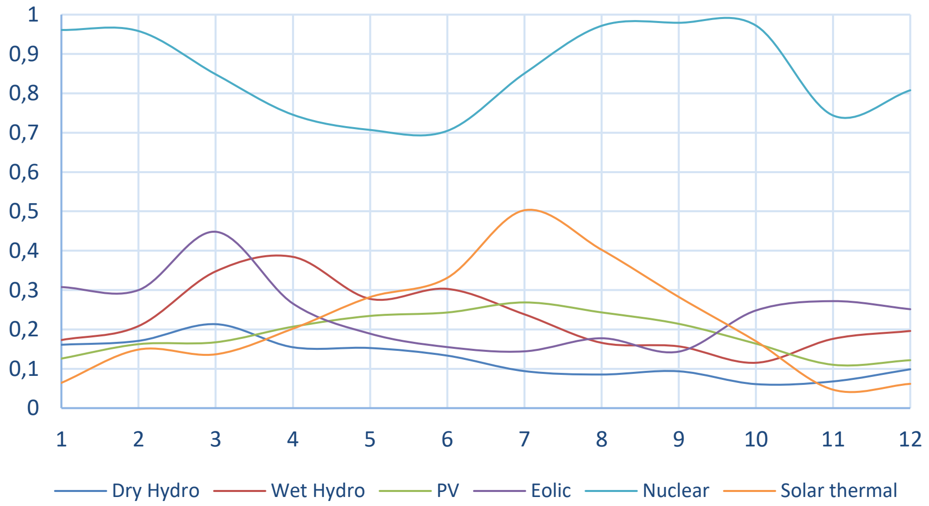

**Figure 18. Monthly Capacity Factor.**

Monthly capacity factor graphic has been made by averaging all the hours of each month, so the graph is much clearer and allows to see in which seasons of the year each type of technology produces more energy. As can be seen PV and solar thermal technologies have more production in the months with higher solar irradiance, while hydro and wind produce more in the spring and winter seasons.

The following graph shows the capacity factor hourly evolution of the 2018 during the day by energy source. As expected, PV and Solar thermal have more production in the middle hours of the day, when there is more solar radiation. It can also be seen a two-hour shift of the solar thermal curve with respect to the PV curve, this displacement is mainly due to the thermal inertia that CSP plants have. In addition, solar thermal power plants, unlike PV, can produce energy during the night thanks to the deposits of molten salts that allow to store energy.

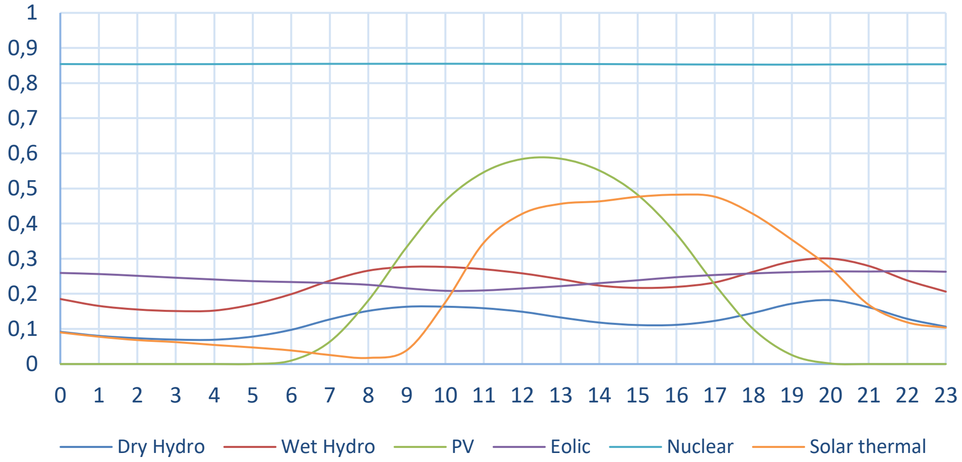

**Figure 19. Hourly Capacity Factor.**

### Electricity demand

The electricity demand distribution values are relative (between 0 and 1) to the annual electricity demand.

Two distributions have been used for electricity demand: the 2018 annual distribution extracted from esios [76] and the COVID19 distribution.

The COVID19 distribution is a variation of the 2018 distribution COVID19 distribution is flatter than 2018 distribution and it aims to represent the effect that COVID19 may have on society's electricity consumption habits over the coming years.

The following steps have been taken to carry out the COVID19 distribution:

1. Comparison of the demand of the year 2020 with the demand of the year 2018 of the same period.

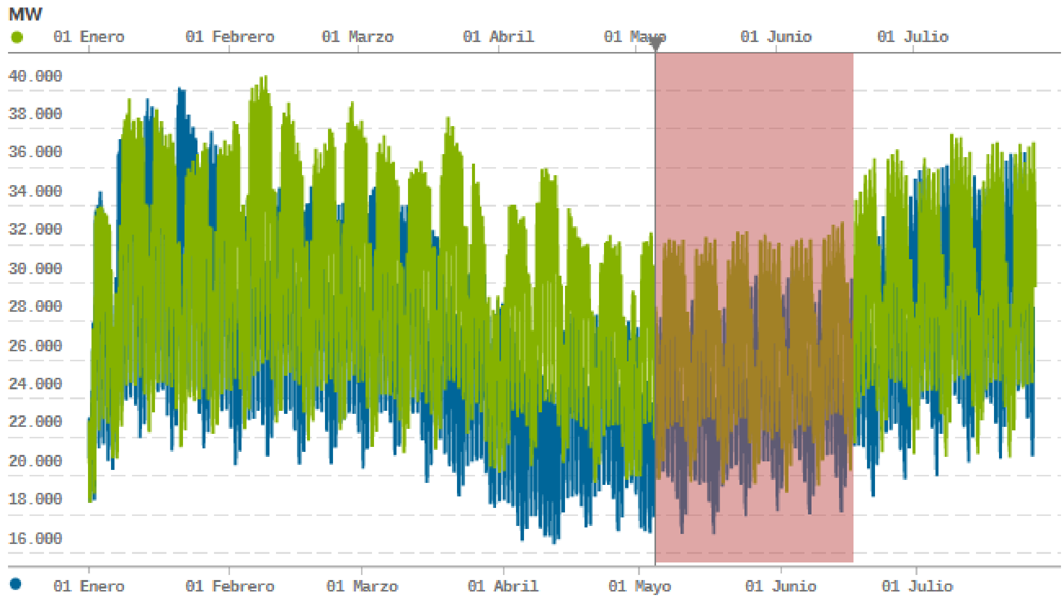

**Figure 20. Evolution and comparison of electricity demand in 2018 (green) and 2020 (blue).**

2. Choice of the weeks where demand remains most stable to make the new distribution. The six weeks marked with red in Figure 20 and which are between May 4 and June 14 have been chosen.

Figure 21 shows in detail the evolution of electricity demand in the six weeks chosen. It can be clearly differentiated, as demand in 2018 decreases over the weekends, while durign the COVID-19 period, there is not much difference between the weekday and weekend. It can also be noticed a delay, so the electricity consumption peak started earlier and finished earlier, as people id not have to move from home to work and back.

**Figure 21. Evolution and comparison of electricity demand in the chosen period.**

3. Calculation of the average week for the year 2018 and 2020. The average of the 6 weeks has been made for both years. Below can be seen the 2 profiles:

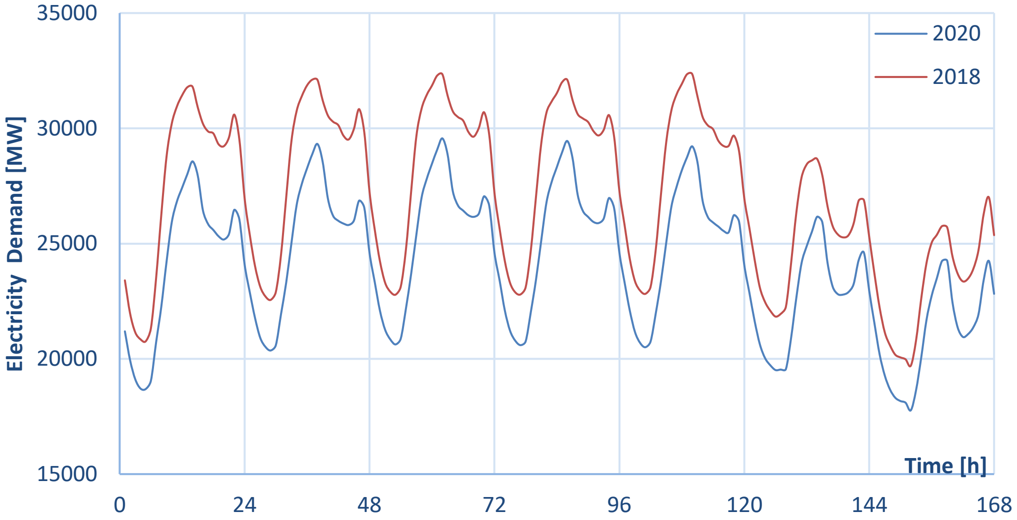

**Figure 22. Average week of the electricity demand.**

4. Calculation of the percentage decrease in demand for each hour of the average week. This value has been obtained by dividing the decrease in demand by the demand in 2018 for each hour. The percentage decrease in demand ranges between 5.64% and 15.86%. We can see that at the end of the lockdown period, the reduction value decrease as people start to move around and get back to previous routines. The following is a graph of the percentage decrease over a week:

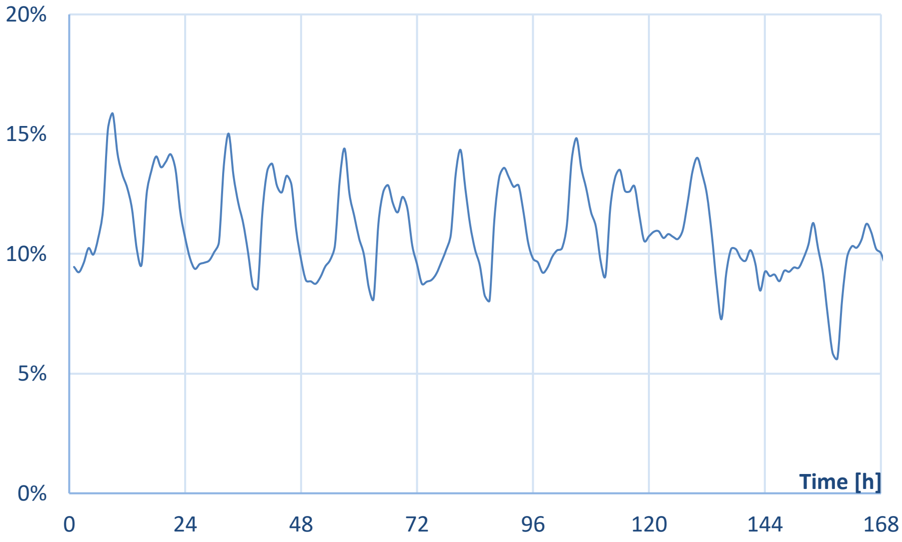

**Figure 23. Decrease of COVID19 demand with respect to 2018 year.**

5. Finally, the percentage decrease in demand has been applied to all weeks of 2018 to prepare the COVID19 distribution. It should be noted that the difference between the maximum and minimum value of the COVID19 distribution is smaller than in 2018, so it has a flatter demand curve.

Once the COVID19 distribution has been obtained, the graphs below show the hourly load curve and the monthly load curve of both distributions:

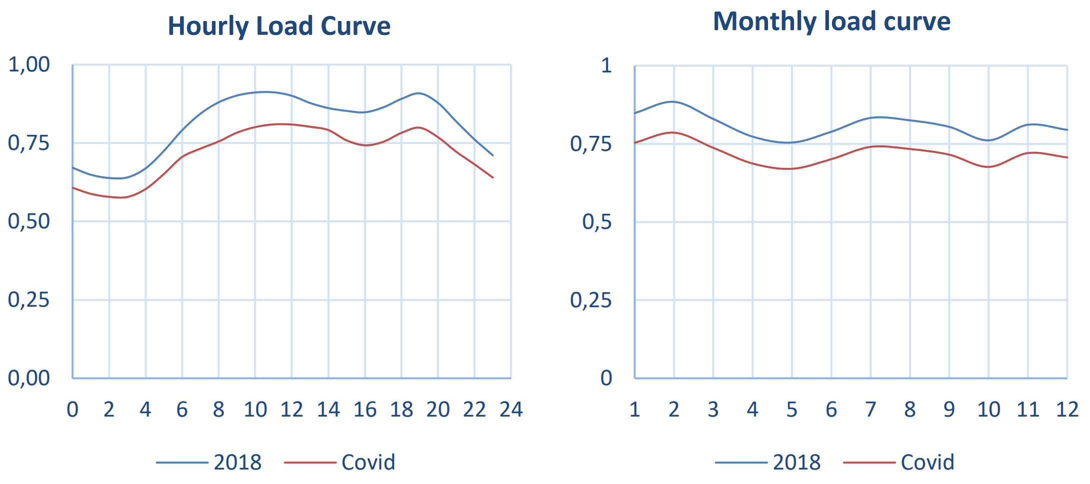

**Figure 24. Hourly load curve and monthly load curve distributions**

**Energy Price**

Fort the energy price distribution, all the values are absolute and have been obtained from [75]. Below it is possible to see the hourly evolution energy price of the average day of the year 2018:

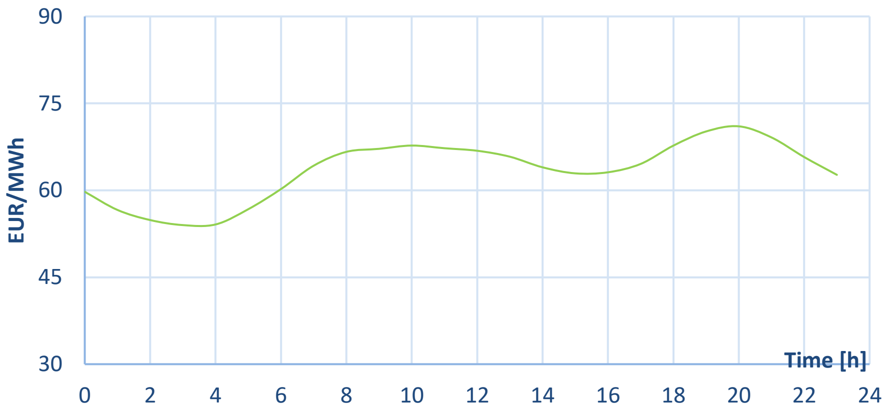

**Figure 25. Hourly price distribution.**

## 4.3 Results

For each scenario, various simulations have been made combining different inputs, in order to be able to choose the best energy storage strategy. Below, these are the inputs that have varied in the different simulations:

- Installed power of the batteries.
- Economic/Technical simulation.
- Wet hydro/Dry hydro distribution. To see the influence of dry and rainy year.
- Simulation strategies.

For the analysis of the results, different indicators have been used depending on the simulated scenario. The main indicators used are annual costs of the electric system, $CO_2$ emissions, RES% and saturation of the interconnection line.

### 4.3.1 2018 scenario

This scenario is the reference model and it has been used to verify that the distributions and the program are working properly and can reproduce the current energy system of Spain.

For the 2018 scenario calibration, two simulations have been performed, one with Wet hydro distribution and the other with Dry hydro distribution. All other inputs have remained the same.

In the simulation that has been used the dry hydro distribution, it is intended to check that the generation of electricity produced by the hydraulic power plants is the same that in 2017. While the other simulation, checks that the generation of renewables, PP and Nuclear have similar values to those generated in 2018.

The results of electricity generation with the Wet hydro distribution are the following:

**Table 70. Economic and technical results of Wet scenario 2018.**

| | Official [TWh] | Economic [TWh] | Error % | Technical [TWh] | Error % |
|---|---|---|---|---|---|
| Eolic | 48.95 | 48.98 | 0.1% | 48.98 | 0.1% |
| River Flow | - | 3.31 | - | 3.31 | - |
| Hydraulic | 34.10 | 34.10 | 0.0% | 34.03 | -0.2% |
| Hydro Pump | 2.01 | 1.21 | -40% | 0.00 | -100% |
| Solar PV | 7.37 | 7.40 | 0.4% | 7.40 | 0.4% |
| Solar thermal | 4.42 | 4.45 | 0.6% | 4.45 | 0.6% |
| Others RES | 4.28 | 6.53 | 52.7% | 3.15 | -26.3% |
| **RES** | 101.14 | 105.98 | 4.8% | 101.32 | 0.2% |
| **PP** | 92.56 | 86.83 | -6.2% | 89.01 | -3.8% |
| **Nuclear** | 53.20 | 53.39 | 0.4% | 53.39 | 0.4% |
| **Generation** | **246.89** | **246.20** | **-0.3%** | **243.72** | **-1.3%** |

In both economic and technical simulation, the results offered by the program are very similar to those of reality. The main difference is that EnergyPlan, both in the Technical and Economical optimization, assumes a higher generation from hydro a other renewables and lower generation from thermal power plants (PP). This means that in real management of the Spanish grid, the use of renewables follows more conservative rules of integration than the ones simulated in EnergyPlan. Further, the value of PP (power plants) includes coal plants, cogeneration, combined cycle, and non-renewable waste. However, the way Energyplan distributes the generation among these technologies, varies from the real values, which means that the program assumes slightly different dispatch rules between thermal generation than the ones actually followed. However, as the objective is to test systems with 100% renewables, it will not have a significant impact in the results for 2040 and 2050.

In the dry scenario, the generation of electricity produced by hydro technology has been 18.51 TWh in the economic simulation and 18.48 TWh in the technical simulation. These results are similar to the 18.36 TWh indicated in the REE report for 2017 [78].

Therefore, it is considered that the calibration of the system and the distributions work correctly achieving results very similar to reality.

### 4.3.2 2030 Scenario

For 2030, the next 6 hypothetical scenarios have been performed:

**Table 71. Simulated scenarios of the year 2030.**

| Scenario | Dry/Wet Year | Batteries [MW] |
|---|---|---|
| 1 | Wet | 0 |
| 2 | Wet | 2500 |
| 3 | Wet | 5000 |
| 4 | DRY | 0 |
| 5 | DRY | 2500 |
| 6 | DRY | 5000 |

Also, for each scenario, an economic and a technical simulation of the electric system have been made. For the identification of the simulations, the legend of the graphs indicates the simulation number indicated in Table 71 accompanied by a suffix. The suffix E is used for economic simulations and the suffix T is used for technical simulations. Therefore, the "4E" simulation would be the economic simulation of scenario number 4 in the previous table.

The results of the indicators explained above are shown below.

#### *Percentage of renewables in electricity generation*

In the following graph, only 2 technical simulations of the program are represented, since the percentage of renewables, in the technical simulation, is exactly the same for simulations 1,2,3 and 4,5,6, which means that the use of batteries dos not change with the available battery capacity.

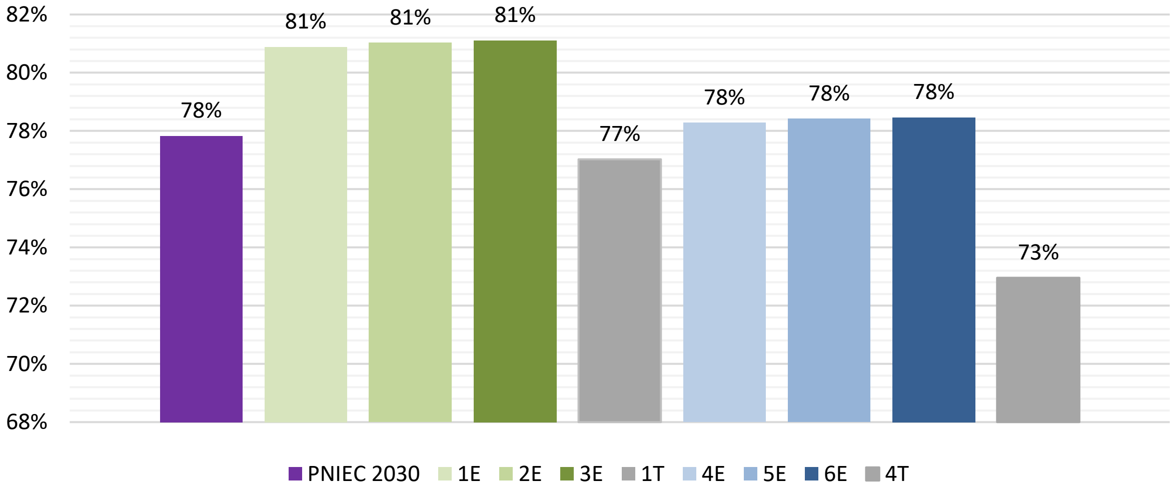

**Figure 26. RES % of 2030 scenario simulations.**

As can be seen in Figure 26, a higher installed power of batteries has a small positive influence on the generation of renewables when economic scenarios are considered. In addition, economic simulations tend to have a greater penetration of renewables in the system.

### *Saturation of interconnection line*

In the 2030 scenario, the interconnection line is saturated several times in all simulations. This is because the percentage of interconnection capacity is well below of the 15% of the installed capacity recommended by the European Union.

### *Annual costs*

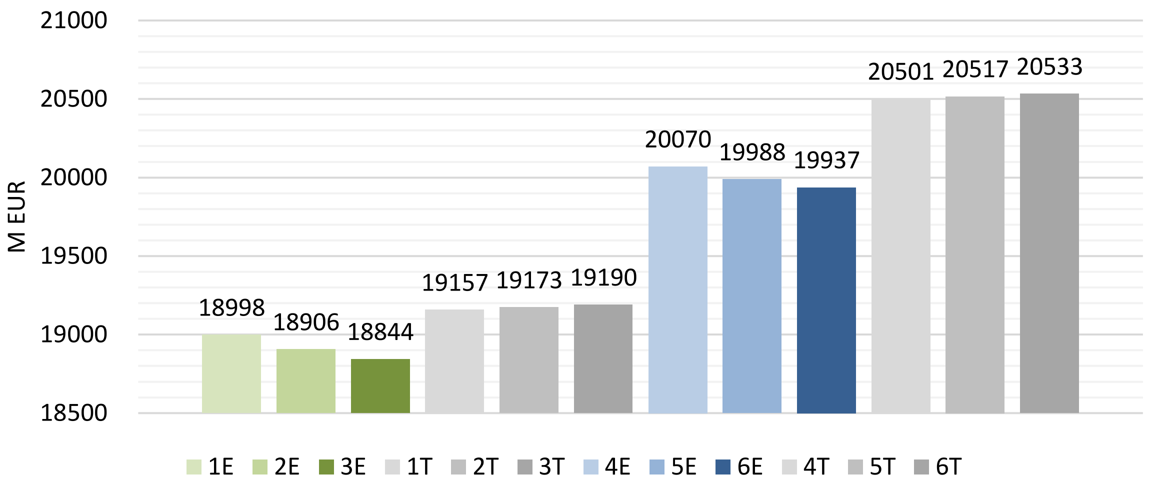

**Figure 27. Annual Costs of electric system in 2030 scenario simulations.**

As expected, the costs in the less rainy years are higher, as hydro generation needs to be replaced by thermal generation. It should also be noted that the effect of increasing the installed power of the batteries has the opposite effect in technical and economic simulations. In economic scenarios, the cost decrease with the increasing capacity of batteries as they enable the use of additional renewables, while in technical simulations the overall costs are very similar (and the small increase has to do with the additional investment in batteries)

### *Optimal scenario*

Figure 28 presents the energy mix production of 2030 Scenario, for the dry and wet years, considering the installed battery power of 2500 MW (value proposed by the PNIEC). Can be observed that the reduction of hydropower generation is compensated by the absorption of more wind and an increase in the thermal generation (combine cycle, cogeneration), nuclear and biomass.

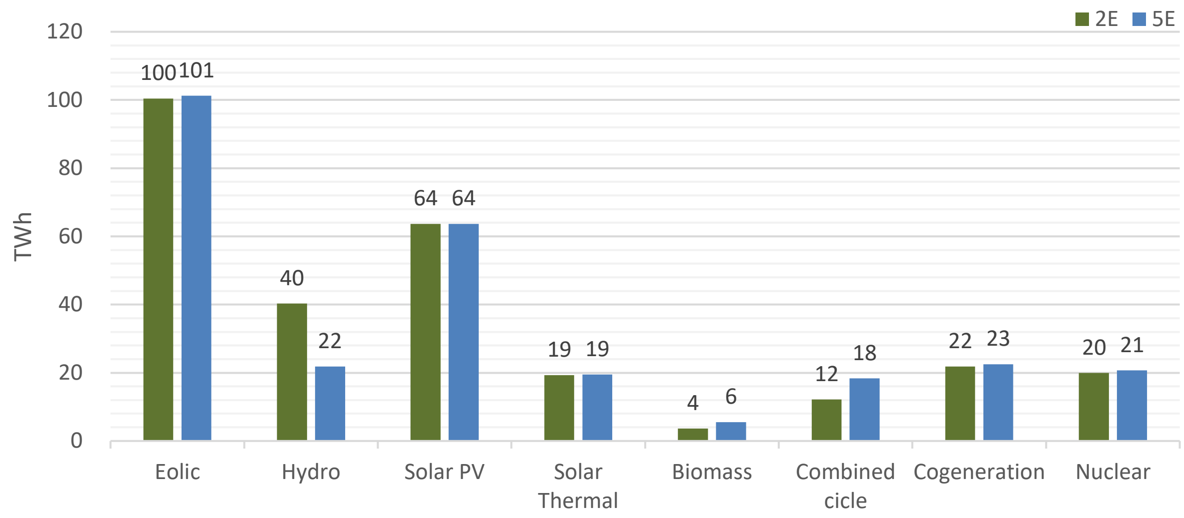

**Figure 28. Energy mix production of 2030 Scenario.**

### 4.3.3 2040 Scenario

For 2040, 10 different scenarios have been simulated.

As can be seen in the following table, demand distribution COVID19 (which simulates a future with less mobility between home and work and therefore less consumption in office buildings and more residential consumption) has been combined only with 7000 MW of battery installed power. This is because, in the previous 8 simulations have shown that taking into account the indicators Annual Costs, RES % and Saturation of the line, the best solution was the one with an installed battery power of 7000 MW.

Table 72 shows the combinations made for each simulation:

**Table 72. Simulated scenarios of the year 2040.**

| Scenario | Dry/Wet Year | Batteries [MW] | Demand Distribution |
|---|---|---|---|
| 1 | Wet | 0 | 2018 |
| 2 | Wet | 5000 | 2018 |
| 3 | Wet | 7000 | 2018 |
| 4 | Wet | 7000 | COVID19 |
| 5 | Wet | 9000 | 2018 |
| 6 | DRY | 0 | 2018 |
| 7 | DRY | 5000 | 2018 |
| 8 | DRY | 7000 | 2018 |
| 9 | DRY | 7000 | COVID19 |
| 10 | DRY | 9000 | 2018 |

### *Percentage of renewables in electricity generation*

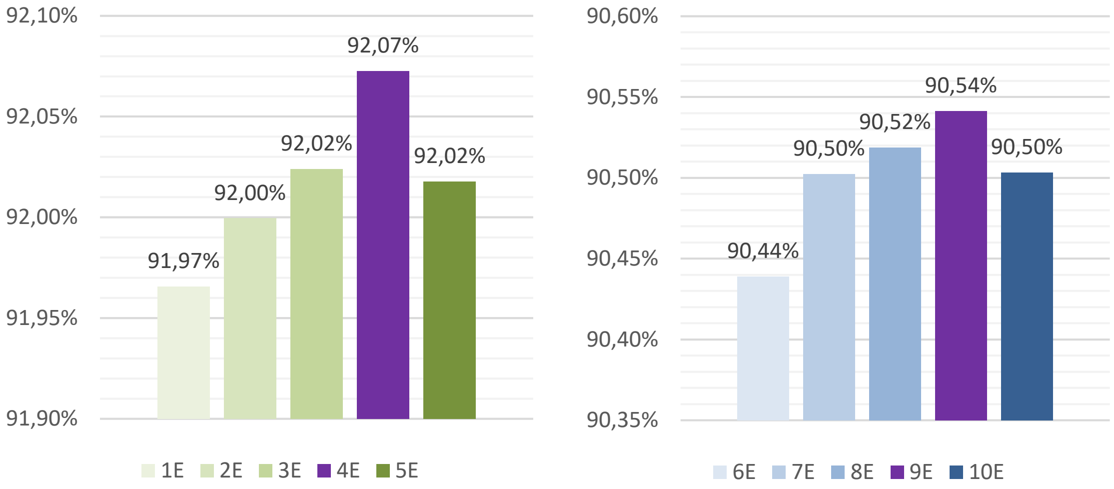

**Figure 29. RES % of 2040 scenario simulations.**

In the technical simulation, all wet scenario simulations have a RES penetration of 89.61% while in dry scenario simulations it is 87.36%. All simulations have very similar values, but in simulations 4E and 9E, the cases where a demand similar to the one observed during COVID19, the RES % is slightly higher.

### *Saturation of interconnection line*

Figure 30 presents the results for the interconnection maximum value. The 1T simulation refers to all technical simulations. As can be seen in the graph, in all technical simulations the interconnection line reaches the saturation point several times during the year. Regarding economic simulations, they never get saturated. It should be noted that in 4E simulation (COVID19 demand in a wet year), the value of the maximum imports/exports is much lower than the others.

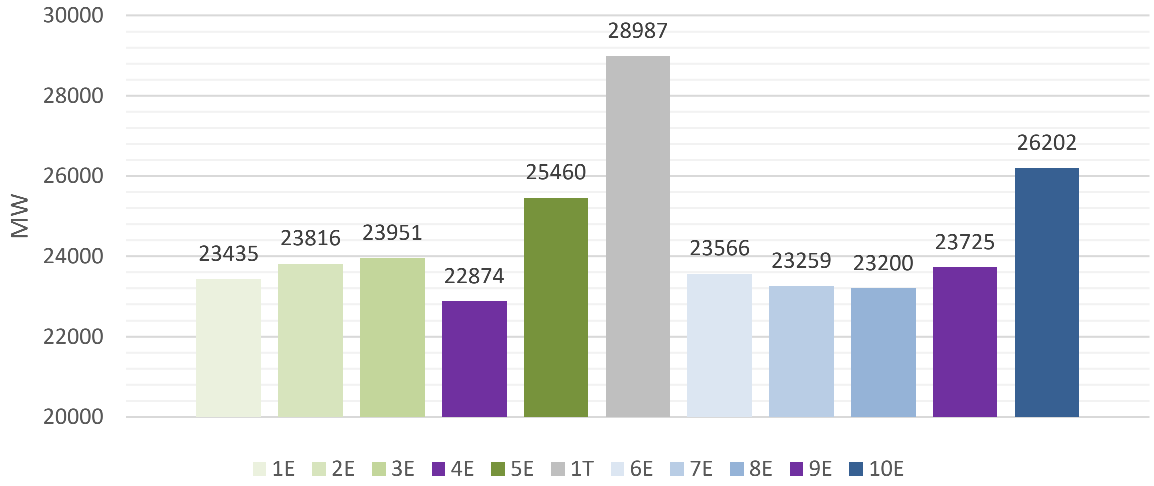

**Figure 30. Maximum annual value of Imports/Exports in the 2040 scenario.**

### *Annual costs*

As seen in Figure 31 and Figure 32, in both dry and rainy years, scenarios with an installed battery power of 7000 MW have a lower cost than the rest. In addition, when the COVID19 distribution has been used, the costs are lower than using the 2018 demand distribution.

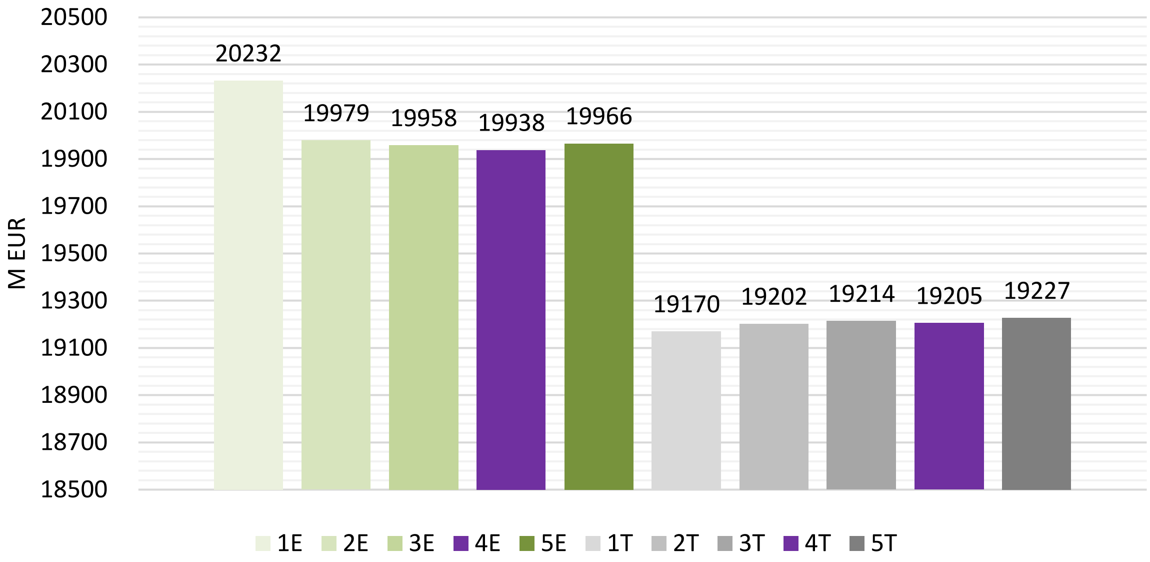

**Figure 31. Annual Costs of electric system in 2040 Wet scenario simulations.**

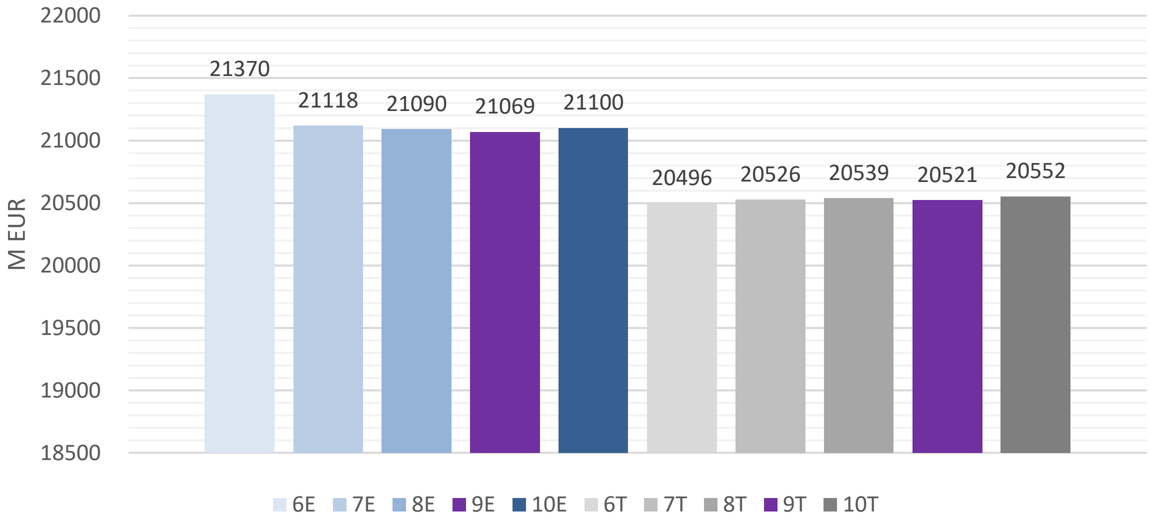

**Figure 32. Annual Costs of electric system in 2040 Dry scenario simulations.**

### *Optimal scenario*

The most optimal scenario is number 9, as it has the highest RES percentage, the interconnection line is not as saturated as the other options and generally has a lower annual cost of the electric system. The following is the mix of electricity generation by type of technology:

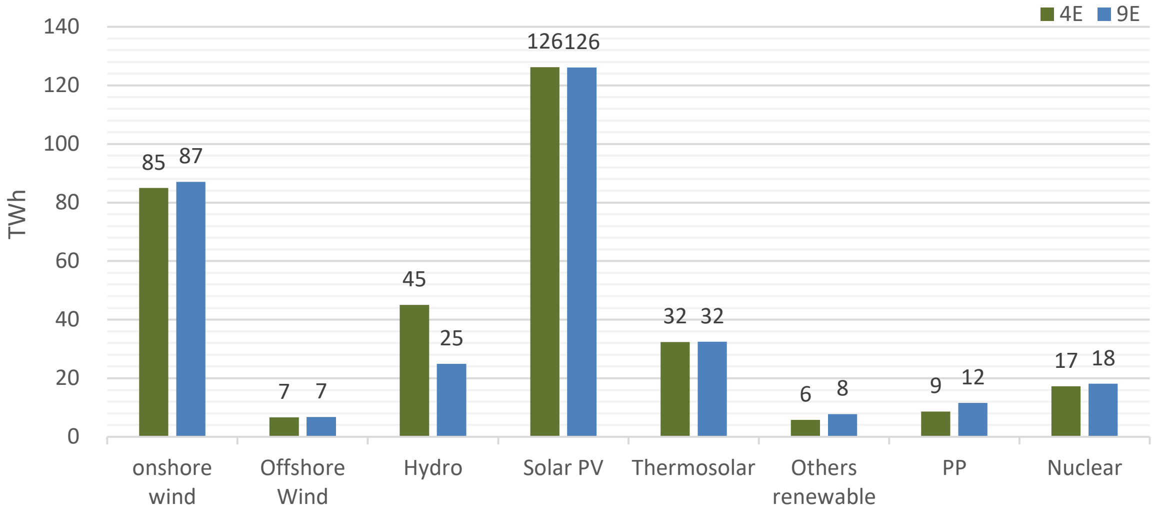

**Figure 33. Energy mix production of 2040 Scenario.**

It should be noted that the generation of electricity from wind is slightly lower than the 2030 scenario. This is because the program, as a stabilization tool, allows to stop the generation of electricity from renewable sources when there is a critical excess of electricity production, to prevent the collapse of the electrical system. This means that the installed capacity of renewables is above the required in case the demand decreases significantly, as simulated in COVID19 demand.

### 4.3.4 2050 Scenario

In 2050, 10 simulations have been performed. For this year, it is considered that the entire generation of electricity comes from renewable sources, so there is no section that explains the RES% of the different simulations made, as it is 100% in all cases. As in the 2040 scenario, the COVID19 distribution has been only used in 2 scenarios (4 and 9 scenarios). The election of the chosen scenarios was made in the same way as in the previous section. The following table shows the different scenarios proposed for 2050.

**Table 73. Simulated scenarios of the year 2050.**

| Scenario | Dry/Wet Year | Batteries [MW] | Demand Distribution |
|---|---|---|---|
| 1 | Wet | 7000 | 2018 |
| 2 | Wet | 10000 | 2018 |
| 3 | Wet | 12000 | 2018 |
| 4 | Wet | 12000 | COVID |
| 5 | Wet | 14000 | 2018 |
| 6 | DRY | 7000 | 2018 |
| 7 | DRY | 10000 | 2018 |
| 8 | DRY | 12000 | 2018 |
| 9 | DRY | 12000 | COVID |
| 10 | DRY | 14000 | 2018 |

### *Saturation of interconnection line*

As shown in Figure 34, In both rainy and dry years, technical simulations exceed the maximum interconnection capacity of 33180 MW, so they are discarded as valid simulations. It can also be verified that the saturation of the line increases as the installed power of the batteries increases, except for the 10E simulation, which seems to indicate that the batteries are being charged by the interconnection electricity.

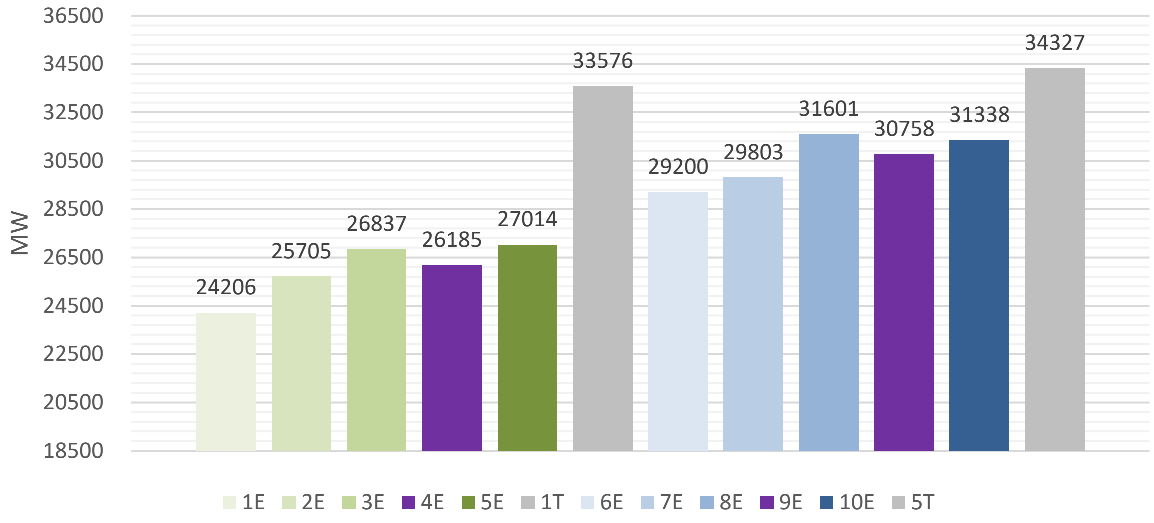

**Figure 34. Maximum annual value of Imports/Exports in the 2050 scenario.**

### *Annual costs*

In Figure 35, we can observe that the costs of the technical simulation are lower. However, as mentioned above, the results of the technical simulations are not considered valid due to the oversaturation of the line. Also, can be seen that the annual costs tend to be lower when more battery power is installed.

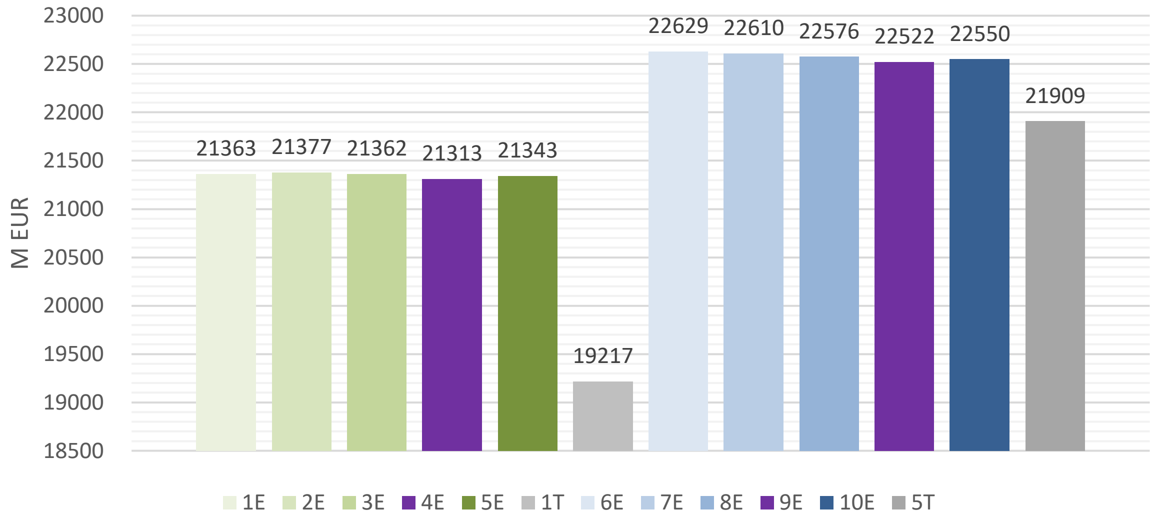

**Figure 35. Annual Costs of electric system in 2050 scenario simulations.**

### *Optimal scenario*

Taking into account the indicators discussed above, it is considered that the scenarios with an installed battery power of 12000 MW are optimal. This is an arbitrary opinion, the 5E and 10E simulations could also have been chosen as optimal. The electrical power generation mix for simulations 4E and 9E is represented in Figure 40 It can be seen that in the wet scenario there is a lot of renewable electricity that is not being used, as the diminish of generation of 19 TWh by hydro power plants from wet to dry year is compensated by an increase of only 6TWh in biomass, wind and solar. This means this solution is resilient to decreases in hydro power generation.

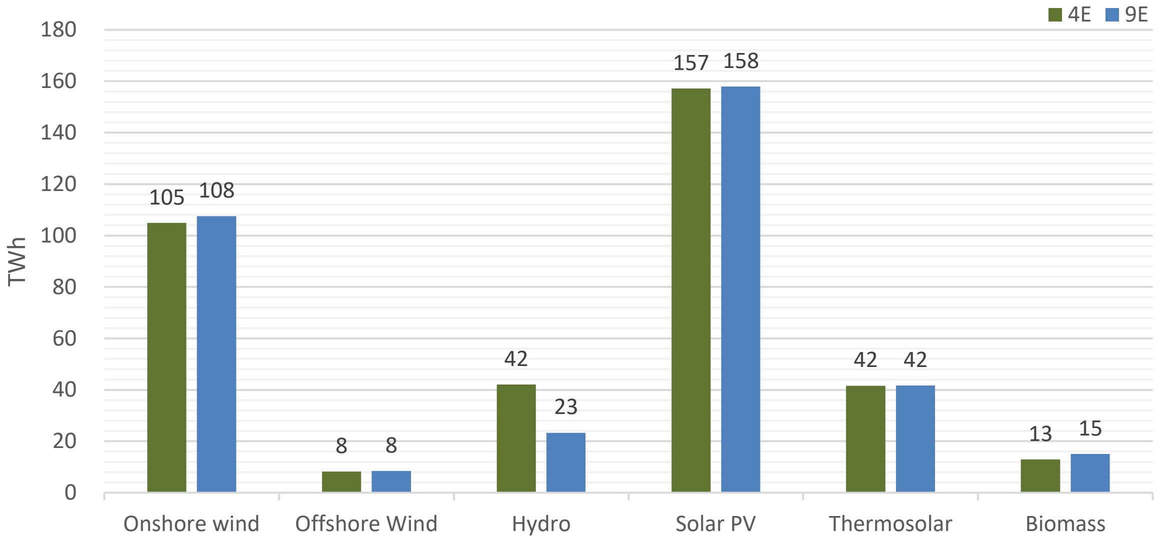

**Figure 36. Energy mix production of 2050 Scenario.**

## 4.3.5 H2040 Scenario

In H2040 Scenario, 10 scenarios have been performed as before, with 2 simulations for each scenario, one economic and one technical. The next table shows the combinations made for each scenario:

**Table 74. Simulated scenarios of the year H2040.**

| Scenario | Dry/Wet Year | Batteries [MW] | Demand Distribution |
|---|---|---|---|
| 1 | Wet | 0 | 2018 |
| 2 | Wet | 5000 | 2018 |
| 3 | Wet | 7000 | 2018 |
| 4 | Wet | 7000 | COVID |
| 5 | Wet | 9000 | 2018 |
| 6 | DRY | 0 | 2018 |
| 7 | DRY | 5000 | 2018 |
| 8 | DRY | 7000 | 2018 |
| 9 | DRY | 7000 | COVID |
| 10 | DRY | 9000 | 2018 |

### *Percentage of renewables in electricity generation*

The percentage of RES is quite similar between the simulations of the rainy years and between the simulations of the dry years. It should be noted that the technical simulations and those that have used the distribution of demand COVID19, the penetration of renewables into the electrical system is slightly lower.

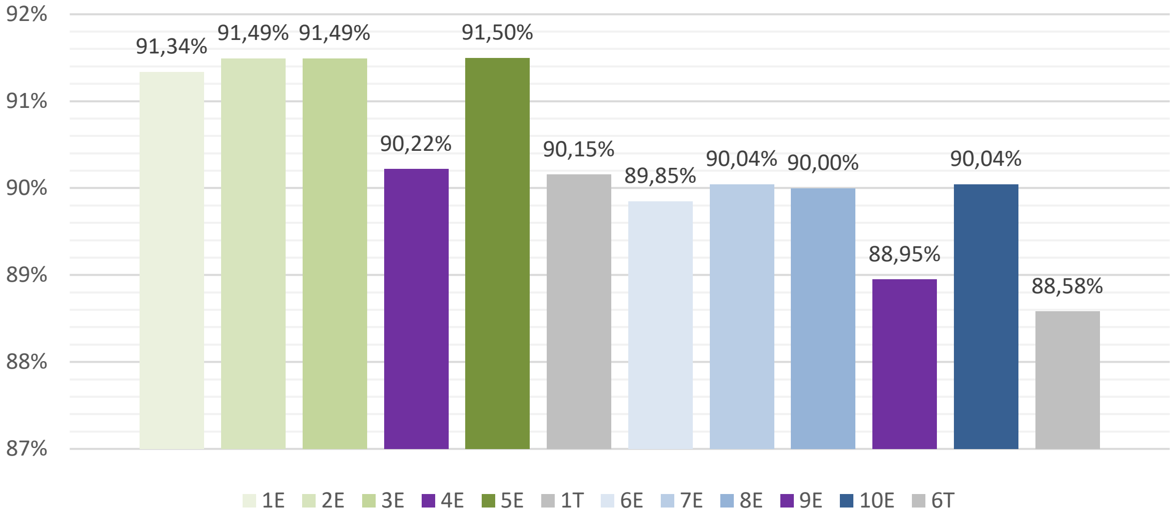

Figure 37. RES % of H2040 scenario simulations.

### *Saturation of interconnection line*

As in the 2040 scenario results, the 1T simulation refers to all technical simulations. As can be seen in the graph, in technical simulations the interconnection line it is saturated several times during the year. Regarding economic simulations, it should be noted that the scenarios with a battery installed capacity of 7000 MW, the value of the maximum imports/exports is much lower than the others.

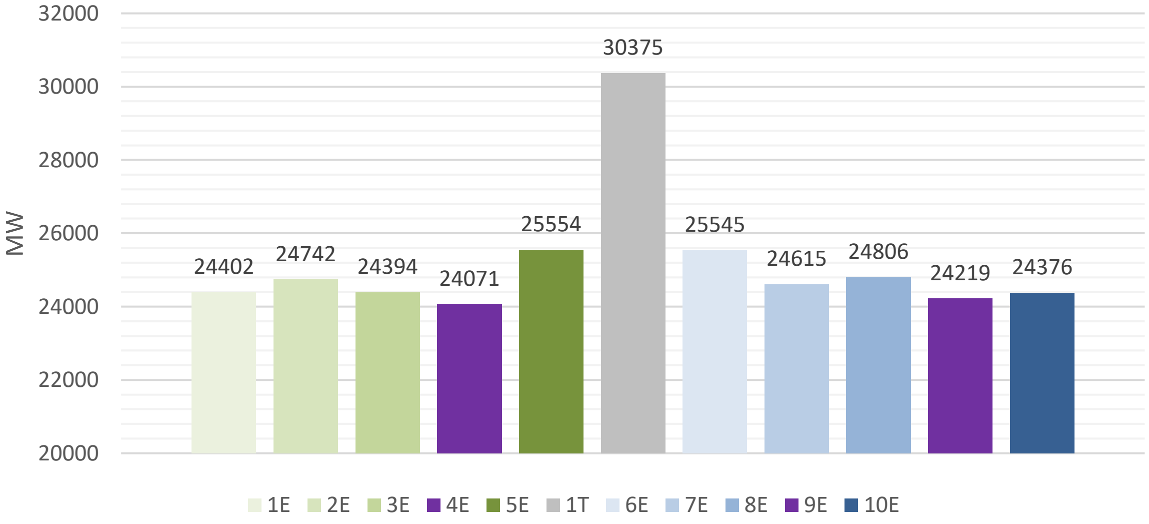

Figure 38. Maximum annual value of Imports/Exports in the H2040 scenario.

### *Annual costs*

Figure 37 shows a lower annual cost in technical simulations. This is possibly due, to a greater use of the line of interconnection with other countries at times of peak generation or peak demand. In terms of economic simulations, the scenarios with the lowest annual cost are those with an installed battery capacity of 7000 MW.

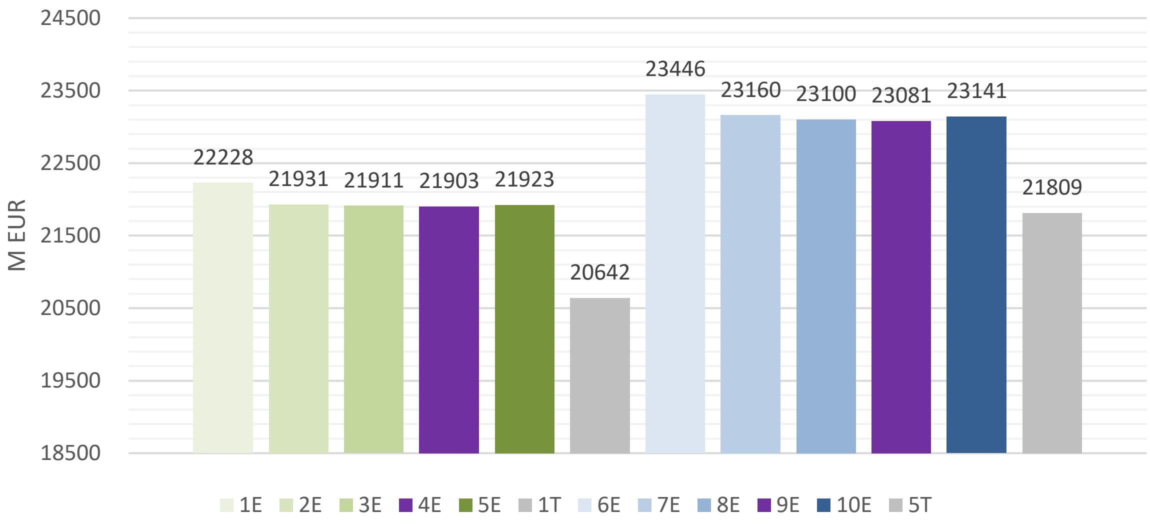

**Figure 39. Annual Costs of electric system in H2040 scenario simulations.**

### *Optimal scenario*

Below is show the electric generation mix by technologies of 4E and 9E scenarios. These are the scenarios that saturate the least the interconnection line and that have the lowest annual cost. As can be seen, the sources that use the solar resource generate most of the electricity. It is also necessary to emphasize the importance of thermal power plants in the years where hydraulic energy has less impact.

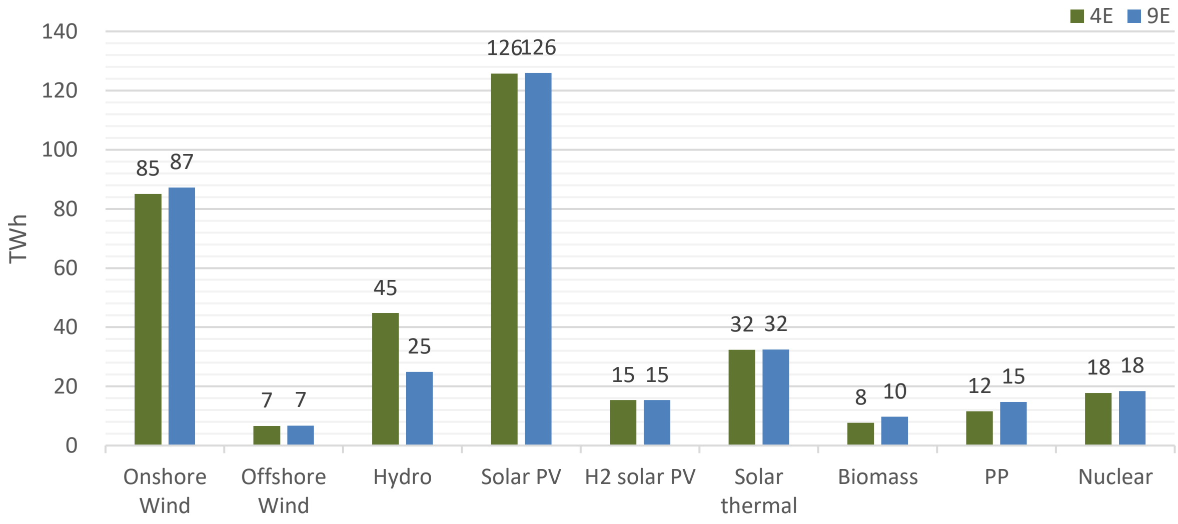

**Figure 40. Energy mix production of H2040 Scenario.**

### 4.3.6 H2050 Scenario

Finally, in H2050 Scenario, 10 possible scenarios have been developed. As above, COVID19 distribution has been only used in 2 scenarios. The following table shows the different scenarios proposed for 2050:

**Table 75. Simulated scenarios of the year H2050.**

| Scenario | Dry/Wet Year | Batteries [MW] | Demand Distribution |
|---|---|---|---|
| 1 | Wet | 7000 | 2018 |
| 2 | Wet | 10000 | 2018 |
| 3 | Wet | 12000 | 2018 |
| 4 | Wet | 12000 | COVID |
| 5 | Wet | 14000 | 2018 |
| 6 | DRY | 7000 | 2018 |
| 7 | DRY | 10000 | 2018 |
| 8 | DRY | 12000 | 2018 |
| 9 | DRY | 12000 | COVID |
| 10 | DRY | 14000 | 2018 |

#### *Saturation of interconnection line*

As indicated in Figure 39, the technical simulations, and some of the economic ones exceed the capacity of the line which is 35708 MW. The simulations that saturate less the line are those that consider the demand distribution COVID19.

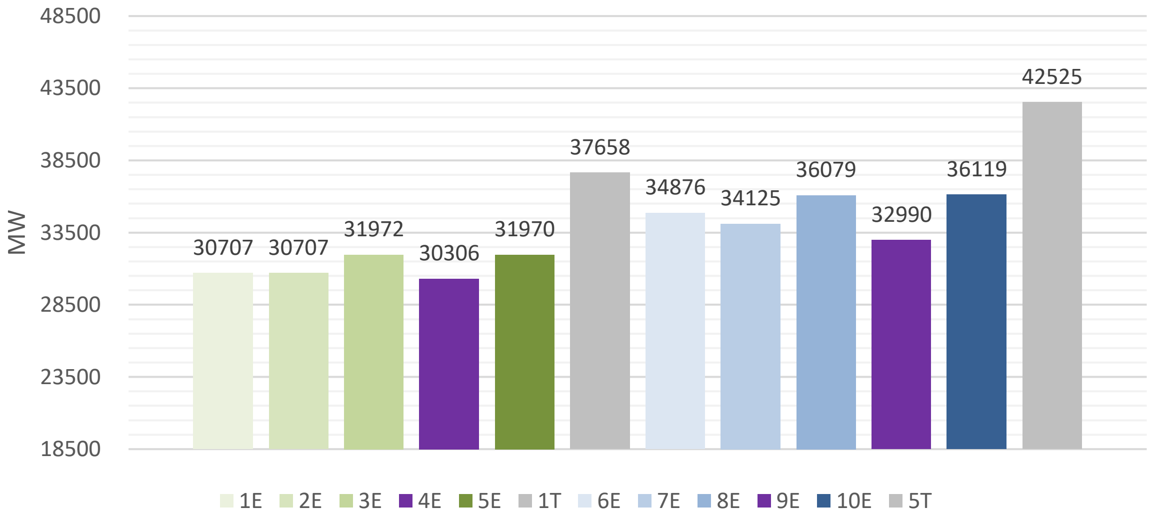

**Figure 41. Maximum annual value of Imports/Exports in the H2050 scenario.**

#### *Annual costs*

As can be seen in the graph, when the installed battery power increases, the annual cost is lower. As indicates Figure 42, the simulations 8E, 10E and the technical simulations oversaturate the line of interconnection with the other countries. Therefore, the valid lower cost simulations are 4 and 9.

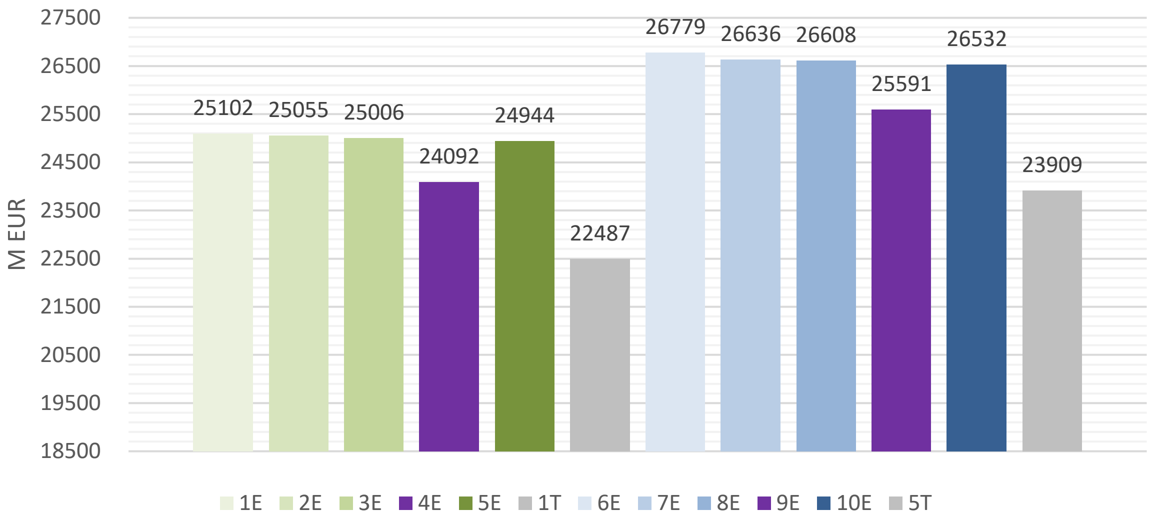

Figure 42. Annual Costs of electric system in H2050 scenario simulations.

### *Optimal scenario*

From everything discussed in the two graphs above, it is considered that the optimal simulations are the 4E and 9E. The energy mix is shown in Figure 43. The production of electricity from wind plants is increasing again, after the decrease in production in 2040, due to an oversizing of the system. Therefore, wind power replaces part of the electricity generated by traditional thermal plants, which operated precisely at times of lower solar irradiance.

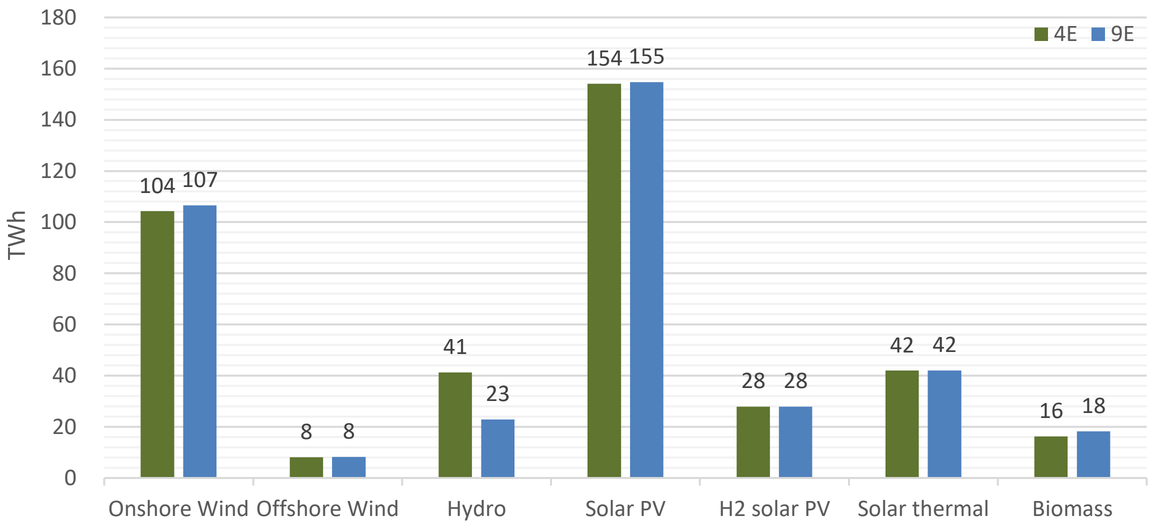

Figure 43. Energy mix production of H2050 Scenario.

## 4.4 Summary of results

In this section is shown the evolution of the electricity system from 2018 to 2050. Also, it is analysed the incidence of different energy technologies in the stabilization of the electricity system.

### 4.4.1 Evolution of the Spanish electrical system

To show the evolution of the electrical system, the wet year values of the optimal scenarios have been used. These values have show that are resilient to the decrease of hydro power generation in dry years.

#### *RES%*

As can be seen in the following graph, both the electric scenario and the $H_2$ scenario, the evolution of the percentage of renewables in the electricity generation mix is as expected. The goals set by the PLCCTE are achieved: the presence of renewables in 2030 is at least 70% and the Spanish electric system in 2050 is 100% renewable.

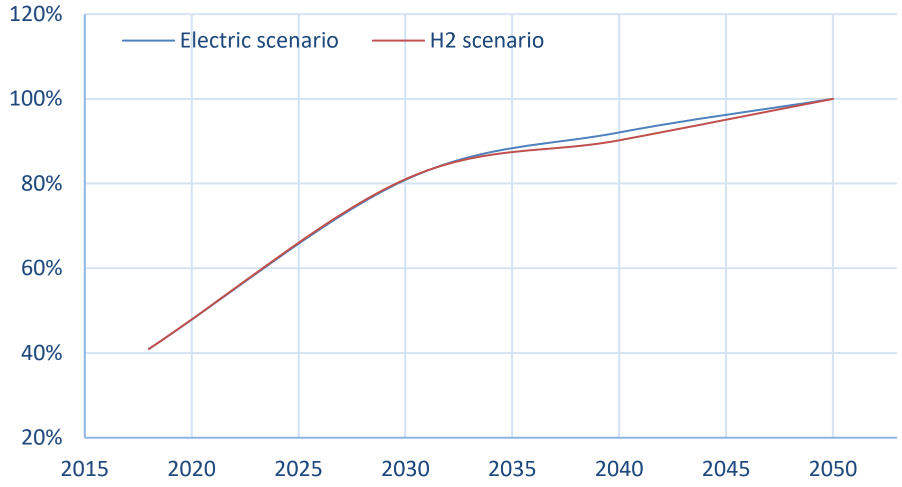

**Figure 44. Evolution of RES%.**

#### *$CO_2$ emissions*

$CO_2$ emissions from the Spanish electricity system are reduced to a value of 0 kg in 2050, as the system is 100% renewable.

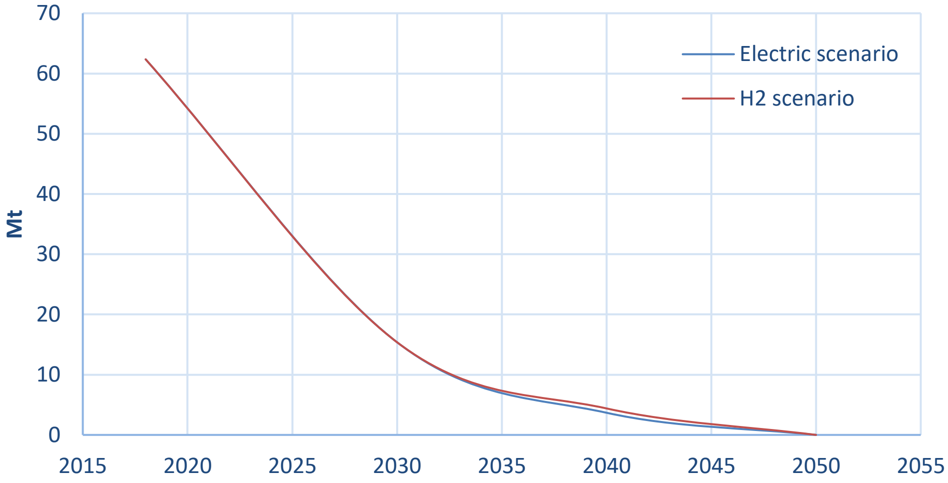

**Figure 45. Evolution of $CO_2$ emissions.**

In 2040, the result of $CO_2$ emissions in the $H_2$ scenario is 4.4 Mt, while in the electrical scenario 3.68 Mt are emitted. This is because the demand is higher in H2040 scenario and, even though more photovoltaics have been installed, thermal power plants are working more hours to stabilize the system.

According to [79], 0.182 kg of $CO_2$ are emitted for every kWh of natural gas used. By 2040, hydrogen production will be 10.81 TWh. Assuming that, if the hydrogen produced replace natural gas in the industry, 1.97 Mt of $CO_2$ are going to be saved, which largely compensate for the increase in direct $CO_2$ emissions of electricity.

The following table shows the annual $CO_2$ emissions and the estimated emissions avoided with the use of hydrogen:

**Table 76. Evolution of $CO_2$ emissions until 2050.**

| $CO_2$ emissions [Mt] | 2018 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Electric scenario | 62.3 | 15.4 | 3.68 | 0 |
| $H_2$ scenario | 62.3 | 15.4 | 4.40 | 0 |
| $H_2$ emissions avoided | - | - | 1.97 | 3.7 |

### *Generation mix*

The evolution of the generation energy mix is shown below. As can be seen, traditional generation technologies loose importance, until they have been completely replaced by renewable energy sources. The largest investment is expected to be done with solar.

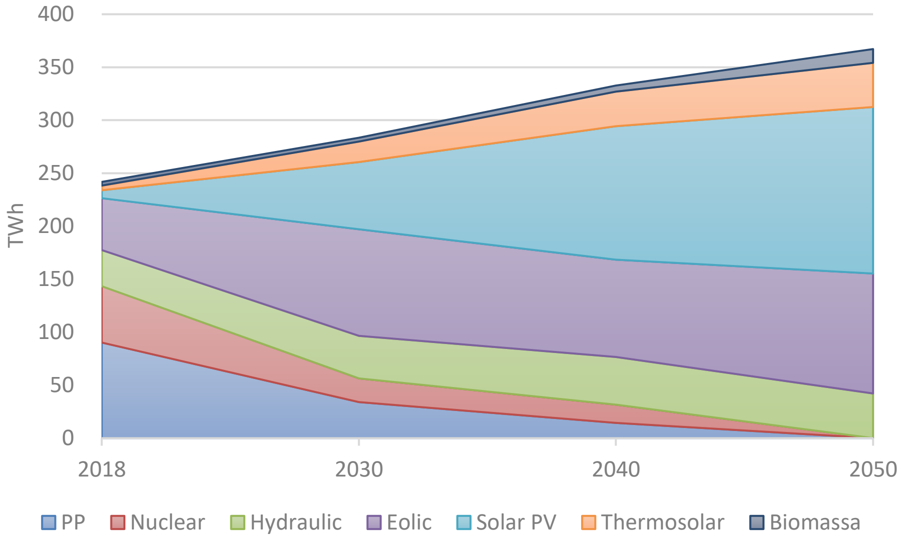

**Figure 46. Evolution of the generation mix in $H_2$ scenario until 2050.**

### *Storage production*

The following graph shows the evolution of electricity generation from batteries and pumped hydro. To perform the analysis, the optimal simulations (chosen in the results section) of the dry and wet scenarios are plotted. The aim is to see how it affects rainfall and the installed capacity to electrical energy storage systems. To differentiate them, the simulations of wet years are indicated with the suffix W, while dry years with the suffix D.

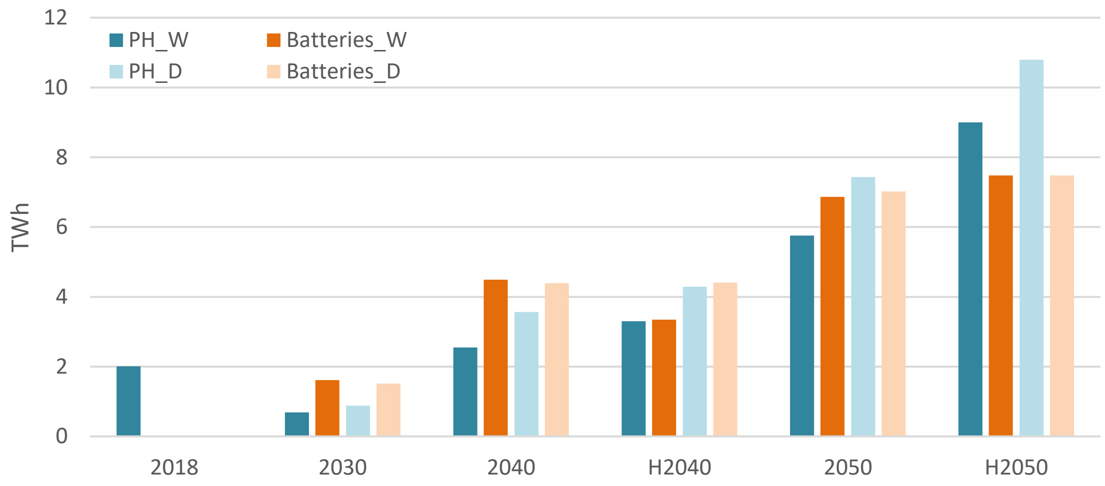

**Figure 47. Evolution of electricity production by storage technologies.**

As expected, electricity production from storage systems is increasing and batteries can play a role as important as the hydro pump storage. This is mainly due to an increase in the installed capacity of storage systems, but also to a higher production of energy from intermittent renewable sources.

For example, the scenarios of the 2040s and 2050s have the same installed power of pumped hydro. However, production has been almost double. This indicates that the more intermittent the system is, the variation in prices makes storage systems more profitable.

Regarding the influence of rainfall, the production of batteries practically does not change, while pumping stations produce more in dry years than in rainy ones, which means that are used to capture the excess of renewables and compensate for the lack of hydro generation.

### 4.4.2 Hourly data

This section represents the average hourly data distributions of the results obtained in the H2050 scenario. These distributions allow us to analyse the effects of the different technologies on the system.

#### *Price*

The hourly curve of the electricity price is quite similar to the curve of demand. The highest prices correspond to the hours when there is more electricity demand and lower electricity production.

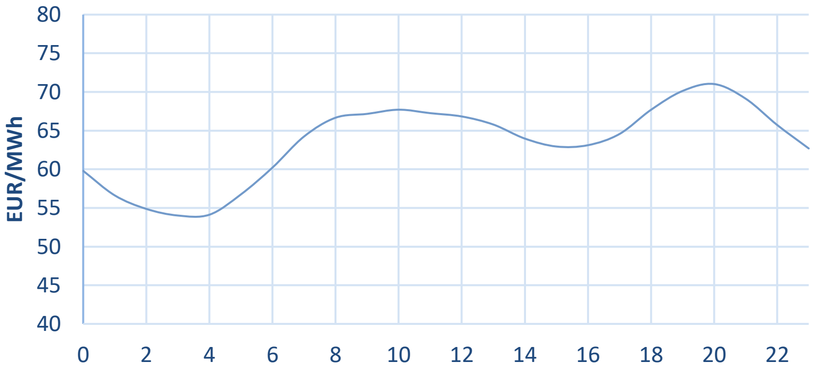

**Figure 48. Hourly curve of the electricity price.**

### *Production by technology*

The following graphic shows the hourly data curve of power generation by technologies. The energy demand curve is also represented.

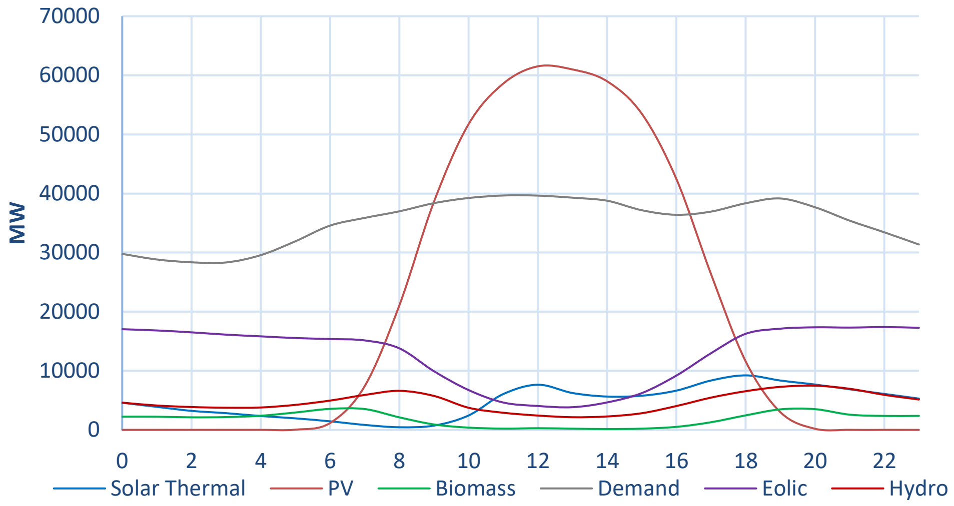

**Figure 49. Hourly data curve of power generation by technologies and hourly demand curve.**

Biomass power plants work mainly as a load following power plants, producing electricity when the system needs it, especially during the morning increase and even increase. The graph shows that biomass peaks occur at a time when demand is high and photovoltaic energy does not generate much energy.

About solar thermal technology, its production curve does not correspond to the irradiance curve. Due to the thermodynamic cycles of these plants, the production of electricity is delayed with respect to irradiance. In addition, solar thermal plants have deposits of molten salts that allow them to store energy and produce it during the hours when the irradiance is very low or zero. As you can be seen in the graph, the time of maximum electricity generation corresponds to 6pm, when the demand of electricity and the price of energy are high and the irradiance is low.

As Figure 49 shows, photovoltaic panels have a high production during the central hours of the day. This causes, especially in the summer months, a critical excess of electricity production. In order to prevent the electrical system collapse, the program decreases the production of electricity from wind energy, implying a loss of efficiency in the system. To avoid this, it would be better to have a more balanced energy mix of different renewable energy sources, PV power plants with different inclinations/orientations or wind parks located in uncorrelated climate areas.

### *Import/Exports*

As can be seen in the graph, electricity is exported during the central hours of the day, which, as mentioned above, is the time of the biggest production of electricity. It can also be seen that imports occur at times of low production and/or high demand. Therefore, interconnections can be considered as a system that helps stabilize the network by allowing greater penetration of renewables.

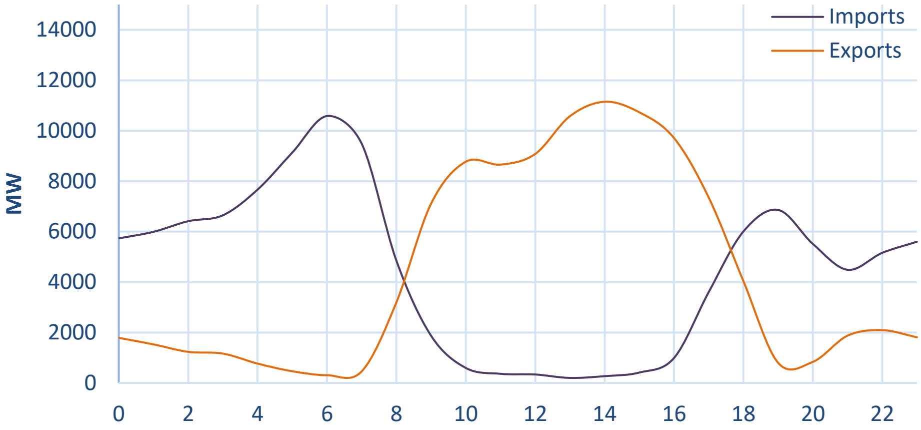

**Figure 50. Hourly data curve of Imports and exports.**

### *Battery and hydro storage*

As in the case of exports and imports, storage systems store energy in the middle hours of the day and produce electricity at times when demand cannot be met by energy production. In fact, the import and turbine curves are virtually identical.

Regarding the discharge of the batteries, this occurs for a few specific hours. This may happen because these are the hours when energy is most expensive.

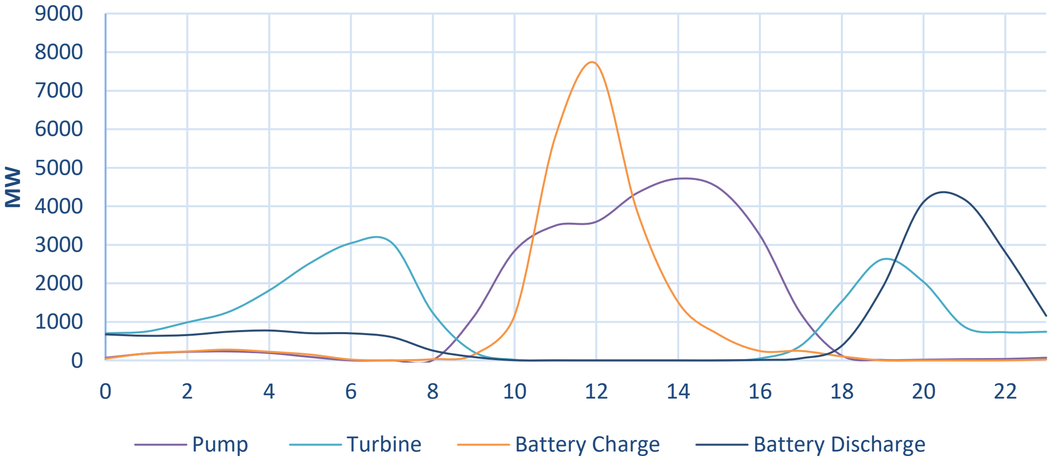

**Figure 51. Hourly data curve of storage technologies.**

### *V2G and $H_2$ production*

Both V2G and $H_2$ are elements that help to stabilize the network at times of maximum production. These two systems consume energy at times of higher production, preventing interconnections from saturating themselves when exporting excess energy. They also take advantage of the energy that would possibly be lost as in the case of the wind energy discussed above.

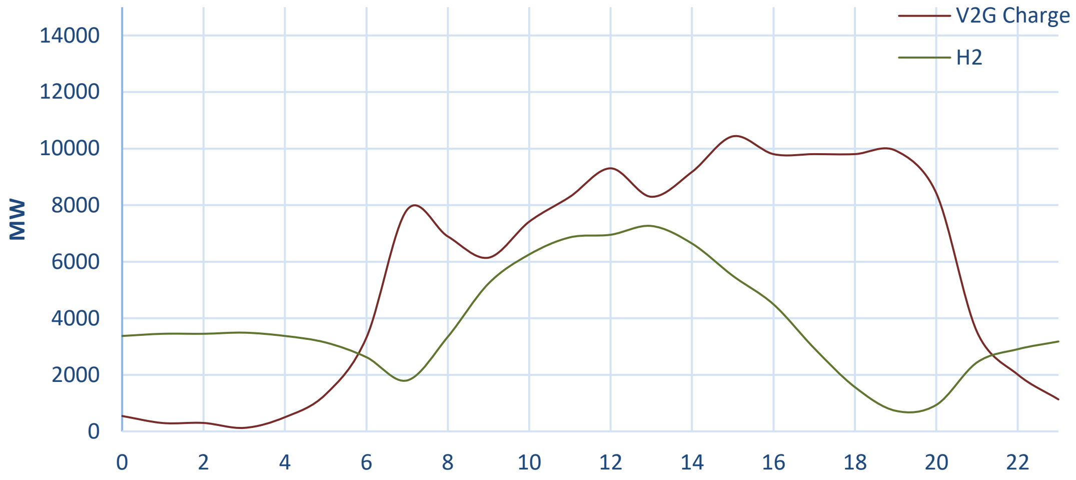

Figure 52. Hourly data curve of V2G charge and $H_2$ production.

### *Weekly distribution*

Below there are two graphs provided by the program. In them, it is possible to see how the different technologies act in order to stabilize the electrical system.

For example, at peak production, electricity is stored or exported. On the other hand, when power-generating systems do not produce enough electricity to supply demand, storage technologies release electricity or the electricity is imported from other countries. We must also comment on the importance of biomass plants, which allow us to generate electricity when production cannot meet demand.

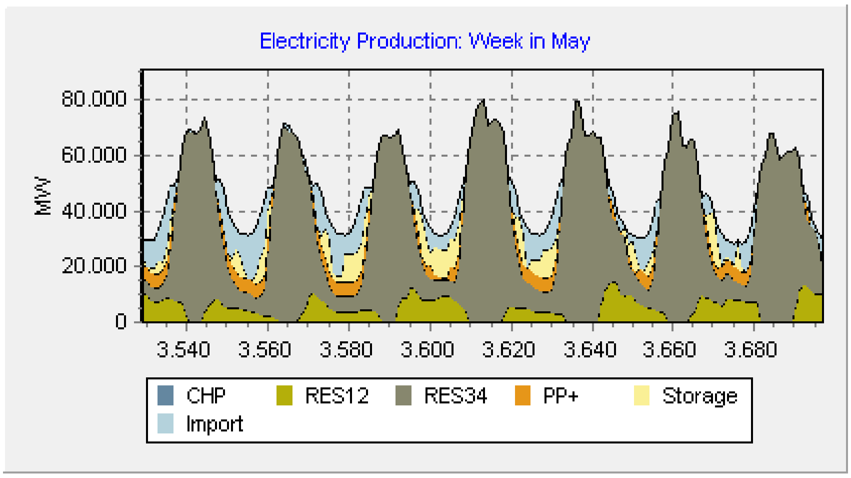

Figure 53. Electricity production curve

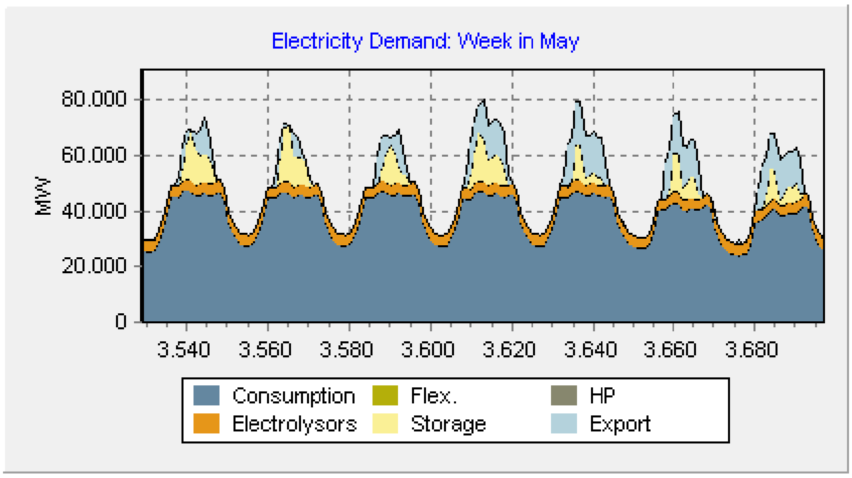

**Figure 54. Electricity demand curve.**

## 4.5 Comparative with Spanish 2050 long-term strategy

Once the study was completed, the Spanish state released the document “Borrador de la Estrategia de Descarbonización a Largo Plazo”. It is a roadmap to move towards climate neutrality by the 2050 horizon, with intermediate milestones in 2030 and 2040 [80].

In this section, a comparison is made between the different values used or obtained in the work and the values presented in the document ELP (Estrategia Largo Plazo) by the Spanish Ministry of Energy Transition. The following are the scenarios used to compare results:

**Electric scenario:** Scenario constructed in the present work where it is assumed that hydrogen will not have incidence on the industrial and transport sectors.

**$H_2$ Scenario:** Scenario constructed in the present work where it is assumed that will has incidence on the industrial and transport sectors.

**Trend Scenario ELP (TS ELP):** PNIEC target scenario extended until 2050 and does not meet the climate neutrality target.

**Climate Neutrality Scenario (CNS):** Expected scenario in ELP report, if the policies and measures needed to achieve the 2050 climate neutrality target are implemented.

### 4.5.1 Electricity demand

As can be seen in Figure 55, the demand forecast for the scenarios described in the ELP is lower than that used in the work. From 2030 onwards, the demand for the "climate neutrality scenario" follow a growth trend very similar to the $H_2$ scenario. In the event that the ELP document had proposed the same demand as the PNIEC for the year 2030, the evolution of the demands would be practically the same.

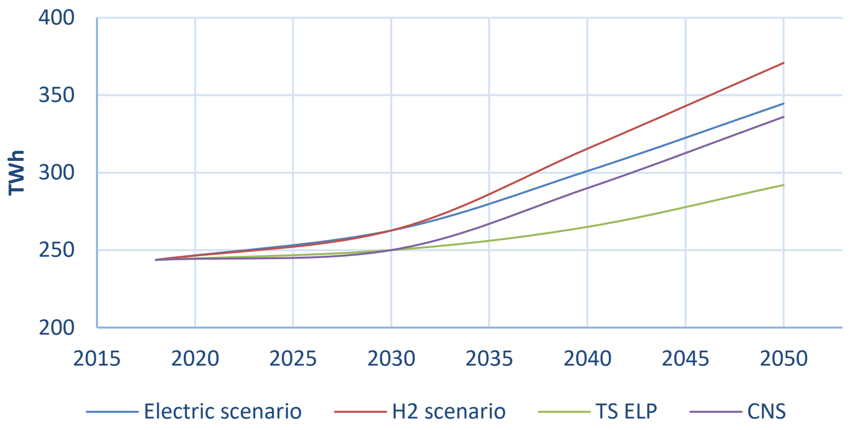

**Figure 55. Electricity demand comparation.**

## 4.5.2 Installed power

The evolution of the installed power in the Climate Neutrality Scenario and in the $H_2$ scenario is shown below.

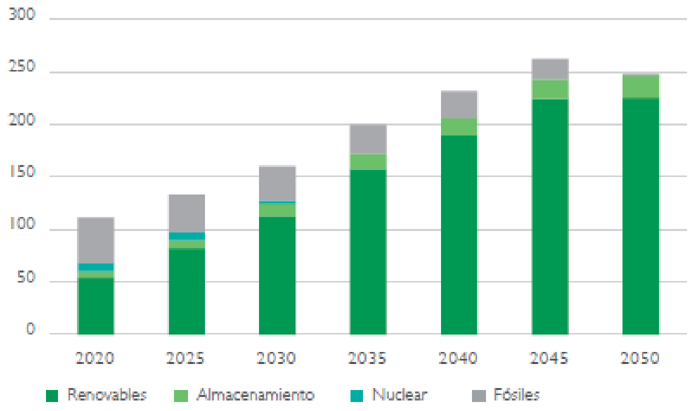

**Figure 56. Electric power generation [GW] park in the Climate Neutrality Scenario. [80]**

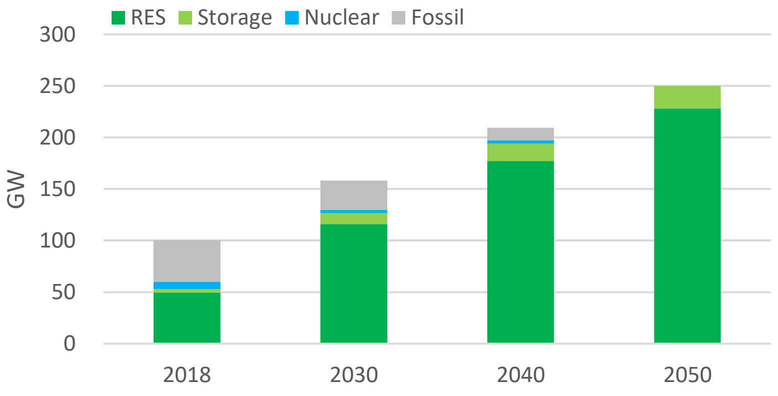

**Figure 57. Electric power generation mix in the $H_2$ scenario.**

As can be seen in the graphs above, both the installed power of RES and the installed power of storage are similar. The main differences are in the installed power of nuclear energy and power plants that consume fossil fuels. In scenario $H_2$, nuclear power plants will continue to be used until 2040, while in the CNS they are used only until 2030.

On the other hand, the Climate Neutrality Scenario proposes that fossil plants are going to be used until 2045 with an installed capacity of near 20 GW. In contrast, in scenario $H_2$, fossil plants are used until 2040 but with an installed capacity of 12 GW, almost half of what is proposed in Climate Neutrality Scenario.

# 5 Conclusion

This research aimed to contribute to the development of a national strategy for storage systems in Spain up to 2050. To do that, it has been necessary to study in depth the different storage technologies, analyse the potential and infrastructure installed in Spain of storage technologies, and develop possible models of future scenarios of the Spanish electricity system.

After carrying out the work, the following conclusions have been identified:

- Hydraulic pumping and batteries must be the pillars of the Spanish national strategy for storage system. These 3 technologies have features that allow them to work with large volumes of energy at a low economic cost. In addition, due to the climatic and orographic characteristics of the peninsula, hydro pumping and molten salt deposits are considered technologies with great potential in Spain.

- Hydrogen production and V2G are technologies that in the future will play a relevant role in the energy sector. The intelligent use of V2G will allow the vehicle fleet to function as a large battery, helping to match the curve between production and demand. On the other hand, hydrogen production will be a key element in the decarbonization of the industry and will work as a seasonal storage technology.

- A high capacity of interconnection, the use of biomass power plants and having a balanced energy mix, are elements that help to have a more stable and secure electrical system. Interconnection capacity can supply electricity almost instantly, which allows to reach the peaks of demand. Biomass plants allow to produce in the times of need. In addition, having a balanced energy mix makes the production curve smoother and therefore storage systems can work less.

- Energy legislation is an essential element in achieving the goal of 100% renewable. Without regulations, and only with the regulation of the economic market itself, it would be very difficult to achieve the decarbonisation targets by 2050.

On the other hand, the following limitations of the work and the lines to be followed for new studies are considered:

- For new studies, it is recommended to update the economic and technical characteristics of storage technologies, especially those that are immature. Most of the predictions that are made are usually wrong and from one year to the next the values can change a lot.

- In the simulations carried out, the program did not take into account the import or export needs of neighbouring countries. This fact does not correspond to reality, as it is possible that at the same time, Portugal, Morocco, France and Spain need to import or export energy. For future studies it is recommended to perform simulations in conjunction with models from neighbouring countries. In this way, it is believed that the calculation of interconnections, and of the system in general, will be closer to reality.

- Finally, it is also recommended to use the scenarios provided by the ELP once the official document has been submitted. The installed power scenarios used in the work have been developed using different assumptions. For future work, it is recommended to use scenarios built from computer programs specialized in these topics.

In short, it is believed that this work contributes to the knowledge related on storage systems and how they affect with the development of the Spanish electricity system. In addition, the specific and personal goals of the project are considered to have been achieved.

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