# Energy storage strategy in Spain for 2050

Lluís Ferrer
lluis.ferrer.frau@gmail.com

Instituto Superior Técnico, Universidade de Lisboa, Portugal
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## ABSTRACT

Nowadays, climate change has become one of the main problems to face by our society. For solving this problem, the EU, with its long-term strategy for 2050, has fixed the goal of decarbonising the countries of the European Union by 2050. To achieve this goal, it is necessary to have a 100% renewable system and carry out a storage strategy that helps with 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 Spanish energy system until 2050, in order to consider different scenarios and technological options. From the results obtained during the performance of the work, it is considered 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, the peninsula, due to orography and climatic conditions has great potential to use these technologies. To finish, it is considered that a high capacity interconnection, the use of biomass power plants, the hydrogen production, and having 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.

**Keywords**: Energy storage, energy systems modelling, renewable energy, energgPLAN.

## 1. Introduction

Today, climate change is one of the main problems that has the humanity and especially future generations. It has various consequences, such as rising sea levels, rising temperatures, originating extreme climatic events like droughts and/or floods. In short, climate change can modify 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 [1]. The Paris Agreement establishes a global framework to prevent the temperature rise from exceeding 2 ° C. Consequently, the EU has established its long-term strategy for 2050, fixing the goal of decarbonising the countries of the European Union by 2050 [2].

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

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, the work is structured in 3 parts. Firstly, a literature review is done. This section provides a compilation and comparison of the economic and technical characteristics of energy storage technologies. It also summarizes the current situation in Spain of the main technologies. Secondly, the methodology used to create and simulate future energy scenarios is explained. Finally, the results and behaviour of the storage technologies obtained in the simulation are shown.

## 2. Literature Review

### *2.1 Characteristics of energy storage technologies*

This section explains the most relevant technologies for the study. Also, Table 1 and Table 2 compile technical and economic characteristics of energy storage technologies, gathering the most recent data.

### *Pump Hydro (PHES)*

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. It stands out for the large volumes of energy it can store at a competitive cost.

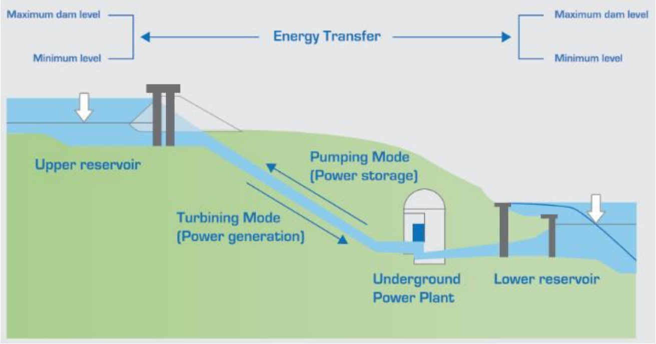

*Figure 1. PHES operating principle. (Source: EASE)*

### *Flywheels*

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.

It is considered a very efficient technology that can supply a lot of energy with a short reaction time. On the other hand, the main limitation of this technology is that the energy cannot be discharged for periods longer than minutes.

### *Thermal storage (TES)*

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. In this work, special emphasis will be placed on molten salts technology, as it is a technology widely used with combination of CSP plants. 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

### *Hydrogen production*

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.

### *Power to Gas (P2G)*

P2G 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…) [3]. 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 [4] of the order of TWh [5].

*Table 1. Technical characteristics of energy storage technologies*

| Technology type | Power Range [MW] | Energy Range [MWh] | Efficiency [%] | Discharge Duration [t] | Response time [t] |
|---|---|---|---|---|---|
| PHES | 100 – 5000 [6] | 100 – 100000 [7] | 70 – 87 [7] | h – days [6] | s – min [7] |
| Molten Salts | 1 – 300 [8] | 1 – 5000 [9] | 90 – 99 [9] | min – h [10] | min [9], [10] |
| Li-Ion Battery | 0,001 – 100 [7] | < 200 [7] | 90 – 98 [11] | min – h [11] | ms [11] |
| VRB | 0,5 – 100 [12] | < 100 [8] | 75 – 85 [13] | s – h [13] | ms [13] |
| Flywheel | 0,002 – 20 [13] | 0,005 – 5 [13] | 90 – 95 [10] | s – min [10] | ms – s [10] |
| Supercapacitor | 0,01 – 5 [8] | 0,001 – 0.005 [8] | 94 – 98 [7] | s – min [6] | ms [6] |

Table 2. Economic characteristics of energy storage technologies.

| Technology type | Power Invest. Cost [€/kW] | Energy Invest. Cost [€/kWh] | Maintenance Cost [€/kW/year] | Lifetime [years] |
|---|---|---|---|---|
| PHES | 500 – 4600 [14] | 70 – 350 [7] | 5 – 40 [7] | 50 – 100 [6] |
| Molten Salts | 100 – 300 [8] | 25 – 70 [9] |  | 30 [10] |
| Li-Ion Battery | 150 - 1300 [8] | 180 – 1000 [9] | 6 – 20 [9] | 10 – 20 [11] |
| VRB | 150 – 1500 [15] | 100 – 1000 [6] | 17 -47 [6] | 5 – 20 [6] |
| Flywheel | 100 – 300 [6] | 1000 – 3500 [6] | 1 [7] | 15 – 20 [6] |
| Supercapacitor | 10 – 400 [6] | 300 – 20000 [6] |  | 16 – 40 [7] |

### Supercapacitors

Supercapacitors 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.
Due to their high charge/discharge velocity and efficiency this technology is very used in the field of electronics or electric vehicles are some examples.

### Secondary batteries

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.
There is a wide variety of batteries, but the 4th types most used for energy storage are: Lead-Acid, Li-ion, NaS, NiCd, [14].
At Table 1 and Table 2 can be seen the principal characteristics of Li-ion battery.

### Redox Flow Batteries

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 [15][16].

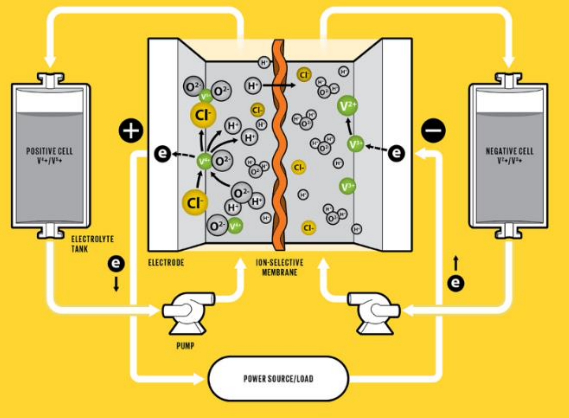

Figure 2. Operation of a redox flow battery during the charging process. Illustration: James Provost

## 2.2 Comparative of energy storage systems

Figure 3 and Figure 4, compare different ES technologies, including some that are not explained in this report. As can be seen, CAES, P2G, PHES, molten salts and battery technologies are the most suitable systems to use on a large scale. For example, these systems are very useful for storing surplus energy from renewable energies or for generating energy during 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, by regulating the frequency and voltage of an electrical network.

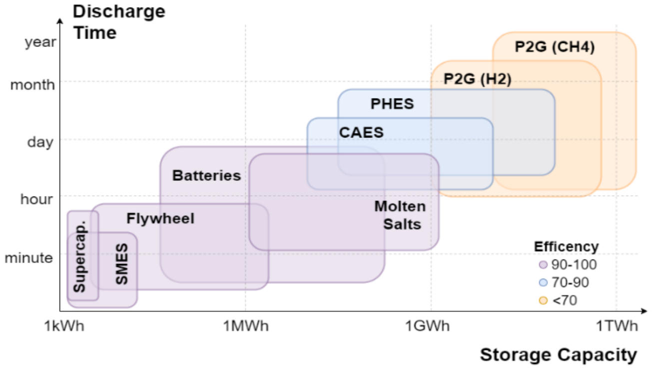

Figure 3. Comparative of ES technologies in a Discharge Time - Storage Capacity graphic.

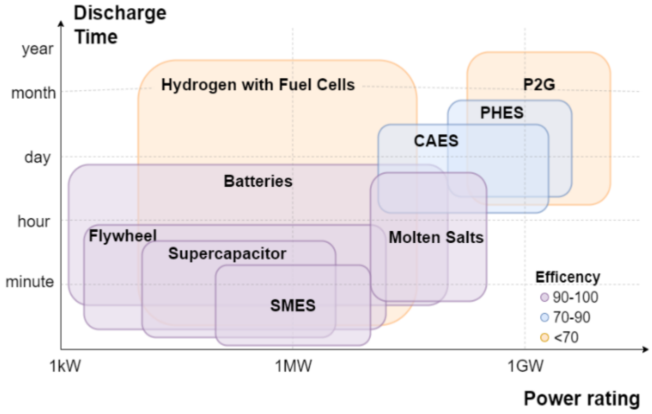

*Figure 4. Comparative of ES technologies in a Discharge Time - Power Rating graphic.*

## 2.3 Installed power in Spain

Regarding the *Global Energy Storage Database*[17], 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.

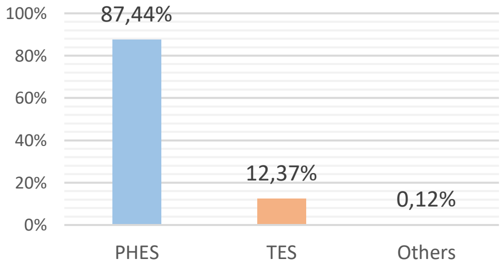

*Figure 5. Installed Power mix of energy storage technologies in Spain.*

### *PHES technology*

The Spanish potential with PHES technology is enormous, it is the second country in Europe with the most theoretical potential after Turkey [18]. At present, Spain is the 4 country in the world and the first in Europe with more PHES installed power with 8 GW [19], spread over 20 plants. In addition, in the coming years it will be the country of Europe where the installed power will grow more [20].

### *Molten Salt Technology*

Spain is the country with the most installed power CSP plants in the world [21]. 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. Unfortunately, this system cannot store electricity coming from the grid and is therefore not considered as effective as the PHES system. In Spain, there are about 26 plants that have deposits of molten salts, with a total installed power of 1,13 GW and with a storage capacity of 8,42 GWh. [17][22][23]

### *Electrochemical batteries*

There are between 3 and 4 MW of installed capacity of electrochemical batteries in Spain. Can be found 3 different types of battery installations: Lithium-Ion battery, Vanadium Redox Flow battery and Lead-Acid battery. The principal uses of these plants are: 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, development and demonstration of rapid charging of electric vehicles.

### *Flywheels*

Nowadays, 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 with imbalances in frequency and voltage between generation and demand [24]. These characteristics of the islands cause instability in the system when there are 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 [25]. So, the main function of these two projects is to regulate the frequency and voltage of the system.

### *Supercapacitors*

There are two active projects that use supercapacitors as a storage system, one in Madrid and the other in La Palma.
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 other plant 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 lifetime by 20 to 25 percent [26].

## 3. Modelling future scenarios

A total of 6 possible energy scenarios have been developed for the study, which follow a deterministic model.
**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 [27] and PLCCTE [28], 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 must be 100% renewable.
3. The renewable presence in 2030 must be at least 70%.
4. The mobility sector will drastically reduce its emissions in 2050.
5. The electrical system should be the main vector of decarbonization.

### 3.1 *Final electricity demand*

The value of the 2018 and 2030 scenarios has been obtained from the REE [29] and the PNIEC [27] values respectively.

For the electric scenario of the years 2040 and 2050, an annual growth in demand of 1.36% has been considered as indicated in the article [30] based on the results of the *Global Calculator Tool* [31]. Finally, he electricity demand of the $H_2$ scenarios is the sum between the demand of the electric scenario of the same year and the electricity used for hydrogen production. Table 3 shows the evolution of demand for all scenarios.

*Table 3. Evolution of the electricity demand [TWh].*

| Scenario | 2018 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Electric | 243.7 | 262.7 | 301.0 | 344.6 |
| $H_2$ | | | 315.4 | 370.8 |

### 3.2 *Installed power*

As in the Final electricity demand, the electricity demand, the value of the 2018 and 2030 scenarios has been obtained from the REE [29] and the PNIEC [27] values respectively.

The installed power mix considered in 2040 scenario 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. 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.

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.
2. The hydroelectric installed power maintains the same value as in the 2040 scenario.
3. The installed Biomass power is 5000 MW. An extrapolation of the Portuguese system to Spanish has been made.
4. The rest of installed power is going to be divided following the same proportion than the year 2040.

*Table 4. Evolution of the Spanish installed mix [GW].*

| Technology | 2018 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Wind | 23.1 | 48.6 | 51.0 | 65.8 |
| Hydro | 18.8 | 20.1 | 2.49 | 24.9 |
| Solar PV | 4.5 | 38.4 | 77.0 | 99.4 |
| Solar thermal | 2.3 | 7.3 | 12.3 | 15.9 |
| Others RES | 0.9 | 1.7 | 2.6 | 5.0 |
| Coal | 9.6 | 0 | 0 | 0 |
| CC | 24.6 | 24.6 | 12.3 | 0 |
| Cogeneration | 5.7 | 4.0 | 0 | 0 |
| Nuclear | 7.1 | 3.1 | 3.1 | 0 |
| Others | 0.5 | 0 | 0 | 0 |

The H2040 and H2050 scenarios are not represented in Table 4, as their mix are practically identical of the 2040 and 2050 scenarios. The only difference is that the H2040 scenario has installed 9.26 GW more of solar PV and the H2050 scenario has installed 16.85 GW more of solar PV that the scenarios 2040 and 2050, respectively. This increase is due to the assumption that hydrogen will be generated from photovoltaic plants.

### 3.3 *Storage capacity*

For each scenario, a range of installed battery power has been considered. To make the proposal, an extrapolation of the projection of the Portuguese RNC 2050 [32] document has been made. In this way it is intended to see what changes occur in the results of the system depending on the installed power of the batteries.

The storage capacity of the batteries has been considered 2 hours at nominal power as it is mentioned by the PNIEC.

The following table shows the installed power of PHES and batteries:

*Table 5. Batteries and PHES installed power evolution*

| Technology | 2018 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Batteries | | 2 – 6 | 5 – 9 | 10 – 14 |
| PHES | 3.33 | 7.89 | 10.15 | 10.15 |

Regarding molten salt deposits, is considered that the storage capacity is equal to 9 hours of operation at rated power of the plants showed in Table 4.

### *3.4 International electric energy exchanges capacity*

The values of the Spanish capacity interconnection for 2018 and 2030 has been obtained from the PNIEC and the REE. For the years 2040 and 2050 t is assumed that 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 [33].

*Table 6. Interconnection capacity forecasts.*

| Scenario | 2018 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Electric | 5.2 | 13.1 | 28.9 | 33.2 |
| $H_2$ | | | 30.4 | 35.7 |

## 4. 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.

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.

## 5. Results

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

1. Installed power of the batteries.
2. Economic/Technical simulation.
3. Wet hydro/Dry hydro distribution. To see the influence of dry and rainy year.
4. 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.

### *5.1 Evolution of the Spanish electrical system*

#### *Generation mix*

Figure 6 shows the results of electricity generation by energy source of scenarios 2018, 2030, 2040 and 2050. The results of scenarios H2040 and H2050 are very similar to those of scenarios 2040 and 2050. The difference remains in an increase of solar PV generation of 15 and 25 TWh, respectively.

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 PV. It should be noted that the generation of electricity from wind in 2040 scenario, is slightly lower than the 2030 scenario.

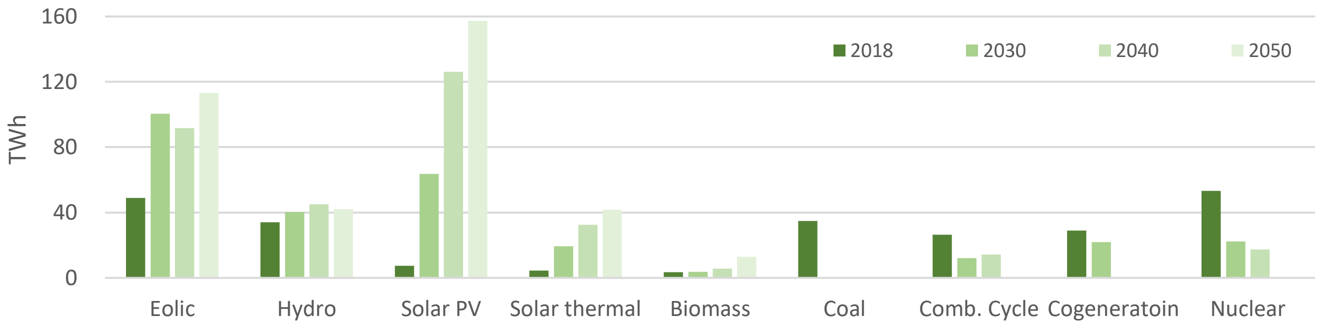

*Figure 6. Electricity generation at 2018, 2030, 2040, 2050 scenarios.*

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.

### *$CO_2$ emissions*

Table 7 show that $CO_2$ emissions from the Spanish electricity system are reduced to a value of 0 kg in 2050, as the system is 100% renewable.

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[34], 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 7. Evolution of $CO_2$ emissions until 2050.*

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

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### *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.

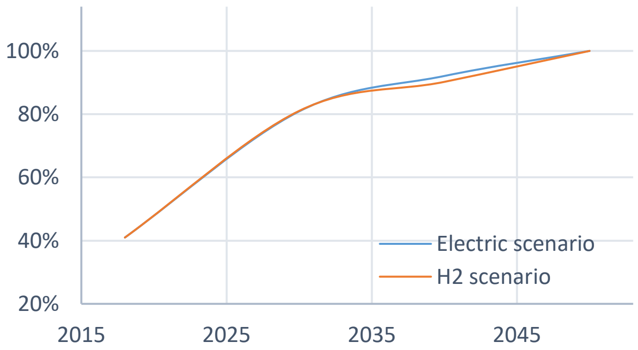

*Figure 7. Evolution of RES%.*

### *Storage installed power*

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) are plotted.

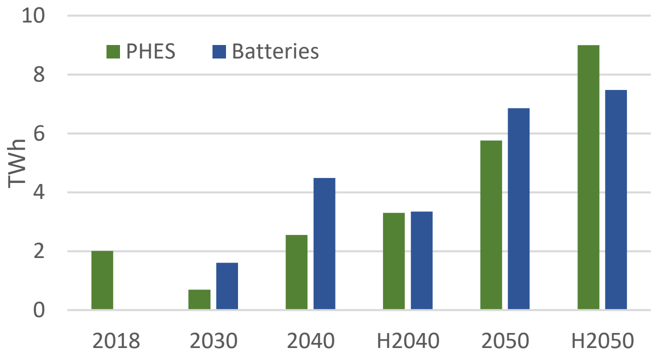

*Figure 8. Evolution of electricity production by storage technologies.*

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.

## *5.2 Analysis of the hourly behavior of different elements of the system*

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..

### *Electricity 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.

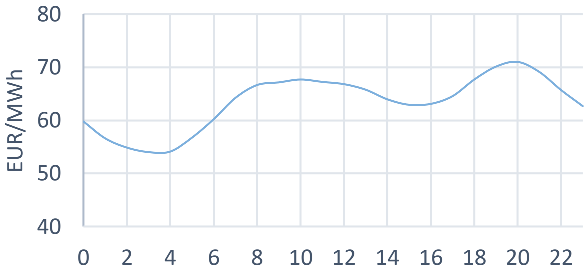

*Figure 9. Hourly curve of the electricity price.*

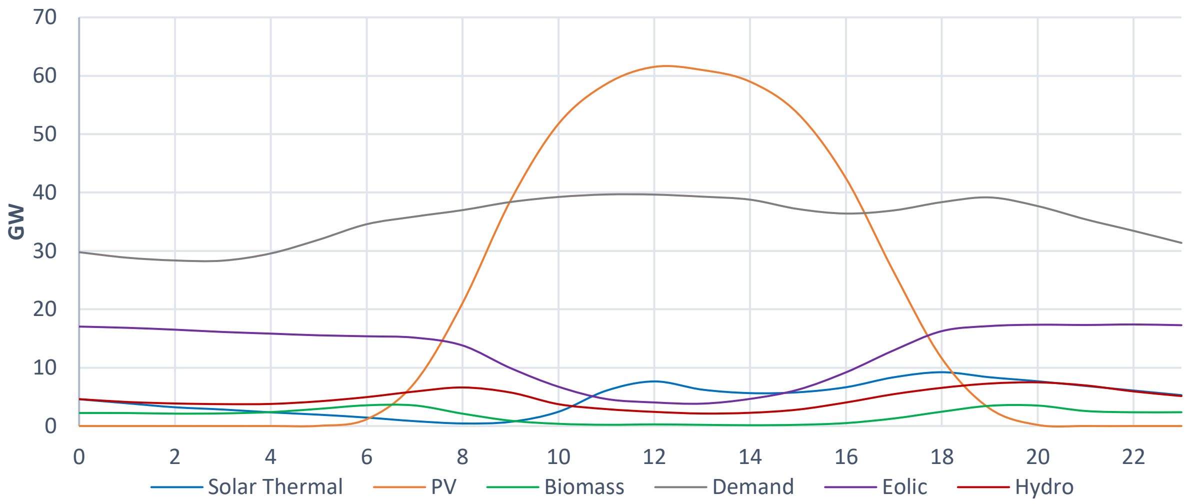

*Figure 10.Hourly data curve of power generation by technologies and hourly demand curve.*

### *Production by technology*

Figure 10 shows the hourly data curve of power generation by technologies. The energy demand curve is also represented.

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 10 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.

### *Imports / 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.

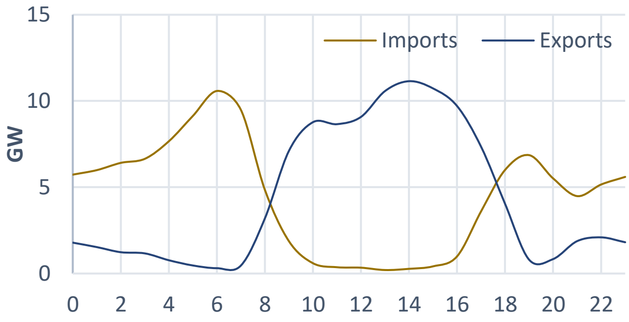

*Figure 11. Hourly data curve of Imports and exports.*

### *V2G & $H_2$ 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.

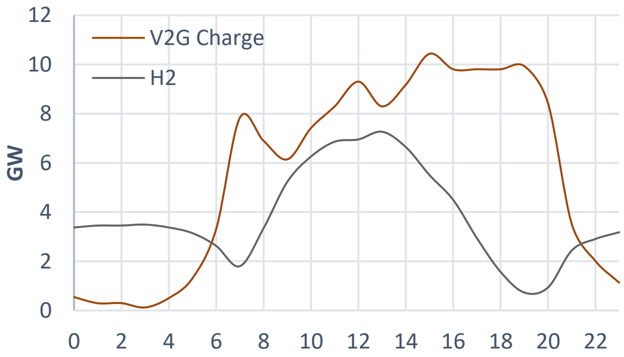

*Figure 12. Hourly data curve of V2G charge and $H_2$ production.*

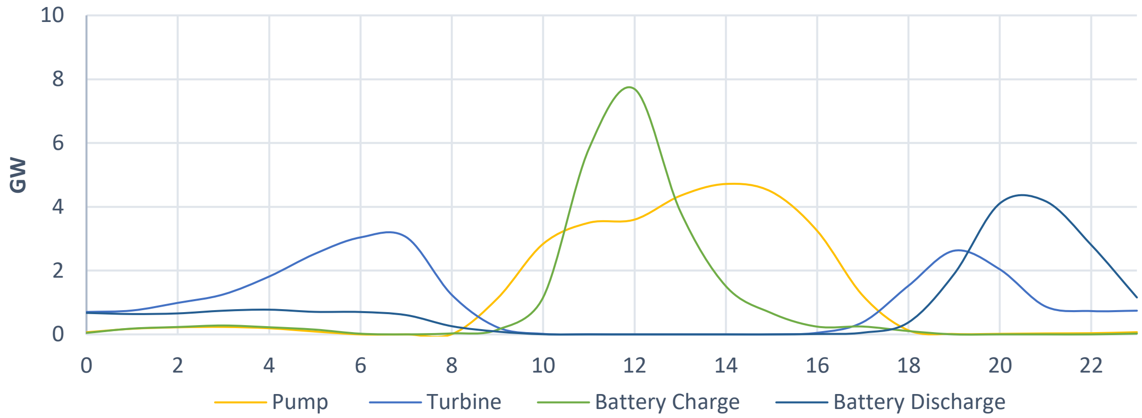

*Figure 13. Hourly data curve of battery and PHES technologies.*

### *Battery and hydro storage*

In Figure 13 can be seen that 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.

### *Weekly distribution*

Figure 14 and Figure 15 are 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.

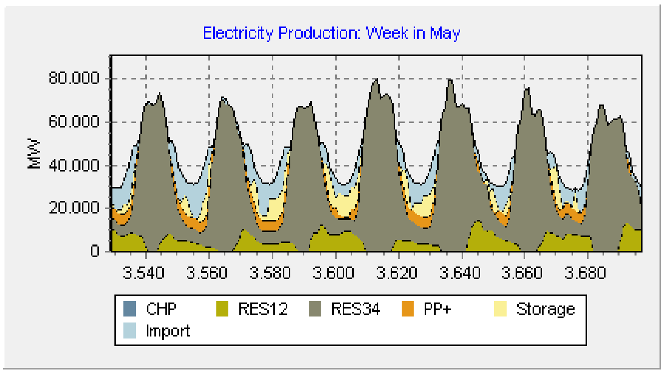

*Figure 14. Weekly electricity production curve*

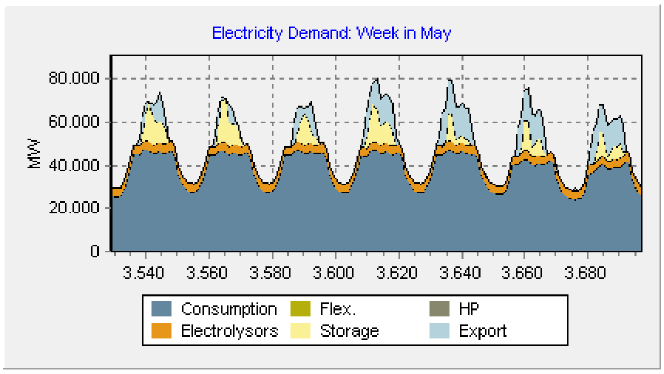

*Figure 15. Weekly electricity production curve*

## Conclusions

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, batteries and molten salts deposits, 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 and biomass power plants can supply electricity almost instantly, which allows to reach the peaks of demand. 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. It is believed that without regulations, and only with the regulation of the economic market itself, it would be very difficult to achieve the decarbonisation targets by 2050.

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