BACHELOR'S DEGREE IN INDUSTRIAL TECHNOLOGIES ENGINEERING

DEGREE´S THESIS

IMPACT OF THE HYDROGEN ECONOMY ON THE ELECTRICITY SECTOR

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Madrid, July 2021

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Collaborating Entity: ICAI-Pontifical University, INESC TEC

ABSTRACT

The Spanish energy market has been evolving during the past years following the directives of environmental sustainability established by the international community. The Green Deal set the necessity of limiting the global warming in 1,5ºC. To achieve it, it is required that CO_2 emissions decrease around 25% for 2030 and reach net zero emissions in 2070. In order to meet the objectives set in the Green Deal and the Paris Agreement, the electricity sector has incorporated an important volume of renewable energy. The renewable sector represents up to 40% of total energy delivered. However, the goal is to get, by 2070, a 70% of penetration rate.

In this decarbonization context, recent studies have analyzed the role of hydrogen in the new economic model. Obtaining hydrogen from renewable sources seems to be key to achieve the goals marked. Its ability to be stored and therefore, to store energy excess would give flexibility and stability to the today´s growing energy system. However, while all hydrogen burns the same, there exist different methods of producing it. Depending on its obtention method and their CO_2 emissions, the following can be distinguished grey, blue, and green hydrogen. Therefore, as the objective is achieving a decarbonized economy, this study will be focused on green hydrogen which comes from electrolysis, a process powered by renewable sources, such as wind or solar.

Aligned with the international objectives, the European Union published in July 2020 its hydrogen roadmap. On this agenda, achieving a climate neutral Europe could be possible following a three-path roadmap. From now to 2024, 6 GW of electrolysers should be installed in the EU and up to 1 million tonnes of green hydrogen should be produced. Secondly, during the period 2025 to 2030, at least 40 GW electrolysers must be deployed and up to 10 million tonnes of renewable hydrogen should be produced. Finally, for 2030 and beyond, the hydrogen should become an intrinsic part of the integrated energy system, in order to reach in 2050, the climate neutrality.

In Spain, the Ministry for Ecological Transition and Demographic Challenge published its own hydrogen roadmap. Indeed, it follows the structure for the hydrogen deployment determined by the European Commission. However, it is also interesting to highlight that it gives importance to its own energy strategy and needs. The aim is to take advantage of the potential in renewable energies with wind and solar plants by implementing "clean" hydrogen in the coming decarbonized industry.

In fact, the Spanish roadmap, that will be updated each three years, has determined two main targets. "Visión 2030" and "Visión 2050". They will serve as a reference for analyzing the development and implementation of the hydrogen agenda. In particular, "Visión 2030" estimates 4 GW electrolysers installed capacity and examines different milestones in the electricity, mobility and industrial sectors with an estimated investment of 8900 million of euros from 2020 to 2030. As an intermediate, in 2024, between 0,3 and 0,6 GW electrolysers installed capacity should be working. By his side, "Visión 2050" establishes that renewable hydrogen technologies should reach maturity and should be deployed on a large scale.

However, in order to understand the impact of this policies, the hydrogen value chain must be explained. The document contains a detailed analysis of the main actors in this chain: producers, consumers, transportation, and storage.

The production of hydrogen has been based for years in natural gas (76%) and coal (23%). However, it is important to highlight that in the Sustainable Development Scenario, Low - carbon hydrogen produced through water electrolysis or with CO_2 capture will account for 99% of global production in 2070 and more than a half will be using electrolysers.

Focusing on the electrolysis process, there are different types of electrolysers. Alkaline electrolysers are the most common and used today because of their rentability and their technical maturity. By his side, PEM technology seems to be the method employed in the coming years due to its evolution in terms of efficiency and price. Finally, SOEC electrolysers are also an additional alternative. However, this technology still in development and it is only considered in long term scenarios.

Analyzing the hydrogen demand, today, hydrogen is employed mostly for industrial applications. The main uses today, in pure and mixed form, are oil refining (70%), ammonia production (25%), methanol and steel production (5%). However, by 2070 the use of hydrogen in the transport sector will increase exponentially accounting for 30% of the hydrogen produced.

It is important to indicate the hydrogen role in the gas sector with Power-to-Gas applications. The injection of the hydrogen in the gas grid has a huge potential to improve power-to-hydrogen economy due to the low investment involved in using an already installed network.

The energy storage is a key element to bring flexibility to the power system and to increase the renewable energy integration. Furthermore, it brings the possibility of storing energy during periods of overproduction or energy surplus to use it in deficit moments. The seasonal storage considers the option of producing large quantities of hydrogen in summer to use it in winter.

The optimal storage solution for each hydrogen application depends on the volume stored, the storage duration, the speed of discharge and the geographic availability of the different possibilities. In general, two types of storage can be identified, geological and tanks reservoirs. The first one is more common for large-scale and long-term and the second one, is more suitable for small-scale and short-term. Salt caverns, depleted natural gas and oil reservoirs or aquifers are the mainly options for geological storage. By his side, tank storage is the most mature technology. Tanks for compressed or liquified hydrogen have high efficiencies and high discharge rate which makes easier the hydrogen extraction.

The last link in the chain is transportation. The low energy density of hydrogen requires high quantities of energy to maintain it. This means that it is very expensive to transport it over long distances. However, there exist a wide variety of options to face this problem. In many countries, there is an extensive gas network that could be used to operate with hydrogen. In addition, new infrastructures can be developed with dedicated pipelines, shipping networks, etc. Normally, gaseous hydrogen is transported using tube trailers or pipelines. On the other hand, liquid hydrogen is moved by road tankers. For short distances, and small amounts, gaseous hydrogen via tube trailers is usually the best option. There exist other options as railway or maritime transport.

In order to extend the actual CEVESA model to include the new hydrogen perspectives, a new H2 model has been included. The model considers production, demand, and storage.

CEVESA, is a dynamic model for operation and expansion of the production plants of the power system (assumed as a single-node). It allows to analyze the interaction between hydrogen and the electricity system, and the impact on the electricity price of the hydrogen production. It is a good approach to the reality of the electricity system.

However, to include the hydrogen actors considered, some hypotheses have been assumed. Firstly, the Spanish and the Portuguese systems are treated like two separate modules. Secondly, the model does not include transportation. This consideration was made considering that the hydrogen transport costs as customs or gasoline costs can be reduced or removed. Furthermore, considering previous studies, the storage and demand coverage is done weekly. In addition, in the model proposed, the production uses a unique electrolyser, the storage employs a unique reservoir, and the demand is assumed to be a unique node. The hydrogen produced can be stored or used to supply the external hydrogen demand. By his side, stored hydrogen can be used to produce electricity or to feed the external demand. It is important to highlight that all processes consider relevant efficiencies and costs in order to create an accurate H2 model. A detailed analysis of the constraints introduced is also developed.

Four scenarios have been tested after careful revision of the future hydrogen framework in Spain, the European guidelines, the investments trends, and other projects under development. The scenarios selected has allowed to validate the model and to understand the impact of some input parameters in the hydrogen economy.

The results show that, hydrogen is produced using energy excess and combined cycles. Hydrogen produced is used to supply the external demand and, if the capacity installed allows it, it is also stored. However, considering the inefficiencies, the model never selects to supply the demand using stored hydrogen. Therefore, stored hydrogen is only employed to produce electricity. Furthermore, having storage capacity gives flexibility and stability to the system. This means that the price curve flattens when hydrogen can be stored and the difference between peak and off-peak areas is reduced.

Comparing liquified and compressed hydrogen, it can be inferred that, even with a lower efficiency, the model produces more hydrogen with liquified storage. This is due to the difference in costs between the two storage types, being more expensive compressed storage.

Finally, from an economic point of view, introducing hydrogen impacts on the average electricity price. This is because new costs are being introduced. However, the difference in prices is not too high, which makes the hydrogen option more cost-effective and attractive for the near future.

For future studies, it will be interesting to analyzed how transportation will affect the model proposed, in order to understand how a decentralized model will work and to take into consideration the possible delays that would occur.

Memory Index

Figure Index

Table Index

1. INTRODUCTION

In the decarbonization context the world is experiencing today, it seems to be necessary to find processes that reinterpret the role of the renewable energy surplus that is produced on the electricity system to create a more efficient system. Even if low-carbon carriers are not new, and the hydrogen as a solution has been studied yet, this new era brings the necessity of attaining the climate neutrality as soon as possible.

Over the last 12 months, the interest for the hydrogen potential as a key sustainable solution for a clean and affordable energy has increased and diverse plans on the national and international panorama have come to light. Many new national hydrogen strategies have been elaborated and published being one of the pioneers Japan in 2017, [1].

On the same way, The European Commission has determined recently, an ambitious project to achieve, in 2030, a model where "renewable hydrogen will be deployed at a large scale across all hard-to-decarbonize sectors", [2].

On this agenda, the objective of a climate neutral Europe will be developed following a three-path roadmap. From now to 2024, 6 GW of electrolysers will be installed in the EU and up to 1 million tonnes of green hydrogen will be produced. Secondly, during the period 2025 to 2030, at least 40 GW electrolysers will be deployed and the production of 10 million tonnes of renewable hydrogen should be a reality. Finally, for 2030 and beyond, the hydrogen should become an intrinsic part of the integrated energy system, in order to reach in 2050, the climate neutrality.

Following the structure for the hydrogen deployment set by the European Commission and attending its own energy strategy and needs, in Spain, the Ministry for Ecological Transition and Demographic Challenge has published the first roadmap, [3], for the implementation of the hydrogen in the coming decarbonized industry. The agenda considers this energetic vector as a viable solution to create new innovative value chains and studies the steps for its gradual implementation to meet the proposal made by the European Union and the objectives set out in the National Integrated Energy and Climate Plan 2021-2030(PNIEC), [4]. Furthermore, it examines the expected challenges and possibilities that this new energetic vector could have in the economic sector and the current and potential uses of the hydrogen and how its versatility and flexibility will help to meet those determined by the EU.

Nowadays, the hydrogen consumption in Spain is around the 500.000 tonnes per year and it is mostly grey hydrogen which is made using fossil fuels like coal or oil. It is important to indicate that there exist two other types, which are blue, corresponding to "grey or brown hydrogen with its CO_2 sequestered or repurposed", and green (project focus), which corresponds to "Hydrogen produced by the electrolysis of water using electricity from renewable sources like hydropower, wind, and solar.", [5]. In this last case, as indicated in [5] zero carbon emissions are produced. Hydrogen is especially employed as a raw material in refineries (70%) and for the manufacture of chemical products (25%). Therefore, this fact reflects the potential of decarbonization on industry by replacing gray hydrogen with green one.

Indeed, the Spanish roadmap, [3], that will be updated each three years, has two main horizons that will serve as a reference for analyzing the development and implementation of the agenda, "Visión 2030" and "Visión 2050". In particular, "Visión 2030" estimates 4 GW electrolysers installed capacity and examines different milestones in the electric, mobility and industrial sectors with an estimated investment of 8900 million of euros from 2020 to 2030. As an intermediate, in 2024, between 0,3 and 0,6 GW electrolysers installed capacity should be installed. "Visión 2050" sets that renewable hydrogen technologies should reach maturity and should be deployed on a large scale.

The Spanish roadmap, [3], is therefore aligned with "The Annual Growth Strategy" (2021)[6] published also by the European Commission which recognizes the future Recovery and Resilience Mechanism as a way to conceive important areas of action at

Europe, being two of these areas, *Power Up* and *Recharge and fuel*, a direct reference of the progress of green hydrogen on the EU.

Therefore, the panorama is set out, and the plan for the energetic transition has been established. However, Spain must start its implementation if it wants to be a benchmark in climate neutrality as it is said in the Spanish roadmap, [3].

1.1 MOTIVATION OF THE PROJECT

Following the path determined by the European Union with the Green Deal, structured in the EU Hydrogen Strategy, and directed in Spain by the Ministry for the Ecological transition and Demographic challenge with the Hydrogen Roadmap, the agenda is settled to decarbonize the EU, and the hydrogen seems to be one of the keys.

In the decarbonization context the world is experiencing today, creating an economy based on renewable energies is so important. Being able to employ and store the energy surplus of wind or photovoltaic resources, is also important to guarantee the solvency of a system based on renewables. Hydrogen produced from electrolysis is, for some, a good way to store this surplus to use it in the future and in consequence to contribute to zero emissions society because other CO_2 based energy resources could be not long needed.

However, as green hydrogen depends on the renewables' production costs because is the way to produce it, its viability is linked to the evolution of that costs. Furthermore, being able to use green hydrogen will also influence energy prices so it seems to be necessary to study the integration of green hydrogen to analyze the interaction between hydrogen, renewable energy in the electricity system and electricity prices. At that point, CEVESA model, [7], allows to simulate the MIBEL integrating, partially, H2 to determine the interactions before named.

In conclusion, following the path established by the Paris Agreement in 2015, the ecological transition is an issue of international importance. Electrifying and reducing the pollutant emissions by promoting renewable energies seems to be the key. Therefore, using green hydrogen and also, as an energy storage, seems to be an important driver for the transition. Hence, its study and the determination of its place in the future circular economy has become an interesting research.

1.2 OBJECTIVES

The aim of this thesis is to analyze the impact of including hydrogen in the electricity sector studying its impact on the electricity price in the MIBEL electrical system. The objective is to include an advanced model of the future hydrogen economy in CEVESA. To reach this target, the following partial objectives will be addressed:

1. Analyse and quantify the main uses of hydrogen (transport, industrial uses, possible uses as a fuel mixed with gas in combined cycles, etc.) for a better characterization of its industrial and transportation demand.
2. Model hydrogen production according to its uses and the temporal restrictions of its production related to its demand and its potential storage.
3. Extend CEVESA MIBEL modelling tool to include operation of H2 production plants considering its possible uses and identified restrictions.
4. Assess with case examples the impact of the H2 economy on the electricity system within the current context of decarbonization of the energy system.

1.3 METHODOLOGY AND RESOURCES

The tasks fulfilled in this report have been:

1. Review of the state of the art by reading of documents, papers, roadmaps, reports, and projects carried out related with the topic.
2. Identification of the parameters needed for the model (efficiencies, lifetime, fuel cells and electrolysers, transport, storage, etc.)

3. Design of the simulation scenarios in order to validate the model (costs, time, network constrains)
4. Formulation of the model to integrate H2 economy into CEVESA according to 3) and 4)
5. Implementation of the optimisation model and integration into CEVESA framework (based on Excel plus GAMS-CPLEX).
6. Testing, validation, and simulation of the scenarios designed in 4)
7. Results analysis, conclusions, and final report writing.

The tools employed for carrying out this report were:

- The optimization tool: GAMS
- CEVESA Model, shared by IIT-Comillas and INESC TEC

2. STATE OF THE ART OF THE HYDROGEN ECONOMY

2.1 GLOBAL VISION

Climate change is one of the drivers for hydrogen in the decarbonization transition. For limiting global warming in 1,5ºC, it is required that CO_2 emissions decrease around a 25% in 2030 and reach net zero in 2070, [8], and for the mitigation of these emissions, hydrogen could be an important asset in the coming decades. The International Renewable Agency´s roadmap, [9], highlighted up to 6% hydrogen share of total final energy consumption by 2050 and the Hydrogen Council agenda suggested an up to 18%, [10].

At present, 120 million tonnes of H_2 are produced each day, being 66% pure hydrogen and the remaining part a mixture with other gases, [9]. The vast majority of this production is made and used on-site in industry. It is important to indicate that the main sources to produce hydrogen are coal and natural gas (95%), which are critical enhancers of the CO_2 emissions, and only 5% comes from electrolysis processes. Demand for pure hydrogen is around 70 million tonnes per year, [11], and the uses of hydrogen go from the production of ammonia and oil refining to it incorporations to the pipeline system (see Figure 1). It can be observed that the hydrogen produced goes mainly to Ammonia production and Refining uses. Furthermore, even if some hydrogen goes to transport, heat and power sector, today is not the main part of the demand. However, as it will be analyzed, this seems to change in the coming years.
Nevertheless, beyond its conventional applications, that have been here for a long time, the importance of hydrogen should come from new usages as transport power or heat, and from a decarbonized supply.

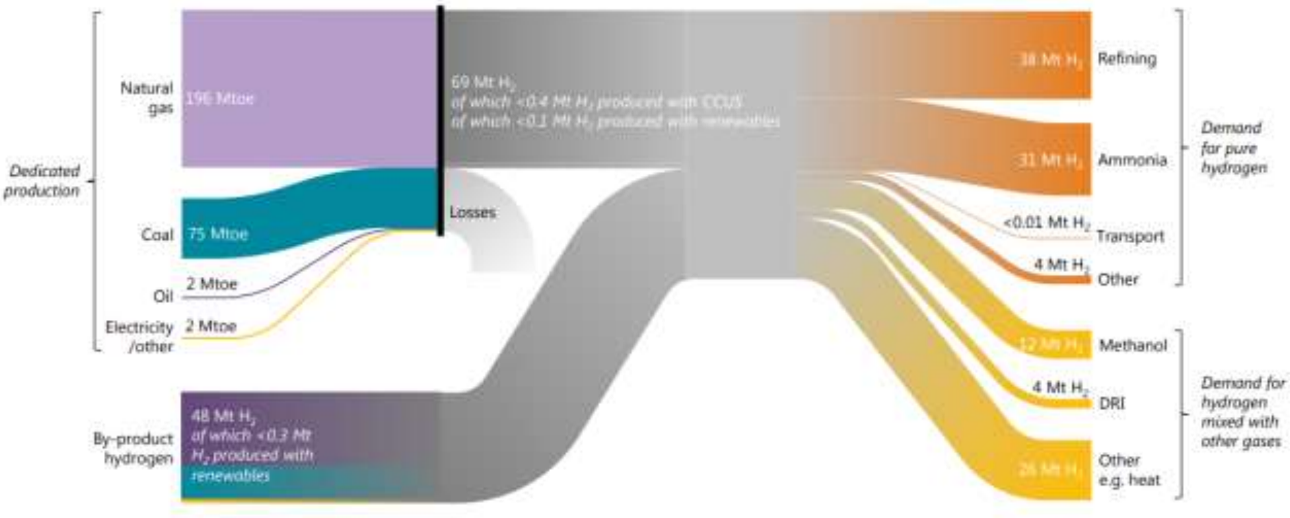

Figure 1. Today´s Hydrogen Value Chain. Source: IEA

The price for green hydrogen is currently around 4-5$/kg (grey hydrogen has a price between 0,045-1,5$/kg, [12])but it is expected to decrease by 50% (2-2,5 $/kg) in 2030 according to the report made by S&P Global Rating, [13]. It sets out that this decrease will be caused by three main reasons. The first one is the decrease of the renewable energy price which represent the 60% of the green hydrogen cost. This decrease will provoke a reduction by 0,4-0,5$/kg in the hydrogen cost. Secondly, if the capital cost of the electrolysers decreases by 250$/kW, the hydrogen will reduce it price in a $0,3-0,4$/kg. Finally, the growth of the electrolyser capacity factor by 40-50% will also reduce the price of green hydrogen by 0,2-0,3$/kg.

On the other hand, it is important to study which are the reinforcing reasons to give an opportunity to hydrogen. The International Energy Agency (IEA), in its report, [9], structured the reasons why investing in hydrogen is worthwhile, in four points:

1. **"Greater attention to the deep emissions reductions that hydrogen can help deliver, especially in hard-to-abate sectors"**: The number of countries that are pointing out ambitious challenges for greenhouse gas emissions reduction is raising rapidly. The 195 partners of the Paris Agreement on climate change in 2015

concluded that they need to increase its efforts toward net zero emissions and to achieve it, different countries have developed its own strategy to face this battle.

- Japan: updated its Strategic Roadmap to add the Basic Hydrogen Strategy, which includes new goals for hydrogen and fuel cells costs and deployment, [1]. The Development Bank of Japan allied with a consortium of companies, publicized Japan H2 Mobility with the objective of building 80 hydrogen refueling stations by 2021 (Japan H2 Mobility, 2020).
- United States: Its Low Carbon Fuel Standard incentives the building of refueling stations and enables CCUS operators (Carbon Capture, Use and Storage) to be part of the production of credits from low-carbon hydrogen (Low Carbon Fuel Standard, 2018).
- Europe: For example, United Kingdom, bet for the innovation in low-carbon hydrogen supply and storage at scale including Power-to-X that could be define as "the means to convert electricity, understood to be primary energy, into an energy carrier, heat, cold, product, or raw material", [14], (Michael Sterner, professor at OTH Regensburg University). Furthermore, it is testing blending a 20% of hydrogen in the UK´s natural gas network. By his side, Spain and its roadmap published last year will be analyzed in more detail below, [3].

2. **"Hydrogen is seen as able to contribute to a wider range of policy objectives":** Even if the development of hydrogen and its interest is closely related with climate transition, an essential broadening of the policy goals to which hydrogen can contribute has been noticed. Hydrogen has important advantages in energy security, air pollution and economic development.

   In terms of energy security, when Hydrogen is introduced, producing or consuming, beside electricity system, electricity can be converted to H_2 and vice versa, or further, transformed into other fuels, making end users less dependent of a specific energy resource, and raising the flexibility of energy supply. In addition, hydrogen can provide a supplementary way to store energy strategically, as the excess of energy from wind and solar plants, in a highly electrified low-carbon power system.

On the other hand, using hydrogen instead of carbon-containing fuels in energy end uses can decrease local air pollution. Urban air contamination and its relationship with health issues are important drivers of energy policy determinations. Furthermore, from an economic point of view, the expansion of hydrogen technologies and infrastructures, and the development of the new Hydrogen value chains will provoke the growth of new producing, transmitting and uses for hydrogen. It is a good opportunity for countries to lead the change, to create job and to become technical experts, in special when they reinforce existing capacities and skills.

3. **"Hydrogen can help ensure the current rapid growth of renewable electricity"**: The reduction of renewable energy cost is one of the keys to rise hydrogen´s potential. The LCOE costs of solar and wind production are becoming cheaper so their expected share of the future primary energy mix rise. However, their output variability continues being a challenge in particular when considering 2050 EU objectives for, a reduction of greenhouse gases emissions on a 90-95%, which implies an almost complete decarbonization of the power production and very high rates of renewables production, [15].

   As hydrogen can be used in a large number of different sectors and can be produced from electricity and stored, it could be an additional source of flexibility for balancing the supply and demand with a large share of renewable production.

   However, the price of producing hydrogen based on electrolysers is still an issue, being the price of the electricity its main component.

   The increase of renewable production will decrease the market prices, in particular at those hours with production excess and very low electricity prices, from which the production of hydrogen could profit.
4. **"Hydrogen can benefit from positive experiences of developing clean energy technologies"**: As it has been stated, a rise in plans for producing hydrogen for

energy and climate purposes have increased in recent years. From 2000, 230 projects have started operating to convert electrical energy in hydrogen for a wide variety of energy and climate applications.

Alkaline and Proton Exchange Membrane (PEM) electrolysers are the most settled technologies.They have achieved efficiency´s percentage around 60-70%. Recent studies have tended to highlight PEM technology over Alkaline, because of its potential for cost reduction and its expected flexibility. To end, another technology that still under development has appeared, SOEC electrolysers that promise better efficiencies. However, with a lower maturity, it probably would take some years to compete with PEM and Alkaline technologies.

After analyzing the key drivers for the inclusion of hydrogen in the current power system, there are still some challenges without clear response, such as the complexity of the value chains, the infrastructure needs, the necessity of a regulation policy and the technology evolution uncertainty.

The global analysis of the current state of hydrogen production, demand and future challenges have been set out.

On the other hand, as this research is focused on the impact of the hydrogen economy in the Spanish power system, it is necessary to analyze in more detail the roadmap developed by the Spanish Government.

Starting with a production analysis, the Spanish roadmap distinguishes two main types of hydrogen producing methods. The first way to produce hydrogen is by electrolysis. Alkaline electrolysers are the most common and used today because of their rentability and their technical maturity. The production is limited to an operation range between 10-100% of its nominal design capacity. On the other hand, Proton Exchange Membrane (PEM) electrolysers which can work between 0-160% of its operation range. Indeed, this type of electrolyser can go from zero load to 160% of its design capacity so it can be overloaded up to 160% of their nominal capacity for some time if the plant and power electronics are designed accordingly. However, even if this technology involves higher costs than Alkaline electrolysers, it seems to be the method employed in the coming years due to its evolution in terms of efficiency and price. Finally, SOEC electrolysers are also an additional alternative. However, this technology still in development and it is only considered in long term scenarios, [9]. The second type to produce hydrogen is from natural gas, not been carbon free process, and also not the focus of this thesis.

Regarding storage and transport issues, it is necessary to consider factors such as the production location, the distance to the end user´s location, the time that elapses from its production to its consumption or the final application. This section will be reviewed in the next chapter.

The Spanish agenda refers to the fact that hydrogen can be shipped in a liquid state as Ammonia or LOHC (Liquid Organic Hydrogen Carriers), in gaseous conditions, liquified or combined with other gases. Road transportation for short distance can be performed using liquid or compressed hydrogen. However, it is important to emphasize the fact that the quantities transported differ according to its state, being more profitable to move liquid hydrogen because of the relation quantity price (0,13€/kg) compared with the gaseous hydrogen (~2,2€/kg) if the cost of compressing or liquifying is excluded. Railroads can be used for bulkier transport. The tanks employed have more capacity than those used for liquid hydrogen and the trailers used for compressed hydrogen. Maritime transportation is reserved for hydrogen melted as Ammonia considering that that state is the preferable one for long distance.
On the other hand, gaseous hydrogen could be transported using the actual infrastructure of the gas sector by injecting renewable hydrogen in the gas pipelines. However, it presents some restrictions to be injected as the adaptation of the pipeline to accept hydrogen or the maximum percentage that can be melted (10-20%).

Focusing on hydrogen storage, for a short-term utilization and in small scale, the most developed technology is the high-pressure deposits. It is used for gaseous hydrogen and need pressures around the 350-700 bar requiring very resistant materials. Nevertheless, the installation of subterranean tanks with pressure up to 800 bar is under research. On the other side, for high amounts and long-term storage, is not yet viable doing it employing tanks because the energy employed would be too high. Therefore, some researchers are analyzing the possibility to use salt caverns, aquifers and depleted deposits of natural gas and oil to solve this problem.

From an economic point of view and according to a conference carried out by Aleasoft and PwC, [16], for hydrogen to be competitive versus gas as a fuel in the industry, its price has to decrease up to 2€/kg, and this will depend also on the gas price evolution, the CO2 emissions rights and the capacity of renewable production installed.

In conclusion, the role of hydrogen on a circular economy can be as an energetic storage, incorporated on the gas pipeline or, in the electricity sector, giving more flexibility to the electrical network by, for example, profiting from the renewable electricity surplus not consumed at the time it is produced by other system demands. Hydrogen offers a great breadth to the operator of the electrical system both to offer resilience and to offer flexibility to big scale.

2.2 HYDROGEN ECONOMY AGENTS

In this section, an analysis of the actual and future hydrogen value chain will be made. The section will be divided following the hydrogen value chain, from production to demand. Therefore, each subsection will be focused on one of the agents that takes part: producers, storage, transport and demand or final uses.

As a synthesis, the following figure shows the hydrogen value chain listed above:

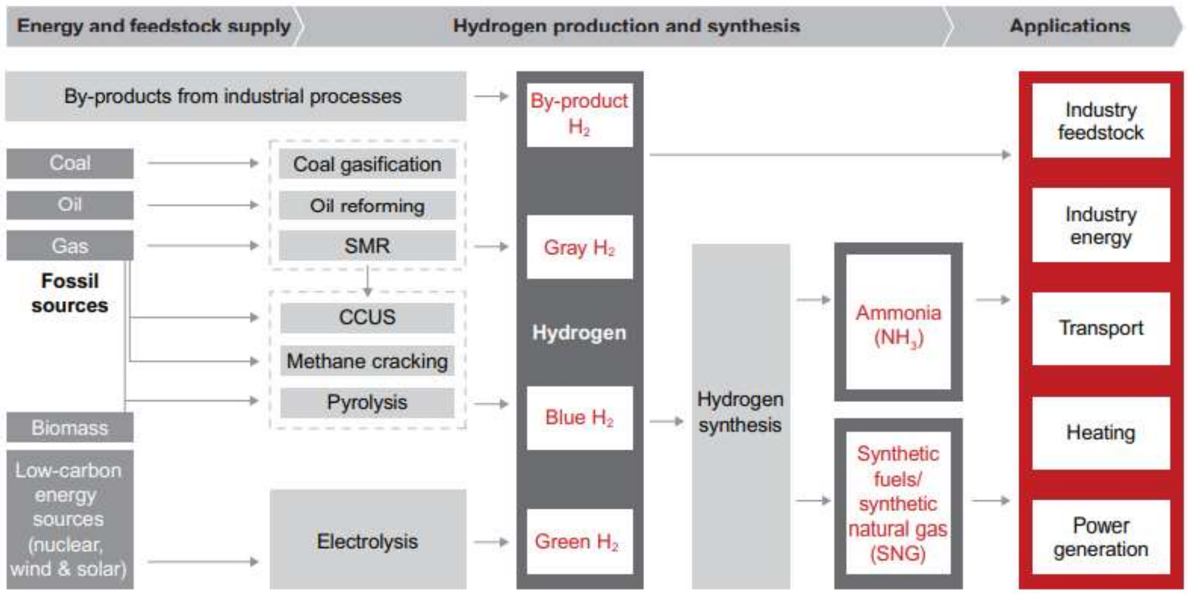

Figure 2. Hydrogen value chain. Source: Bain&Company [17]

2.2.1 PRODUCTION

Going into more detail through the different agents of the hydrogen economy, the production of hydrogen has been based for years in natural gas (76%) and coal (23%). It consumes up to 205 billion m3 of natural gas and 107 Mt of coal around the world. As a consequence, its production is responsible for 830 $MtCO_2$/year which are the annual emissions of Indonesia and United Kingdom combined, [11], or the 2% of global CO_2, [18].

The most widespread method to produce hydrogen from natural gas is reforming. There exist three methods: steam reforming (with water as oxidant and a source of hydrogen), partial oxidation (with the oxygen in the air as an oxidant) or the combination of both methods called autothermal reforming (ATR). The first one, steam reforming, is employed to obtain hydrogen from natural gas, liquefied petroleum gas and naphtha. Partial oxidation is used to extract H2 from heavy fuel coal and oil. Other processes are gasification (raw material turns into a synthesis gas that is transformed into CO_2 and hydrogen) and electrolysis which is minority in total hydrogen production today, mainly used in the chlore-alkali industry as a by-product.

However, it is important to highlight that in the Sustainable Development Scenario, Low - carbon hydrogen produced through water electrolysis or with CO_2 capture will account for 99% of global production in 2070 and more than a half will be using electrolysers, [18].

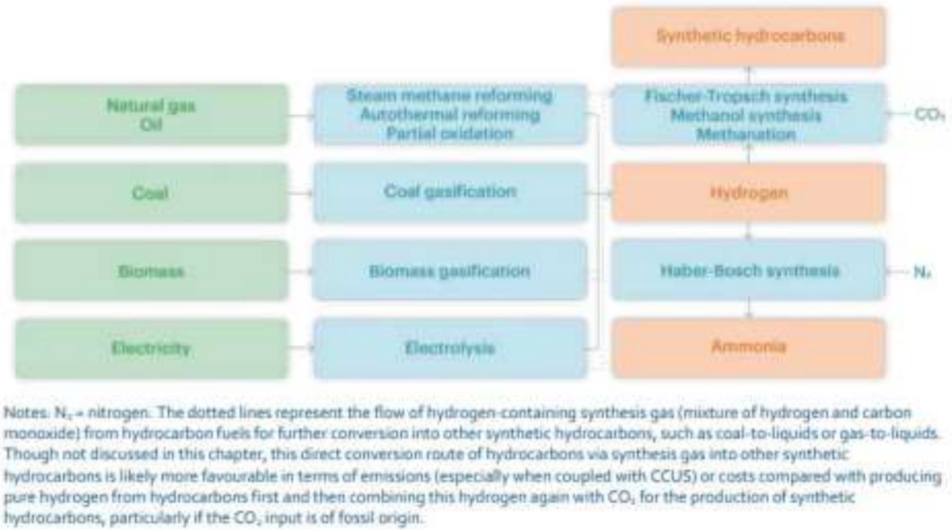

Figure 3. Potential pathways for producing hydrogen and hydrogen-based products. Source: IEA

Even if there exist diverse methods to obtain hydrogen (see Figure 3), this report focuses in the hydrogen produced from electrolysis as it is going to be the process used in the near future to decarbonize. Therefore, this research includes a more exhaustive explanation of the hydrogen produced from water and electricity.

Water electrolysis is an electrochemical process that divide water in oxygen and hydrogen. Today, only around a 0,1% of hydrogen produced comes from water electrolysis and the majority is used in high-purity hydrogen markets as electronics.

Furthermore, looking at a future scenario where the costs from renewable electricity could decrease, in particular due to the increment of solar PV and wind production, interest in electrolytic hydrogen is increasing. The efficiency of electrolysers lies between 60% and 81% depending on the technology and the load factor. To produce all of the current used hydrogen (69 MtH2) using this process, it will require an electricity demand of 3600 TWh, more than the total annual electricity production of the EU, [11].

Electrolysis needs water as well as electricity. In alkaline eletrolysers, producing 1 kg of hydrogen requires 9 L of water and it generates 8 kg of oxygen as a by-product. If all of today's hydrogen were produced with electrolysers, this would result in a water consumption of 617 million m^3 which corresponds to 1.3% of the water consumption of the global energy sector, [11]. In addition, it is interesting to comment that freshwater access can be a problem in water-stressed countries and using seawater could be an alternative especially in coastal areas.

As it has been introduced before, three main technologies are used today, alkaline, PEM (Proton Exchange Membrane), SOECs (Solid Oxide Electroysis Cells), [19].

- Alkaline electrolyser: Is the most mature technology. Its operating range goes from a load of 10% to full capacity 100%, however, this information varies depending on the source. This type of technology is characterized by relatively low capital costs due to the avoidance of precious materials.
- PEM electroyser: They use pure water as an electrolyte solution to avoid the recovery of the potassium hydroxide electrolyte solution needed in Alkaline electrolysers. They can produce highly compressed hydrogen for decentralized production and for storage. It offers flexible operation including the possibility to provide frequency reserve. Its operating rage goes from 0% to 160% of design capacity. However, they need expensive materials as platinum or iridium and they lifetime is shorter than the first type analyzed. For that reason, the overall costs are higher than those of alkaline electrolysers.
- SOEC: is the least developed technology and they are not being commercialized yet. They use low material costs, and they have a high efficiency thus, some companies are aiming to bring them to market. They use steam so they need a heat source. Therefore, if the hydrogen is used to produce synthetic hydrocarbons (power-to-liquid and power-to-gas) the waste heat can be used for further SOEC electrolysis. Furthermore, it is the only technology which can operate in reverse mode as a fuel cell, [19], converting hydrogen back into electricity, meaning that it can provide balancing services to the grid.

The information analyzed before is synthetized in the following table. Furthermore, it adds some other interesting parameters of the technologies described:

	Alkaline electrolyser			PEM electrolyser			SOEC electrolyser		
	Today	2030	Long term	Today	2030	Long-term	Today	2030	Long term
Electrical efficiency (%, LHV)	63–70	65–71	70–80	56–60	63–68	67–74	74–81	77–84	77–90
Operating pressure (bar)	1–30			30–80			1		
Operating temperature (°C)	60–80			50–80			650 – 1 000		
Stack lifetime (operating hours)	60 000 – 90 000	90 000 – 100 000	100 000 – 150 000	30 000 – 90 000	60 000 – 90 000	100 000 – 150 000	10 000 – 30 000	40 000 – 60 000	75 000 – 100 00
Load range (%, relative to nominal load)	10–110			0–160			20–100		
Plant footprint (m^2/kW_e)	0.095			0.048					

Figure 4. Techno-economic charaterisitcs of different electrolyser technologies. Source: IEA

	Alkaline electrolyser			PEM electrolyser			SOEC electrolyser		
	Today	2030	Long term	Today	2030	Long-term	Today	2030	Long term
Electrical efficiency (%, LHV)	63–70	65–71	70–80	56–60	63–68	67–74	74–81	77–84	77–90
CAPEX (USD/kW_e)	500 – 1400	400 – 850	200 – 700	1 100 – 1 800	650 – 1 500	200 – 900	2 800 – 5 600	800 – 2 800	500 – 1 000

Figure 5. Techno-economic charaterisitcs of different electrolyser technologies. Source: IEA

New electrolysers are being isntalled over the last decades, specially using PEM technology. Geographically, most of the projects are in Europe. The average unit size goes from 0.1MW in 2000 to 1MW in 2019. However, projects with a higher capacity are in development.

In terms of production costs, they are influenced by different technical and economic factors as CAPEX, conversion efficiency, electricity cost or annual operating hours.

The CAPEX costs are influenced by the electrolyser operating hours. When the operating hours increase, the levelized cost of hydrogen decreases and the impact of electricity costs rises. Furthermore, a higher utilization rate of the electrolyser leads to a fall in the production cost of a hydrogen kilogram. In conclusion, higher utilization rates help to decrease the impact of CAPEX in hydrogen cost. Nevertheless, for electrolysers connected to the grid a higher utilization rate means higher electricity prices. Therefore, in those cases, the lowest costs are acquired in mid-load operation [11].

In Spain, the evolution of solar and wind technologies is an interesting scenario for the hydrogen implementation. Centralized wind is a potential technology due to the important growth of the installed capacity of these production plants. The big advantage of producing hydrogen in big wind farms is that it corrects the problems with hydrogen integration in the electricity grid.

However, after the research in [20], made by PTE HPC (Plataforma Tecnológica Española del hidrógeno y de las pilas de combustible) the production method with the greatest potential for Spain are biomass plants because of its flexibility and versatility.

It is important to indicate the perspectives in terms of hydrogen production for Europe and, in more detail, for Spain.

The EU Hydrogen Strategy sets an ambitious challenge for 2030, 40 GW of electrolyser capacity within Europe. In addition, 40 GW installed in countries as Morocco from which Europe could import green hydrogen, [21]. To achieve it, the European Commission sets a target for 2024 of 6 GW of electrolyser electrical power installed. In addition, it remarks that the global investments in electrolysers planned to be working in 2030 have increased from 3.2 GW to 8.2 GW since March 2020. From this installed capacity, 57% will be implemented in Europe.

However, even if the production will be based on green hydrogen in a future, in the medium-term other forms of low carbon hydrogen technologies will be needed. To illustrate it, the European Union suggested an investment for 2050 of €180-479 bn for renewable hydrogen and €3-18 bn for low-carbon fossil-based hydrogen. In the short term, the investments in electrolysers could range €24-42 bn. This investment appears to cover only the electrolyser cost (at a mid-range of €900/kW) without the cost of infrastructure or other plant costs. They also expect 80-120 GW of solar and wind installed capacity. Today the costs for green hydrogen is around 2.5-5.5 €/kg which is 65-135 €/kWh, [22].

In addition, in Spain the potential in renewables energies and the action policy that stimulate its implementation, could allow to reach a privileged position in the European energy market. Following the path determined by the EU Hydrogen Strategy, it estimates the installation in Spain of 4 GW that will be located close to the consumers, industries or for the supply of hydropower. The objective is to minimize the cost associated to transport and storage. For 2024 the objective is to have an installed capacity between 0.3 and 0.6 GW, [3].

2.2.2 DEMAND

In 2019 hydrogen demand was 75 MtH2 but it is expected to increase by 2070 to 520 MtH2 considering the Sustainable Development Scenario[18]. Today, hydrogen is employed mostly for industrial applications. The main uses today, in pure and mixed form, are oil refining (33%), ammonia production (27%), methanol production (11%) and steel production (3%) and as it has been explained before all this hydrogen is supplied by fossil fuels. In fact, more than 60% of hydrogen produced for refineries comes from natural gas. However, tougher decarbonization policies could rise the use of green hydrogen in refineries up to 7% by 2030, [11]. In the ammonia and methanol sector, it is expected an important increase in the medium term using natural gas with CCUS or electrolysis but following a low carbon strategy.

However, by 2070 the use of hydrogen in the transport sector will increase exponentially accounting for 30% of the hydrogen produced (see Figure 6). In this scenario, industry uses will be only a 15%. As it can be seeing in Figure 6, other important uses in future hydrogen economy will be Synfuel production (synthetic fuel obtained from a mixture of carbon monoxide and hydrogen), buildings, or power.

In addition, the high versatility of hydrogen would be an important quality for the integration in the different energy sectors. As it is considered in [3], the hydrogen could be used for energy storage. Long- and short-term storage employing green hydrogen, will help to enhance the use of the actual power infrastructure as less energy would be wasted. Furthermore, stored hydrogen could be used in different applications. Some of these applications would be fuel cells or as an intermediary in technologies Power-to-X (conversion technology to transform the stored excess of electricity into gas, heat or liquid, [23]). Another example of its application is its integration in the electricity sector giving more manageability to the grid absorbing the excess of renewables and offering flexibility and resilience to the system operator. In addition, in the gas sector, it offers the possibility to incorporate it gradually to the gas grid using the infrastructure that already exists. However, it is important to indicate that the blending implies losses in the value of the hydrogen in addition to the technical difficulties to the subsequent separation. This application will be analyzed in the following pages.

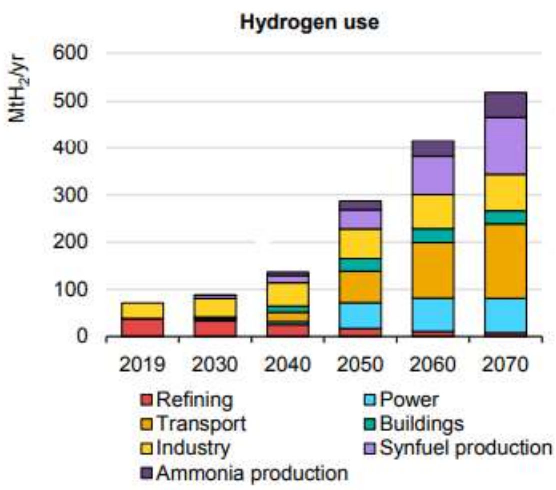

Figure 6. Hydrogen uses evolution. Source: IEA

However, the big uses of hydrogen will be in transport sector and industry sector.

- **Transport**: the fuel based in hydrogen would be used in different transport technologies. Following [18] , 52% will be for shipping, 40% for aviation and a third on road transport. In the document published by the Hydrogen Council, the target for

2030 is to have globally, 10 to 15 million cars and 500.000 trucks fueled with hydrogen. By 2050,the goal is to have up to 400 million vehicles(25%), 5 million trucks(30%) and more than 15 million buses (25%), [24].

In Spain, the demand would be centralized in the transport sector. In particular, it would be focused on the road transport. In this sector, the hydrogen produced would go to mobility applications due to the development of the actual electricity and natural gas infrastructure. Its development would help to ensure its growth in road transportation. In this context fuel cells would be an important asset for the progress of the hydrogen implementation.

However, the introduction of any technology depends on its rentability. It would be determined by the investments made in fixed costs for vehicles development and infrastructure and in variable costs. Fixed and variable costs would determine hydrogen price. It is estimated that for 2035 the hydrogen vehicles will be competitive versus the conventional ones. Furthermore, it is estimated that the inversion could be recovered by 2030, [20]. However without a political support these dates seems to be excessively optimistic, [20].

Furthermore, the position in the transport market is privileged due to the important vehicles market that exists today. The use of fuel cells in combination to batteries (FCHV) will be a competitive option over the electric vehicles especially in heavy transport. It would allow to reduce the charging time and increase the distance before refueling. However, the cost-effectiveness of these vehicles will be lower if it is considered the energy to produce green hydrogen, [25].

Analyzing each transportation method, it can be concluded that:

- Road transport: It includes light and heavy vehicles. According to the data published by the General Direction of Traffic, today, there exist 10 vehicles using hydrogen fuel cells. However, they belong to demonstration projects. In the heavy sector the results are more encouraging. At international level, there are important pilot programs studying the feasibility of using hydrogen. An example of these programs is the truck Hyundai XCIENT, [26]. In Spain, by 2030 the expectation is to have 150 buses and 5000 light and heavy vehicles. In the roadmap is also included the implementation of 100 hydrogen refueling station which is less than 1% of the gas stations installed in Spain.

- Railway transport: Nowadays, the railway sector uses mainly electricity. However, there still existing train tracks without electrification or trains that use diesel. The option of hydrogen is a good option in the cases where electrification is not viable. In the Spanish hydrogen roadmap is considered the implementation of 2 railways boosted by hydrogen by 2030.
- Marine transport: This sector not only considers the use of fuel cells but also, the hydrogen to fuel the machinery used in seaports. However, its viability is currently under study and limited to demo projects. It is interesting to highlight the H2Ports initiative, [27], which is the development of a pilot project in Valencia port to incorporate hydrogen in the logistic operations with the objective of reducing the environmental impact.
- Aviation transport: As it occurs in the marine transport, it is expected that the fuel cells will be an alternative to boost the airplanes and for the machinery employed. It is also interesting the use of hydrogen to produce synthetic fuel as the biokerosene. As an example, Airbus has created its first hydrogen-powered prototype aircraft, [28].

• **Industry**: It would account up to 20% of hydrogen demand, being 15% for the iron and steel sector as a remission-reducing agent, [18].

  In Spain, this sector represents a demand of 500.000 tonnes of gray hydrogen annually. Practically everything is produced in the plants that produce ammonia or in the refineries located in Huelva, Cartagena, Puertollano and Tarragona. In Puertollano, it is interesting to indicate that the construction of an electrolyser is taking place. The project contemplates an installed capacity of 20 MW, [29]. This fact reflects the high potential to decarbonize the industry using green hydrogen. In this sense, there exist three application fields:

  - Refinery Industry: the hydrogen is used to eliminate the crude oil impurities. In addition, it would help to improve the heavy applications as its employment as raw material.

- Chemical Industry: due to its molecular composition, hydrogen is used as a raw material to produce chemical products as ammonia or methanol which require high quantities of hydrogen. At the same time, it is used to produce fertilizers, biofuels, or plastics.
- Metallurgical Industry: in this sector, hydrogen is used to produce some alloys that need high energy quantities as steel. It would be used as an energy source to reach the temperatures required in its production process. It can also help to reduce the use of coal in these processes.

In this sector, the Spanish hydrogen roadmap set ambitious objectives. The main one is using 25% of green hydrogen for industrial purposes.

However, it is also interesting to highlight the role of hydrogen in powering or heating building using fuel cells with cogeneration (CHP). The potential in this sector is up to 2.5 million CHP in Europe by 2040, [30].

In addition, it is also interesting to analyze the hydrogen role in the gas industry:

- Power to Gas: In this sector, hydrogen could substitute some final uses that gas has today in industry, for heating or power uses, etc. A good example is its employment in production plants.

  It can be blended up to a 20% with natural gas, converted to a synthetic natural gas or replace natural gas in dedicated hydrogen grids. It can be used in gas turbines in thermal power plants or cogeneration plants. However, today the hydrogen melted is limited to a 1-5%. By his side, it is in process to arrive to 15%. Nevertheless, it is important to indicate that in Spain, the normative (PD-01 NGTS, [31]) stays that the maximum hydrogen injected in the natural gas is 5%, [32]. Blending 3% of hydrogen in natural gas demand globally would require 12 MtH2. If it came from electrolysis technology it would need 100 GW of installed capacity, which might reduce the electrolyser´s capital cost in a 50%, [11].

However, the optimal blending strongly depends on characteristics of the existing network. Some studies show that up to 10-20% of hydrogen blended will not require major investment or modification, [38]. The most critical application are gas turbines, [39], and compressed natural gas tanks. Concentrations greater than 20% will require significant changes in the existing infrastructure.

The reasons why Power to Gas is an interesting option are, firstly, because is an easy solution to couple production and demand. It transforms the excess of renewable energies in hydrogen that is easily transported as an additive in the natural gas grid or as a synthetic natural gas. Secondly, it is an optimal solution for energy storage and could increase the use of wind in 20-50% by storing the energy surplus. Furthermore, the actual gas infrastructure is so extensive, and therefore, it could allow more renewable penetration. Its capacity is around one order bigger that the electricity network. The storage capacity is also bigger. In TWh, electricity has a storage capacity of 0.04 and Natural gas has 210, [33] (see Figure 7). This highlights the potential of melting hydrogen in the gas grid.

In this context, the target for 2030 is to have around 6.5 million households heated with blended or pure hydrogen which is about 3.5 million tons of hydrogen. Furthermore, 10% of users connected to the natural gas – hydrogen network will use fuel cell combined with heat and power units to decarbonize this sector. By 2050, the expectation is having an 8% of buildings globally, using hydrogen for heat and power applications.

2.2.3 STORAGE

The energy storage is a key element to bring flexibility to the power system and to increase the renewable energy integration. Furthermore, it brings the possibility of storing energy during periods of overproduction or energy surplus to use in deficit moments. The seasonal storage considers the option of producing large quantities of hydrogen in summer to use it in winter.

Hydrogen produced can be deployed in different states. Depending on the storage or transportation method, there are different options. The most important ones are Gaseous, Liquified, Ammonia or LOHC, [3].

LOHC or Ammonia hydrogens´ carriers, as methanol or MCH, are substances easily transportable employing the actual supply networks. Ammonia stands out because of its molecular structure but also because it has its own infrastructure developed.

The problem of having hydrogen in gaseous form is its low density, [34], (3 kWh/Nm3 when a lithium-ion battery has 500kWh/Nm3, [35]). It deteriorates the storage for large scale and long distance. However, this same property, makes easier the compressed storage for example for mobility. Furthermore, the hydrogen in gaseous form can be transported through a dedicated hydrogen grid or, as it is going to be analyzed, blended with natural gas in the actual natural gas grid. However, this last option implies losing some of its intrinsic value and some energy in separating the two gases (gas and hydrogen).

The last option, liquified hydrogen is advisable for large-scale storage. However, if it is also for a long period other alternatives are better. The liquified option requires high quantities of energy to maintain hydrogen in liquid state as it will be studied after.

Today, hydrogen is stored in gaseous or liquid forms in tanks for small-scale and stationary applications. Nevertheless, the increasing operation of large-scale applications and the hydrogen global deployment would require a wide variety of storage solutions.

The optimal storage solution for each hydrogen application depends on the volume stored, the storage duration, the speed of discharge and the geographic availability of the different possibilities. In general, two types of storage can be identified, geological and tanks reservoirs. The first one is more common for large-scale and long-term and the second one, is more suitable for small-scale and short-term.

- Geological storage: Salt caverns, depleted natural gas and oil reservoirs or aquifers are the mainly options for this type of hydrogen storage, [36]. Nowadays, they are used for natural gas storage. These storages supply important economies of scale, high efficiencies, and low operational and land costs. These aspects mean that they are good options to be the lowest-cost possibilities for hydrogen storage even though hydrogen has lower energy density that natural gas.

  Salt caverns have been used for a long time to store hydrogen because of the high efficiency (around 98%, [11], [37]), the low risk to pollute the hydrogen stored and the low cost. Their high pressure facilitates high discharge rate when hydrogen needs to be extracted. This makes this type of storage interesting for industrial and power sectors.

  Oil and gas reservoirs are typically larger that salt caverns. However, they are more permeable and have contaminants that must be removed before hydrogen is extracted.

  In Spain, the useful capacity for using gas caverns for hydrogen storage is 29.141 GWh, [32]. The percentage of hydrogen blended, as it has been analyzed before is 10% with some limitations as the percentage in gas turbines (1-5% of hydrogen) or the PD-01 that limits the hydrogen blended to 5%.

  Using the actual gas grid is a good option in Spain. Companies as Enagas that has 11.000 km of gas pipelines could use them to store hydrogen. Furthermore, they have an underground hydrogen storage potential of 61.700 GWh, [29].

  In addition, as it can be seen in Figure 7, the potential against electricity lies in the capacity to store hydrogen. In the natural gas grid the storage potential is up to 5000 times the storage potential in the electricity grid.

		Electricity	Natural gas
Consumption	TWh /a	610	930
Average power	GW	70	105
Storage capacity	TWh	0.04	210

Figure 7. Hydrogen´s potential in gas grid. Source: Enagas

Aquifers are the least mature storage technology. They were used for years to store gas with 50-60% of hydrogen. Nevertheless, as oil and gas reservoirs, natural barriers trap most of the hydrogen underground. In addition, reaction with microorganisms, rocks and fluids can provoke losses of stored hydrogen. As it is under investigation, their costs are higher due to exploration and development costs. Furthermore, its feasibility has still to be proven.

In this sector a project that stands out is HyGreen Provence, [40], which develops a Solar PV plant that will convert electricity in hydrogen to be stored in salt caverns ready to be used to fuel a public bus float.

- Storage tanks: It is the most mature technology. Tanks for compressed or liquified hydrogen have high efficiencies (its value depends on the paper consulted, around 99%, [11], or 90-85%, [41], and there exist other papers that considers efficiencies around less than a 50%, [42] for compressed hydrogen) and high discharge rates making them the optimal option for small-scale applications where a local stock needs to be easily available.

  Compressed hydrogen (350-700 bar pressure) is equivalent in energy density to a 15% of gasoline energy density, [11] which means that to store the same amount of energy at a vehicle refueling station it would require around seven times the space. In addition, it requires 15% of energy to compress it, [35], [43] and [41].

By his side, liquified hydrogen needs cryogenic temperatures lower than -252,8ºC, and the energy consumption is even greater than for the compressed hydrogen since it needs 30% of the energy to compress it, [43], [41]. The percentage of remaining hydrogen for an initial amount of with 20.000 m^3, is, after six months, one year or two years are 99,94%, 80,33% and 33,4% respectively, [44].

Ammonia has a greater energy density so it will reduce the space needed to store it however, its advantages must be weighed against energy losses and equipment investment for conversion and reconversion when pure hydrogen is needed. For vehicle applications, compressed hydrogen tanks have a higher energy density than lithium-ion batteries which enable greater ranges in cars and trucks.

The main advantages of hydrogen storage are, firstly, discharge rates and storage tank capacity are independent variables, the modular construction, the applicability to a wide range of sizes and power inputs and that it is eco-friendly. However, the main drawbacks are the high costs, [42].

In this type of storage, research is looking for finding ways to reduce the space needed to store the hydrogen which will be useful in densely populated areas, [42], [45], [43]. This includes looking at underground tanks that tolerates 800 bar pressure and can enable greater compression.

2.2.4 TRANSPORT

The low energy density of hydrogen requires high quantities of energy to maintain it. This means that it is very expensive to transport it over long distances. However, there exist a wide variety of options to face this problem. In many countries, there is an extensive gas network that could be used to operate with hydrogen. In addition, new infrastructures can be developed with dedicated pipelines, shipping networks, etc.

Even if the option of blending hydrogen has been studied in the previous sections as it can be considered a storage method and a type of demand, a brief analysis from the transport point of view will be settled out in the following paragraphs.

Blending hydrogen in the actual natural gas grid has the main advantage that it avoids the significant capital cost involved in developing new transmission and distribution infrastructures. If some of this structure is used to transport hydrogen, it could develop the actual hydrogen value chain.

Furthermore, it is important to remind the main advantages of this technique. It allows to coupling production and demand transforming the renewable energy excess in hydrogen. This hydrogen can be easily transported as an additive in the natural gas grid or as a synthetic natural gas. Furthermore, it would help to increase the security of supply as you guarantee the storage of renewable energy excess in hydrogen that can be used later. In addition, natural gas has many other applications where hydrogen, as it has been analyzed, can be blended with a little adaptation.

However, this technique must face numerous challenges, as the low density of hydrogen, the risk of flames spreading or how it would affect to some industrial processes.

Another option to transport hydrogen is with vehicles or cargo ship. The tanks used to store hydrogen can be delivered using those type of transport. However, it is important to know that depending on the hydrogen state, the transport must be one or another.

In road transportation, the hydrogen must be in liquid or gaseous form. The tube trailers can put up with 360 kg of compressed hydrogen and 4.300 kg of liquified hydrogen, [3]. By his side, the distribution with tanks gives more flexibility allowing the supply in different purities and quantities. If hydrogen becomes a globally used fuel for vehicles, tankers could be used for refueling filling stations. It is estimated that delivering using liquid tankers can cost around 0.13 €/kg.

Tube trailers are used for small customers that are close to the hydrogen production in order to reduce the cost related to carry small amounts of hydrogen. The big advantage of this type of transport is the flexibility. This means that it can also be used to deliver hydrogen for users that are not yet connected to the network. The cost of transport using tube trailers is around 0.6 €/kg over a distance of 100 km excluding compression cost. Considering compression cost, the price for tube trailer transport can go up to 2.2 €/kg, [41].

By his side, the railway transport, as in the road one, uses tanker trains to transport hydrogen. In this case, the maximum volume is greater, with capacities between 2.900 – 9.100 kg of hydrogen, [3].

The last one is the maritime transport. The tanks used in this type of transport has capacities of 70 tonnes of hydrogen, [3] which allows the delivery of big quantities and for long distances, [3].

As summary, normally, gaseous hydrogen is transported using tube trailers (they are currently 26 m3 and are at 500 bar for a load of 1100 kg, [46]) or pipelines. On the other hand, liquid hydrogen is moved by road tankers (tubes trailer with a volume of 50 m3 can transport around 3500 kg at a density of 70.8 kg/m3, [46]). For short distances, and small amounts, gaseous hydrogen via tube trailers is usually the best option.

The following figure synthetize the main ideas that have been mentioned. As it is reflected, depending on the distance, the type of transport might be from one type or another. Furthermore, it shows the amount of hydrogen that can be transported (see Figure 8).

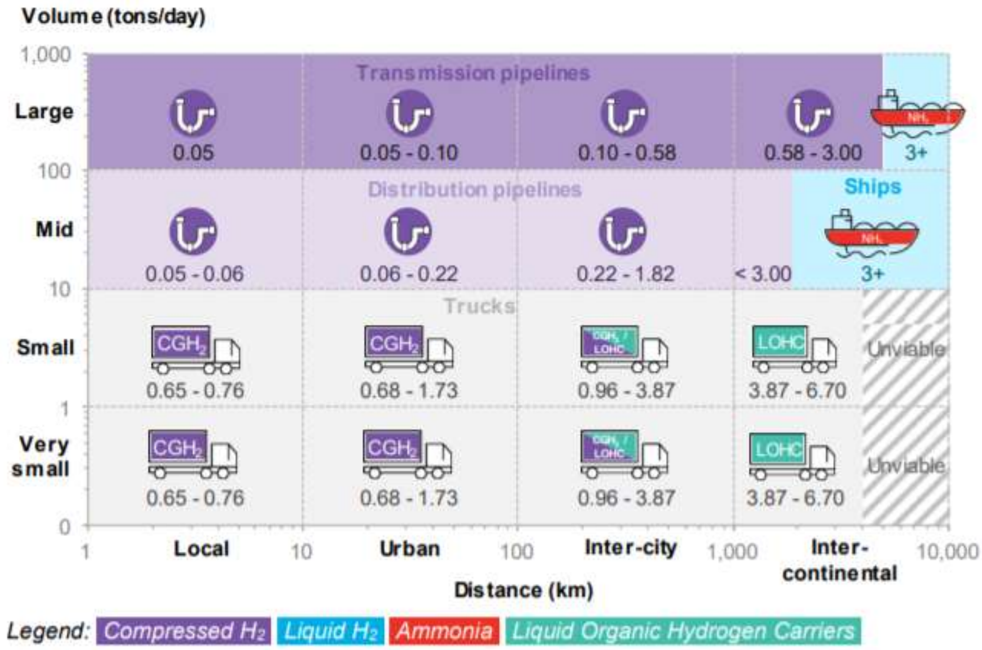

Figure 8: H2 transport costs based on distance and volume, $/kg. Source: Bloomberg NEF, Hydrogen Economy Outlook.

3. CEVESA MODEL

This chapter describes CEVESA Model, in order to be able to understand the hydrogen model included. In addition, the hydrogen Model with storage and "reelectrification", will be also explained and exposed. The hypothesis adopted and the equations employed are also included.

3.1 DESCRIPTION OF THE CURRENT CEVESA MODEL

CEVESA, [25], is a dynamic model for operation and expansion of the production plants of the power system (assumed as a single-node). It allows to analyze the interaction between hydrogen and the electricity system, and the impact on the electricity price of the hydrogen production. It is a good approach to the reality of the electricity system. Its improvement could be an asset for the future of a green electric sector.

It computes investments by, distributed clients in Distributed Energy Resources (DER: production and storage) and by production companies (GENCOs) in Centralized Resources (CR: traditional thermal production, renewable plants and centralized storage). It dispatches different types of production units (hydro and thermal) in order to meet an established demand and secondary reserves, considering the technical restrictions that the plants have, [7], [47]. The plants defined are modeled with a high level of detail. The model considers type of technology, minimum outputs, CO2 emissions, ramp limitation, etc.

In addition, it is also related to the transport sector. It incorporates investments decisions on Electric Vehicles (PEV), Internal Combustion Engine Vehicles (CEV) and the impact of H2 Combustion Engine Vehicles (H2CV) and H2 Electric Engine Vehicles (H2EV). These investments, consider infrastructure deployment, fuel, environmental and social cost of the technologies before named.

The basis of the model is a "conjectural-variation equilibrium with price-response conjectures with hourly detail, energy and endogenous secondary reserve requirements, ramping constraints, and start-ups and shut-downs" as it is defined in [48].

The equilibrium model only considers one level decision of investment and operation, and it is solved as an equivalent quadratic minimization problem, which simplifies finding the optimal solution.

The model is run following an hourly balance of production and consumption. It considers the constraint of covering the peak demand that guarantees the adequate production capacity for a certain security of supply. Both considerations are linked to the maximization of GENCOs profits and minimization customers´ energy bill taking into account tariffs and DER investments.

Furthermore, GENCOs' power plants are represented on a per-offer-unit basis until their expected closure year, but, new investments are computed on a per-technology basis. They can invest in new capacity in combined and open cycle gas turbines, solar photovoltaic (PV), wind and storage technologies. By his side, Distributed customers can sell and buy energy into and from the grid attending to the different energy tariffs depending on the type of transaction. A tariff power term is also applied to them and is proportional to the maximum power extracted from or fed into the grid. Clients can make investments on distributed wind, solar photovoltaic (PV) and storage technologies and batteries. Clients are divided in 12 clusters according to their activity sector. The options are industrial, commercial, or residential and the subsectors are food, paper, chemistry for industrial customers, metallurgy, single family or block for residential customers, and food, restauration, or services for commercial customers.

On the other hand, in the transport sector, the total system cost considering PEV and ICEV is minimized from a social perspective, being the main link between the electricity sector and the transport one, the output variable, the electricity price. The usage profile of these vehicles is an hourly profile which allows a more precise representation of the interaction of PEV technology and the renewable, hydro, or thermal production.

In addition, it uses a cost-benefit model that considers the infrastructure costs (charging points, expansion of the actual distribution network, etc.) and some external factors as the health impact, climate change in order to obtain global costs and benefits of the PEV and ICEV investments.

CEVESA can also consider different EV penetration percentage. These vehicles can function in four different modes, dumb or smart charge, smart charge-production, and smart charge-production-reserve. If they are operated in any of the smart strategies named before, they are centrally dispatched as one different unit and contribute to optimize the system operation.

In terms of renewable energy, it is also possible to consider different penetration percentage over the base wind and solar energy production. It is done using a homothetic transformation that modifies the fixed production profile considering that the profile does not change over the time. This energy does not act as a marginal technology excepts when there is a production excess. In that case, there are spillages, and the marginal price is zero. It is therefore, a "predispatched" production, subtracted from the demand so that the remaining net demand is supplied with thermal and hydro units.

Considering the aspects analyzed above, CEVESA is well suited to simulate future scenarios with different EV or renewable penetration, CO_2 emissions cost, installed capacity for the different technologies, demand evolution, etc. Each scenario will return, in addition to other results (see in Figure 9), the hourly energy price, the hourly production for each unit, CO_2 emissions per units and the hourly reserve price which are the inputs for the financial model.

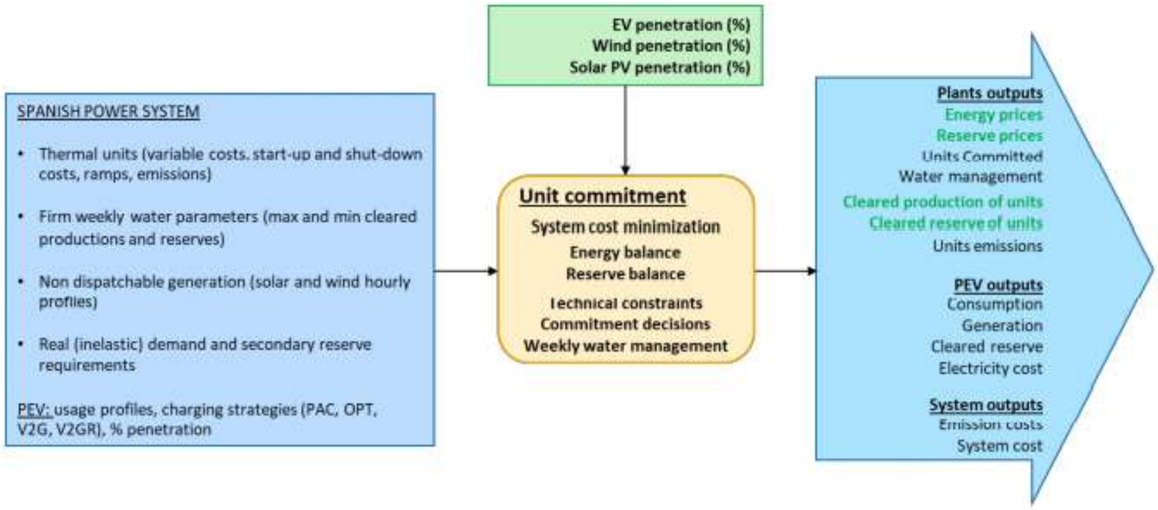

Figure 9. Unit commitment model of the Spanish electric sector. Source: IIT

3.2 CEVESA H2 MODELLING IMPROVEMENTS

In order to extend the actual CEVESA model to include the new hydrogen perspectives, some amplifications must be done. In order to include the agents that will take part in this new power model (production, demand and storage), new equations must be added.

3.2.1 HYPOTHESES

The model proposed, will have three main pillars: production, demand, and storage. This section also explain why transportation was not included in the model. This consideration was made considering that the hydrogen transport costs as customs or gasoline costs can be reduced or removed.

An important assumption for solving the cases is that the Spanish and the Portuguese systems are treated like two separate modules. This means that the process of hydrogen production, consumption and storage is different for each country.

On the other hand, the hypotheses adopted to develop the model will be explained following the structure of the hydrogen agents involved:

- Production: In the model proposed, the production is assumed to be centralized which means that a unique electrolyser feeds all the demand (the demand is also assumed to be centralized, i.e., it does not consider the location of the different consumers). In a first approach, the price for the installed capacity will be the same for all the years considered.

  The capacity installed to produce hydrogen is an input parameter. However, the impact of different hydrogen capacity production was analyzed in the simulated scenarios.

  The model considers that the hydrogen produced can be stored or used to supply the external hydrogen demand. In addition, the hydrogen produced in one hour can be used in the same hour to supply the external hydrogen demand. This is a reasonable assumption, taking into account that hydrogen is often produced in the same industry where it is used, [11].

  On the other hand, the hydrogen is produced using a unique electrolyser. Electrolysis processes require electricity. Therefore, the hydrogen produced represents an electrical demand for the system.

  The efficiency of the electrolyser is based on the information gathered in [11] and [3]. In 4.1 (Input Data) the values employed will be showed.
- Demand: A unique consumption node is considered. This node represents the different hydrogen demand types explained in 2.2.2. The sector considered are transport, industry, power and heat (Power to Gas), [3], [24]. In addition, taking into consideration that during the following years this demand will increase, a growth rate has been applied. However, a more detailed explanation of the demand growth used will be exposed in the next chapter. Therefore, depending on the year simulated, the input demand will be different. The production and the demand are both given in GWh considering the efficiencies involved in the process.

  On the other hand, the demand coverage is assumed to be weekly, and a weekly storage management has been modelled. Thus, this consumption can be covered using hydrogen produced in the same hour or previous hours where it was stored.

- Storage: The storage is also modeled as a centralized unique reservoir. Furthermore, the storage optimization is done weekly. In a first approach, the price for the installed capacity will be the same for all the years considered. The model can be executed using two type of hydrogen storage, compressed or liquified. This means that different efficiencies and costs will be applied depending on the type of storage selected (being an input parameter for the model). However, the parameter is given in kg, so it must be transformed to GWh. The conversion is done considering different works that analyze the power needed to produce a given hydrogen quantity, [41].

  To compress or liquify requires some energy, i.e., energy losses are unavoidable. This situation is reflected using a storage efficiency. In addition, the model considers the efficiency of extracting hydrogen from the storage. Depending on the use of the hydrogen storage, the output efficiency is different.

  The storage model considers that hydrogen can be used to re-electrify producing electricity or to supply the external hydrogen demand (being a model input). The model cannot extract from and store hydrogen in the reservoir in the same hour.
- Transport: It is not modeled in the formulation proposed. The only consideration has been to study Spain and Portugal as different power systems. The hydrogen transportation costs between countries would be too high to a certain extent.

  Therefore, the hydrogen produced is stored and used on site as if everything were in the same location.

3.2.2 FORMULATION

CEVESA can be simulated using exploitation mode or investments. With the first one, the installed capacity to produce and store hydrogen is an input parameter for the model. With the second one, the optimal solution gives the optimal storage and production capacity to supply the demand requested. For the cases studied, the method employed has been the exploitation mode in order to reduce the time between simulations and considering the complexity of the weekly model that has been adopted. However, the model allows an investment approach.

The index employed were, “h” for hour of the day ($h \in (1,24)$), “d” for day of the week ($d \in (1,7)$), “w” for week of the year ($w \in (1,52)$) and “y” for year.

The parameters and variables used are showed in the tables below:

Q_{wy}^{H2}	*weekly H2 external demand*
CAP_y^{H2}	*installed capacity to produce H2*
$CAPS_y^{H2}$	*installed capacity to store H2*
DE_{ydh}	*electricity demand per hour*
$CV1^{H2}$	*variable cost of producing H2*
$CV2^{H2}$	*variable cost of storing H2*
E	*efficiency electrolyser*
N	*storage efficiency*
β	*kWh needed per kg H2*

Table 1. Parameters. Source: Own elaboration.

q_{ydh}^{H2}	*total H2 produced hourly*
qd_{ydh}^{H2}	*H2 produced hourly to satisfy the external H2 demand*
qs_{ydh}^{H2}	*H2 produced hourly and stored*
e_w	*reservoir H2 level*
qg_{ydh}^{H2}	*stored H2 used to produced electricity*
qsd_{ydh}^{H2}	*stored H2 used to satisfy external H2 demand*
ge_{ydh}	*hourly electricity generation*
δ	*Binary variable*

Table 2. Variables. Source: Own elaboration.

With the parameters and variables explained, the constraints can be showed and analyzed:

The hydrogen production is limited by the installed capacity, assuming that the electrolysis process has an efficiency:

$$q_{yh}^{H2} \leq CAP_y^{H2} * E \qquad \forall h$$

The hydrogen hourly production will go to supply the external hydrogen demand or to store:

$$q_{ydh}^{H2} = qd_{ydh}^{H2} + qs_{ydh}^{H2} \qquad \forall h$$

Storage balance: the reservoir level at the end of the week results from the initial level plus the hydrogen stored and minus the hydrogen extracted to produce electricity or to supply the external demand:

$$e_w = e_{w-1} + \sum_{d,h} qs_{yh}^{H2} * N - \sum_{d,h} qg_{yh}^{H2} - \sum_{d,h} qsd_{yh}^{H2}$$

The weekly demand of hydrogen is supplied with hydrogen produced or extracted from the reservoir:

$$\sum_{d,h} qsd_{ydh}^{H2} * N + \sum_{d,h} qd_{ydh}^{H2} \geq Q_{wy}^{H2} \qquad \forall w, \qquad h \in d \in w$$

The hourly electricity demand, including the electricity needed to produce hydrogen, comes from electricity generated this hour and electricity produced from hydrogen stored:

$$ge_{ydh} + qg_{ydh}^{H2} * N = q_{ydh}^{H2} + DE_{ydh} \qquad \forall h$$

The hydrogen stored is limited by the installed hydrogen reservoir capacity. The storing efficiency is also considered:

$$e_w \leq CAPS_y^{H2} * \beta \qquad \forall w$$

To avoid hydrogen extraction from the reservoir and production at the same time, the following constraints were added:

$$qs_{ydh}^{H2} - CAPS_y^{H2} * \delta \leq 0 \qquad \forall h$$

$$qg_{ydh}^{H2} - CAPS_y^{H2} * (1 - \delta) \leq 0 \qquad \forall h$$

The objective function for the hydrogen model (to be added to the CEVESA power system objective function) includes the variable cost of producing and storing hydrogen:

$$cost^{H2} = \sum_{y} qs_{ydh}^{H2} * CV2^{H2} + \sum_{d,h} q_{ydh}^{H2} * CV1^{H2}$$

Hydrogen model fits in CEVESA as a new independent system that produce hydrogen to supply the new external hydrogen demand. However, this hydrogen production is supplied by the conventional technologies already represented in CEVESA and the energy excess. Furthermore, the hydrogen stored can be used to produce electricity and therefore, it is added to the conventional technologies to supply the electricity demand.

The following scheme synthesizes the constraints explained in this section:

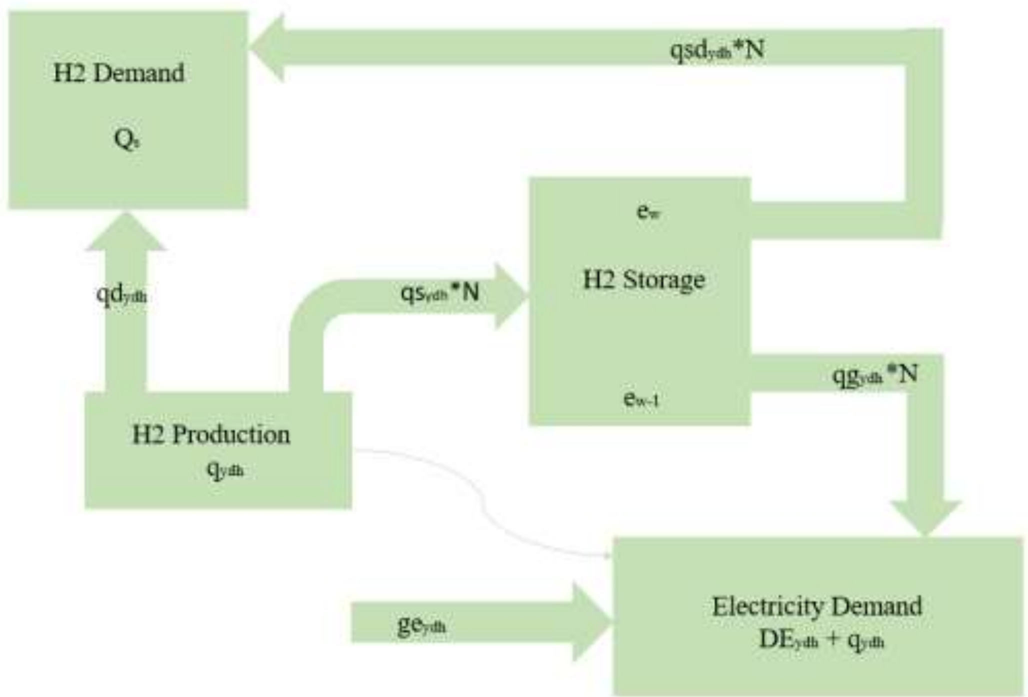

Figure 10 Model Scheme

4. SCENARIO ANALYSIS

This section studies different scenarios in order to test the model explained in 3.2.2. It includes how the scenarios were designed, the parameters employed, and the results obtained.

4.1 DESIGN OF THE SCENARIOS

4.1.1 VALIDATION SCENARIO

For the first scenario modeled, the simulation time is 8 weeks because it is the sufficient time to be able to validate the model. The year chosen is 2030.

The parameters employed are in section 4.1.2. This scenario has used a set of parameters that can be considered "neutral" meaning that there is no parameter "pushed to the limit". The objective is to determine an initial scenario to validate the H2 model introduced in CEVESA.

In this scenario, only Spain is going to be modeled. However, in some cases, it is interesting to analyze the hydrogen impact in the MIBEL system. When this occurs, it will be explicitly indicated.

In addition, in this scenario, two subcases will be modeled. The simulations will consider a first scenario without hydrogen and a second one, considering the hydrogen model explained in section 3.2.2.

4.1.2 CAPACITIES SCENARIO

For this scenario, the time simulated has been 8 weeks. Even if once the model is validated, longer scenarios can be run, it is interesting to analyze the model with the same simulation time in order to be able to compare the results obtained. The year selected is 2030.

The parameters employed have being explained in section 4.1.3. The objective of this scenario is to determine the role of the capacities installed to produce or store. It would analyze if it is better to store or to produce hydrogen, considering the actual cost that each option has, and knowing the efficiency related to each process. Therefore, this scenario will include two cases. The first one will consider a lower installed capacity to produce in order to force hydrogen storage and the usage from the hydrogen stored. For the second one, the storage installed capacity will be lowered, to force the production of hydrogen.

4.1.3 PRICES SCENARIO

This scenario will be focus on the production and storage costs. The simulation time has been also 8 weeks, and the year is also 2030. The parameters employed are in section 4.1.4.

This scenario will also consider, two subcases. The first one considers a high electrolysis price. The objective is to determine wether it is worth paying to produce or wether it is better to store. The second one will do the opposite; the storage cost will be higher in order to determine the most cost-effective option.

For this scenario, the storage selected will be the compressed one. However, the same analysis could be made using the liquid storage. This scenario, is therefore, a pessimistic scenario, with very high costs. However, considering that the hydrogen roadmap, [3], determined ambitious objectives for 2030 and 2050, it is interesting to analyze the impact of not achieving the goals proposed.

4.1.4 STORAGE SCENARIO

For the last scenario, the time simulated has also been 8 weeks from 2030. The parameters employed are described in section 4.1.5.

This scenario will analyze the impact of the hydrogen storage type specified in section 3.2.1. Hydrogen can be stored in compressed tanks or liquified. As it has been analyzed, the efficiency and the storage cost are different for each option even if the capacity installed is the same in both cases. Compression is expensive but has a good efficiency. By his side, liquification is a cheap option however, the efficiency is worse than for the hydrogen compressed.

Therefore, this scenario will study two cases. The first one focused on the compressed hydrogen storage and the second one, employing liquified hydrogen storage. The objective is to determine which option is the most cost-effective one.

4.1 INPUT DATA

4.1.1 INPUTS KEPT CONSTANT FOR ALL THE SCENARIOS

There are some input parameters kept constants for all the scenarios. In addition, this section includes parameters that follows a linear evolution through the years. However, its input table for the year considered (2030) is the same for all the scenarios and therefore, they are explained in this section.

The hydrogen external demand (Q_{wy}^{H2}) represents the weekly hydrogen consumption. It considers green and non-green hydrogen used in industry, transport, heat, power, etc. This parameter is introduced per hour, country and year. However, it is computed as a weekly demand because what the model does is to add up the hours in a week.

The Spanish value is modeled following a linear progression applying the global demand growth given in [24]. From [3] were obtained the values for the lineal interpolation. 0% of hydrogen demand is considered in 2020, 25% is estimated in 2030 and 100% for 2050. The table below shows the information described. Even in GWh, the demand is constant because the value was obtained applying the conversion factor between kg and KWh (Table 6):

External Hydrogen Demand (GWh)						
ESP.H0001	2020	2021	2022	2023	2024	2025
	0	0,05707192	0,11414384	0,17121575	0,22828767	0,28535959
	2026	2027	2028	2029	2030	2031
	0,36145548	0,43755137	0,51364726	0,58974315	0,66583904	0,88223673
	2032	2033	2034	2035	2036	2037
	1,09863442	1,31503211	1,53142979	1,74782748	2,06410103	2,38037457

	2038	2039	2040	2041	2042	2043
	2,69664812	3,01292166	3,32919521	4,3017958	5,2743964	6,246997
	2044	2045	2046	2047	2048	2049
	7,2195976	8,1921982	9,52149829	10,8507984	12,1800985	13,5093985
	2050					
	14,8386986					

Table 3. Pure Hydrogen Demand. Source: IIT

Secondly, the electricity demand without considering the hydrogen production (DE_{ydh}) is given in Table 4, taken from previous applications of CEVESA based on the NECP of Spain and Portugal:

Electricity Demand (MW)						
ESP.H0001	2020	2021	2022	2023	2024	2025
	27386,195	26991,8805	27483,6252	28129,0482	26696,917	28277,9606
	2026	2027	2028	2029	2030	2031
	28167,6171	27762,0515	28267,8274	28931,6665	27458,6718	29084,8279
	2032	2033	2034	2035	2036	2037
	28971,336	28554,1981	29074,4055	29757,1863	28242,1619	30936,9969
	2038	2039	2040	2041	2042	2043
	30491,5569	30674,5063	30858,5533	31043,7046	31229,9669	31417,3467
	2044	2045	2046	2047	2048	2049
	31605,8507	31795,4858	31986,2588	32178,1763	32371,2454	32565,4728
	2050					
	32760,8657					

Table 4. Original Electricity Demand. Source: IIT

Thirdly, the electrolyser´s efficiency (E) is showed in Table 5. It is a PEM electrolyser because it is the technology with a more prolific future, and it is estimated to be the mechanism used in the coming years. The values were obtained from [11]. [11] considers that in 2020 the efficiency would be 60%, 68% for 2030 and in 2050 (long term), 74%. As it has been done with the first two parameters, it has been assumed a lineal evolution between years. In addition, this parameter changes also with the country.

Electrolyser efficiency (%)						
ESP	2020	2021	2022	2023	2024	2025
	0,6	0,608	0,616	0,624	0,632	0,64
	2026	2027	2028	2029	2030	2031

	0,648	0,656	0,664	0,672	0,68	0,683
	2032	2033	2034	2035	2036	2037
	0,686	0,689	0,692	0,695	0,698	0,701
	2038	2039	2040	2041	2042	2043
	0,704	0,707	0,71	0,713	0,716	0,719
	2044	2045	2046	2047	2048	2049
	0,722	0,725	0,728	0,731	0,734	0,737
	2050					
	0,74					

Table 5. Electrolyser efficiency. Source: Own elaboration.

Finally, the last constant parameter is the conversion factor (β) between kg and kWh. It shows the kWh necessary to produce or store 1 kg of hydrogen. This parameter will not change depending on the year or the country. The value was obtained from [49]. The table below synthetize the parameter described:

Conversion Factor (KWh/kg)	
ESP	20

Table 6. Conversion factor. Source: Own elaboration

4.1.2 Validation scenario

Data employed in the first scenario modeled in order to validate the equations proposed.

4.1.2.1 Production

Hydrogen is produced in a unique electrolyser. However, before the simulation the installed capacity has to be set.

The European Union established two visions, [2]. For 2020-2024, 6 GW of electrolyser must be installed and for 2025-2030, 40 GW. In Spain, aligned with this objectives, the hydrogen roadmap, [3], has determined that for 2030, 4 GW must be installed. Hence, for the first scenario, as 2030 is going to be simulated, the capacity installed to produce (CAP_y^{H2}) will be 4 GW. This value is fixed and will not change for the whole year.

However, even if there is not an inversion cost because there are no hydrogen capacity decisions computations, it is necessary to add a production cost ($CV1^{H2}$) related to the hydrogen produced per hour. It represents the cost of using the electrolyser. To produce hydrogen water and power is needed and they have a cost that must be reflected in the model. It has been supposed a water cost of 0,01111 €/kg, that 9 kg of water are needed to produce 1 kg of hydrogen and that to produce 1 kg of hydrogen, 20 kWh are needed. These suppositions derive to an electrolysis cost of 3 €/MWh.

In addition, for 2030th year the electrolyser´s efficiency is 68% (see Table 5. Electrolyser efficiency. Source: Own elaboration.).

The following table synthetizes the production parameters considered in this first scenario:

Parameter	Value
CAP_y^{H2}	4 GW
$CV1^{H2}$	3 €/MWh
E	68%

Table 7. Production Parameters (Validation scenario). Source: Own Elaboration.

4.1.2.2 Demand

The model considers two types of demand, the external hydrogen demand and the electricity demand without hydrogen. Both were described in **¡Error! No se encuentra el origen de la referencia.**.

For 2030, the external hydrogen demand is 0,66583904 GWh per hour. This value is the same for all the hours considered. Hence, as the model does a weekly optimization, the weekly demand is 111,86095872 GWh.

The total electricity demand for the 8 weeks simulated is 48034212,71 MW. The original electricity demand varies with the hour. The energy balance is made hourly so the Table 8 will only show the value for the first hour (27458,6718 MW).

The following table synthetized the information described:

Parameter	Value
Q_{wy}^{H2}	111,86095872 GWh

DE_{ydh}	27458,6718 MW

Table 8. Demand Parameters (Validation scenario). Source: Own elaboration

4.1.2.3 Storage

For the model, hydrogen is stored in a unique reservoir. However, two methods to store in the tank can be chosen, compressed hydrogen or liquified hydrogen.

The installed capacity is an input parameter. Therefore, an intermediate capacity that can be used with the two types of storage will be "installed". In [46], the tanks considered are tubes that can be transported in trailers. Hence, in order to make an accurate simulation, the value selected is a tank that can be delivered in trailers. For gaseous hydrogen, taking in consideration its low density, the load delivered is around 1100 kg. On the other hand, in liquid tanks, at a density of 70 kg/m3, the volume that can be transported is around 3500 kg. Thus, the capacity installed for storage ($CAPS_y^{H2}$), in this first scenario is, 1750 kg.

Depending on the storage type the cost is different. Even if liquid transport is cheaper, for this first scenario, the storage selected is the compressed one. The impact of compression on hydrogen cost is because of the electricity cost to run compressor and the capital cost of the compressor. From [41], considering that the equipment, a 300 bar compressor, would cost between 45000 € and 90000 €, the capital cost would be 0,63 €/kg-1,63 €/kg. By his side, the electricity cost for compression is around 0,3 €/kg -0,45 €/kg. Hence, the total compression cost would be 0,9 €/kg -1,75 €/kg, [41]. For the model, the cost ($CV2^{H2}$) reflected is 1,325 €/kg, an intermediate value.

To obtain compressed hydrogen, around 10-15%, [19], [41] [18], is consumed in the process, so the efficiency is around 85-90%. The model would consider that compressed storage has an efficiency (N) of 88%.

The following table synthetizes the storage parameters:

Parameter	Value
$CAPS_y^{H2}$	1750 kg

$CV2^{H2}$	1,325 €/kg
N	88%
β	20 kWh/kg

Table 9. Storage Parameters (Validation scenario). Source: Own elaboration

4.1.3 CAPACITIES SCENARIO

The parameters employed for this scenario are developed in the following section.

4.1.3.1 Production

This scenario will consider two cases as it has been described in 4.1.2. In the first one the capacity limited will be the hydrogen production installed capacity.

In the original scenario this capacity was 4 GW as it was considered in the Spanish roadmap. However, for this first case, this value will be 1,5 GW limiting the capacity but making the model feasible. The rest of the values employed will remain the same.

In the second case, as the changed value will be the storage capacity, the production data will be the same that for the validation case.

The following table synthetized the information described:

Subcase	Parameter	Value
1	CAP_y^{H2}	1,5 GW
2	CAP_y^{H2}	4 GW
1&2	$CV1^{H2}$	3 €/MWh
1&2	E	68%

Table 10. Production Parameters (Capacities Scenario). Source: Own Elaboration

4.1.3.2 Demand

The focus of this scenario is not the external hydrogen demand or the electricity demand. Therefore, these values will continue being the same than for the validation scenario. More information about how this information have being obtained is available in 4.1.2.2.

However, it is convenient to remind the information employed in these cases. The following table synthetized the information described:

Parameter	Value
Q_{wy}^{H2}	111,86095872 GWh
DE_{ydh}	27458,6718 MW

Table 11. Demand Parameters (Capacities scenario). Source: Own elaboration

4.1.3.3 Storage

The storage capacity will change in the second subcases considered.

The original value was 1750 kg, and for the second scenario, the value will be 50 kg because is low enough to force the hydrogen production. The rest of the values employed will be the same than for the validation scenario.

For the first scenario, where the value changed is the hydrogen production installed capacity, the installed capacity to store hydrogen will be the original one (1750 kg). To have two different cases will help to determine the cost-effective option between producing or storing.

The following table summarizes the ideas expressed before:

Subcase	Parameter	Value
1	$CAPS_y^{H2}$	1750 kg
2	$CAPS_y^{H2}$	50 KG
1&2	$CV2^{H2}$	1,325 €/kg
1&2	N	88%
1&2	β	20 kWh/kg

Table 12. Storage Parameters (Capacities Scenario). Source: Own Elaboration

4.1.4 PRICES SCENARIO

4.1.4.1 Production

This scenario will analyze the impact of the hydrogen costs involved in the model. The costs that must be minimized are the electrolysis cost and the storage one.

In the first case, the parameter that will increase, is the electrolysis production cost. The original price, from the validation scenario was 3 €/MWh, now, the price will rise up to 100 €/MWh which continue being a reasonable price for an electrolyser in [11]. This price takes into consideration the water price, the electricity cost and the CAPEX investment. In addition, the objective is to have a production cost much higher than the storage one in order to analyze if the model stores or prefers to produce at that price.

For the second subcase, the production cost will stay as in the validation scenario because the parameter that will change is the storage cost.

The rest of the parameters will stay the same as for the validation scenario. However, it is convenient to remind the parameters that will play in these cases:

Subcase	Parameter	Value
1&2	CAP_y^{H2}	4 GW
1	$CV1^{H2}$	100 €/MWh
2	$CV1^{H2}$	3 €/MWh
1&2	E	68%

Table 13. Production Parameters (Prices Scenario). Source: Own Elaboration

4.1.4.2 Demand

The focus of this scenario is not the external hydrogen demand or the electricity demand. Therefore, these values will continue being the same than for the validation scenario. More information about how this information have being obtained is available in 4.1.2.2.

However, it is convenient to remind the information employed in these cases. The following table synthetized the information named:

Parameter	Value
Q_{wy}^{H2}	111,86095872 GWh
DE_{ydh}	27458,6718 MW

Table 14. Demand Parameters (Price scenario). Source: Own elaboration

4.1.4.3 Storage

The first case is related to the electrolysis cost. Hence, it is described in the production section of this scenario (4.1.4.1). For that first case, the storage data employed will be the same than for the validation scenario.

On the other side, in order to study the impact of the storage price, the second case will play with its variable cost. In the validation scenario the storage cost was 1,325 €/kg considering compressed storage. The price decided for this second case is 60 €/kg. This price is much greater (1000 times) than the original production cost that will be considered in this second case. The objective of this case is to analyze if the model will continue storing even with such a difference in the storage price.

However, it is convenient to synthetize the information described above. The following table summarizes it:

Subcase	Parameter	Value
1&2	$CAPS_y^{H2}$	1750 kg
1	$CV2^{H2}$	1,325 €/kg
2	$CV2^{H2}$	60 €/kg
1&2	N	88%
1&2	β	20 kWh/kg

Table 15. Storage Parameters (Prices Scenario). Source: Own Elaboration

4.1.5 STORAGE SCENARIO

4.1.5.1 Production

In this scenario the cases analyze will focus on the type of storage employed. Therefore, the production data used will be the same than for the validation scenario. To know more about how this information have being obtained go to 4.1.2.1.

However, it is convenient to remind the information employed in these cases. The following table synthetized the information described:

Parameter	Value

CAP_y^{H2}	4 GW
$CV1^{H2}$	3 €/MWh
E	68%

Table 16. Production Parameters (Storage Scenario). Source: Own Elaboration.

4.1.5.2 Demand

The focus of this scenario is not the external hydrogen demand or the electricity demand. Therefore, these values will continue being the same for the validation scenario. More information about how this information was obtained is in the section 4.1.2.2.

However, it is convenient to remind the information employed in these cases. The following table synthetized the information described:

Parameter	Value
Q_{wy}^{H2}	111,86095872 GWh
DE_{ydh}	27458,6718 MW

Table 17. Demand Parameters (Storage scenario). Source: Own elaboration

4.1.5.3 Storage

For this last scenario the parameter that will change is the type of storage employed and hence, the parameters related to this characteristic. Depending on the type of storage, the model will have different efficiencies and costs.

However, as the validation case is simulated with compressed storage, in this section there is going to be explained the information related to the liquid storage. Nevertheless, in the results section (4.2.4), the two subcases will be showed together.

Liquid storage is a complicated process that consumes around 30-40% of hydrogen energy content. This lies to an efficiency between 60-70%. Therefore, the efficiency selected is 65%. However, it increases hydrogen density by around 800 times compared with compressed hydrogen, which allows hydrogen storage at relatively low pressure. This characteristic reduces the total cost of this process. In terms of capital cost, its value is between 0,5 €/kg and 1,1 €/kg. The value chosen for the simulation has been 0,8 €/kg, an intermediate value that will be the same for all the hours simulated.

Therefore, one type of storage is better in terms of efficiencies and the other one in terms of costs.

The following table will synthetize the information described above and will remind the data related to compressed hydrogen (subcase 1) in order to have it on the same simulation table:

Subcase	Parameter	Value
1&2	$CAPS_y^{H2}$	1750 kg
1	$CV2^{H2}$	1,325 €/kg
2	$CV2^{H2}$	0,8 €/kg
1	N	88%
2	N	65%
1&2	β	20 kWh/kg

Table 18. Storage Parameters (Storage scenario). Soruce: Own elaboration

4.2 RESULTS & CONCLUSIONS

4.2.1 VALIDATION SCENARIO

This scenario studies two different situations in order to analyze the impact of introducing hydrogen in the actual power system. The two cases studied are “with hydrogen” and “without hydrogen”.

From a production point of view, it is interesting to analyze the impact that hydrogen has in the rest of the technologies available. As it can be seen in Figure 11, some technologies do not experience any changes. Wind, solar, solar thermal, nuclear, conventional hydraulic, cogeneration or pumping are the ones that its annual production does not change. Wind, solar, solar thermal and nuclear do not change because they are not dispatchable. In addition, hydraulic, cogeneration and pumping plants have constraints that prevent their total production from changing but do allow them to change how they are dispatched.

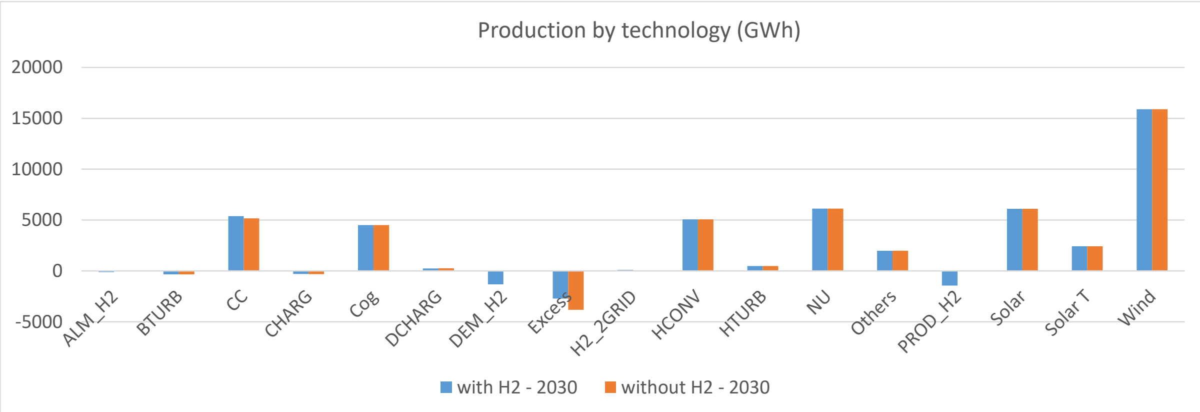

Figure 11. Production by technology. Source: Own elaboration

Figure 12 shows the total production of the technologies concerned by hydrogen production.

As it can be seen, this new production is made with the excess, as it decreases when the model produces hydrogen, and with combined cycles, as it increases when there is hydrogen production.

In addition, the hydrogen produced is largely going to cover the demand directly. Around 90% of hydrogen produced goes to cover the new hydrogen demand. Thus, the hydrogen storage is going to be around a 10% of the total produced. Furthermore, the stored hydrogen is only employed to produce electricity. This is due to the inefficiencies that the storage has. As it can be inferred, the solution less costly is to directly produce the hydrogen needed without using storage. Using the storage to cover the demand is clearly less efficient, considering that it will be a big waste of energy.

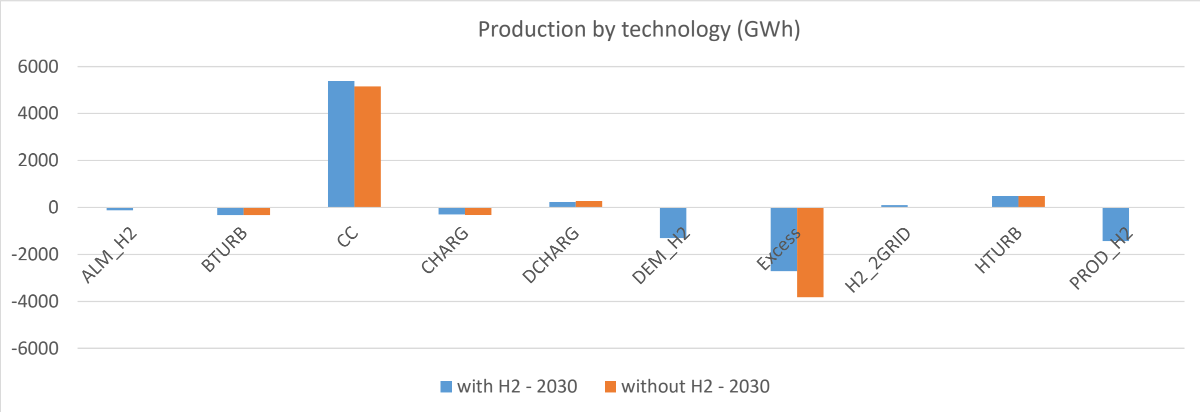

Figure 12. Production by technology (Detail). Source: Own elaboration

By his side, the annual average price per MWh It increases because new costs are introduced but it does not experience big changes. In Figure 13 can be seen that the average price goes from 18 €/MWh (without H2) to 19,84 €/MWh (with H2).

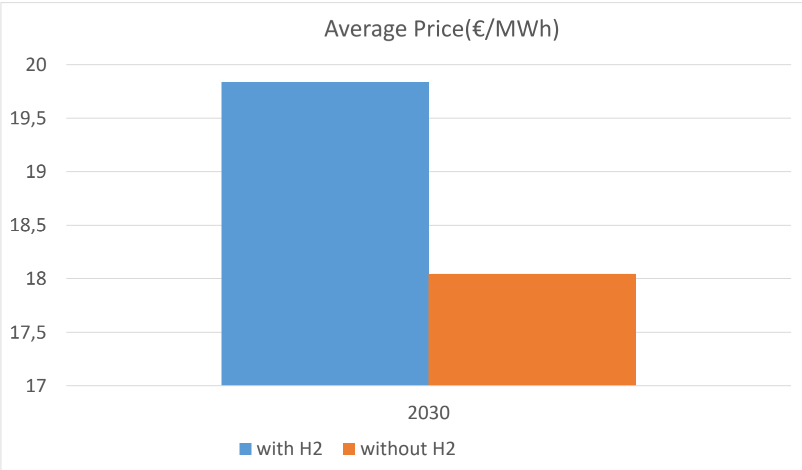

Figure 13. Average Price. Source: Own elaboration

Furthermore, it is interesting to analyze that introducing a new technology, with cost for storage and production is not changing the hourly price model (see Figure 14). This can happen because of how hydrogen is being produced, using energy excess that has no cost and, if it is needed, using combined cycles but to a low extent. In addition, it could be assumed that introducing hydrogen, and therefore, stored hydrogen that gives flexibility to the power system, provokes that the price curve flattens. This detail can be observed clearly, if Portugal and Spain are simulated together (see Figure 15).

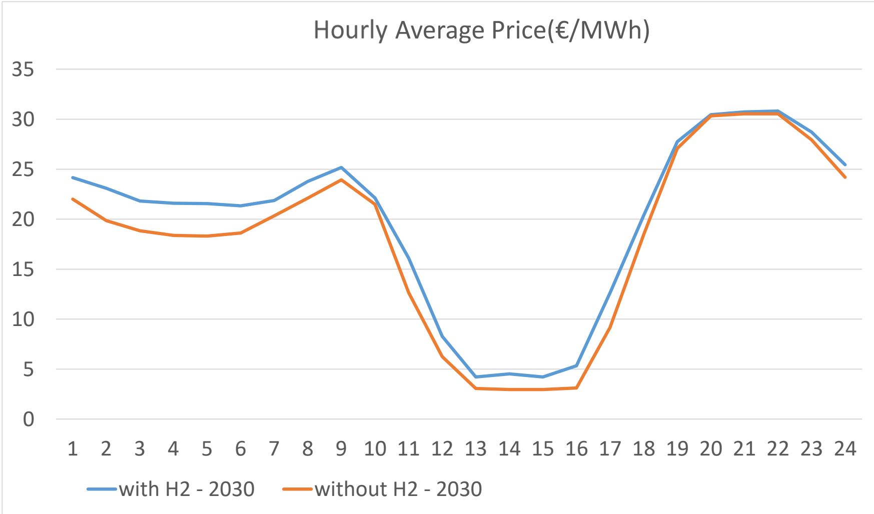

Figure 14. Hourly Average Price. Source: Own elaboration

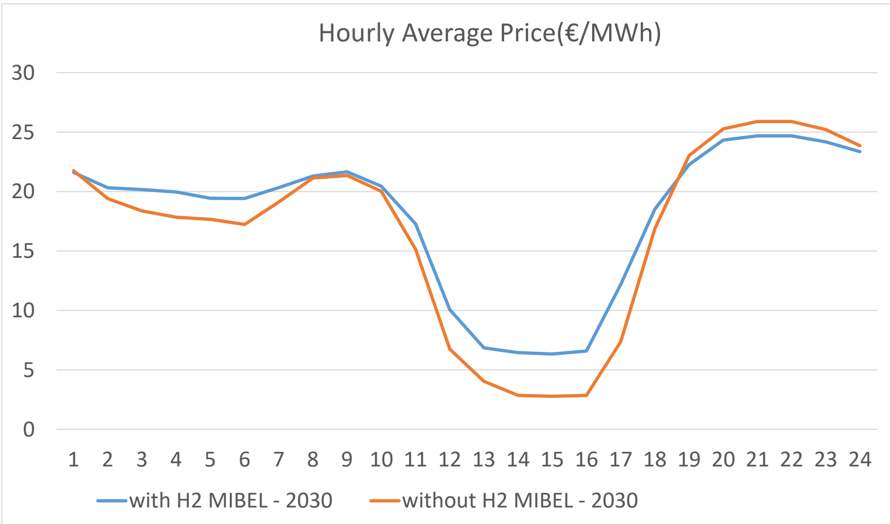

Figure 15. Hourly Average Price (MIBEL). Source: Own elaboration

Analyzing 1236th hour (see Figure 16) it can be seen that the model decides to not pump even if it has excess. This is because the model has a weekly maximum pumping limitation. For this week, the pump arrives to its limit so it cannot pump more in this hour and doing it in the other hours is more cost-effective. In this hour, the excess is used to produce hydrogen and this hydrogen is employed to cover the demand and to be stored. No more excess can be used to produce hydrogen because the installed capacity to produce hydrogen has already been reached.

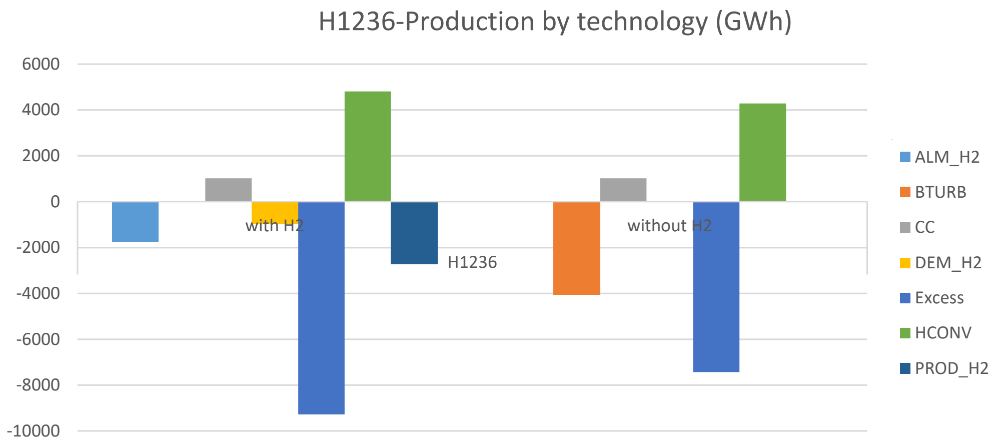

Figure 16. Production by technology (H1236). Source: Own elaboration

Hour 1195th (Figure 17) shows a situation where the model decides to use hydrogen to produce electricity. This reduces the combined cycles and hydro production, which reduces the electricity price for this hour as can be seen in Figure 18.

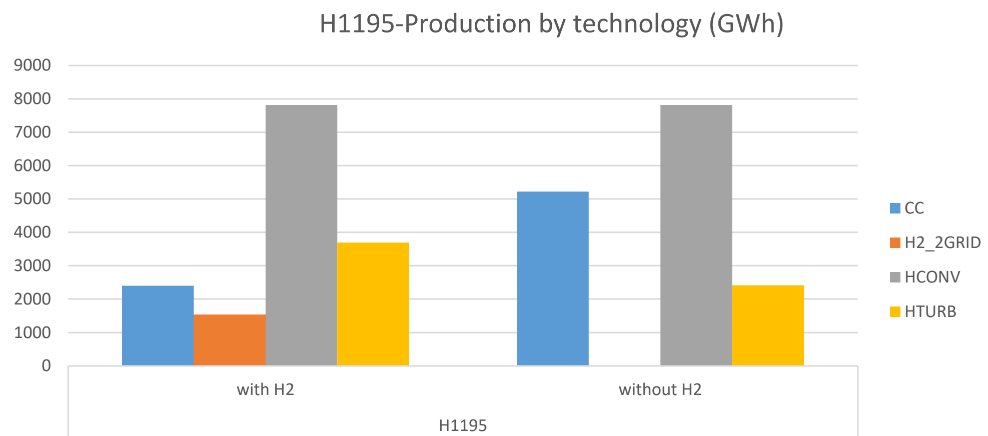

Figure 17. Production by technology (H1195). Source: Own elaboration

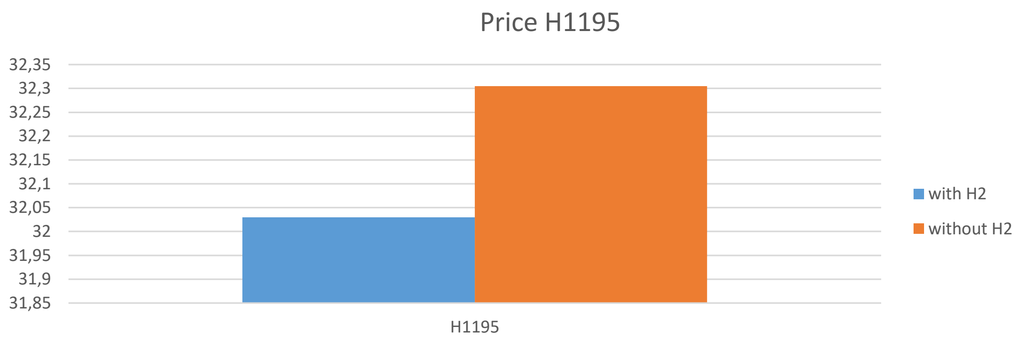

Figure 18. Energy Price (H1195). Source: Own elaboration

The next hour in being analyzed is the 60th hour (see Figure 19). This hour is interesting because the model decides that the hydrogen produced from the excess is only used to cover the demand.

Indeed, no more hydrogen can be produced because the capacity installed has already been reached. In addition, the combined cycles would not be affected because with the hydrogen produced from the excess is sufficient to supply the demand of this hour.

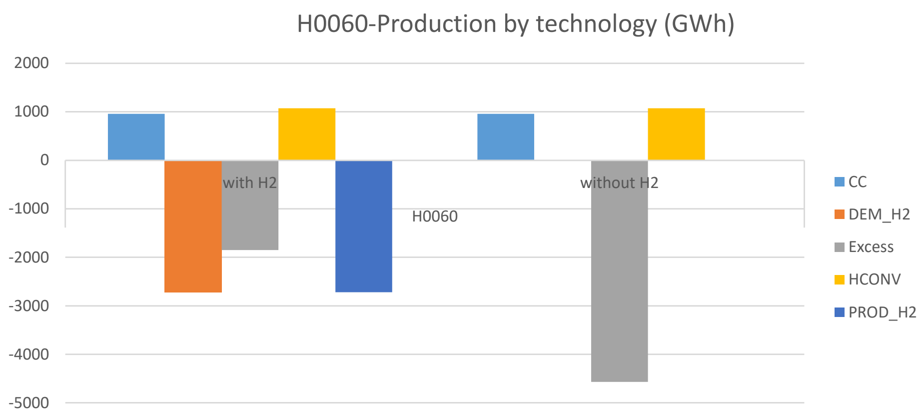

Figure 19. Production by technology (H0060). Source: Own elaboration

1154th hour (see Figure 20) is representative because the excess is all used. It is employed to produce hydrogen and with the leftover it will charge the battery. In this case, the hydrogen produced goes a large part to storage. Furthermore, the combined cycles production does not change from one scenario to the other. This is because, no more energy is needed and with the excess the hydrogen production is supplied.

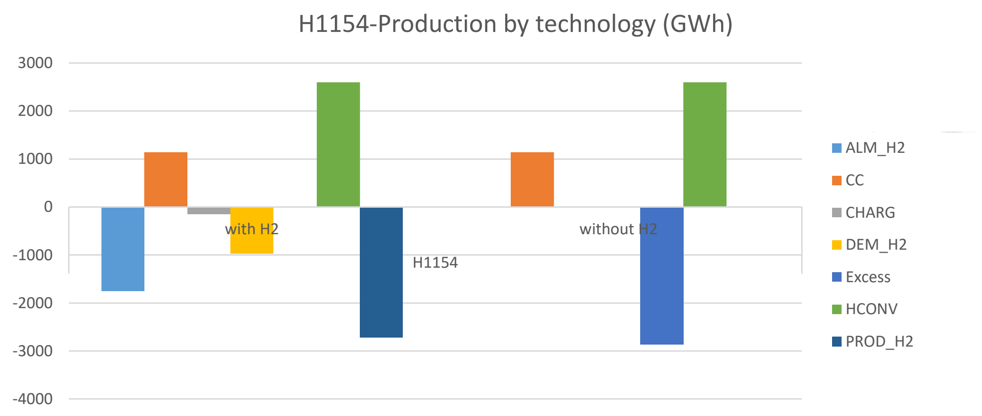

Figure 20. Production by technology (H1154). Source: Own elaboration

The last hour in being analyzed is the 36th hour. As it can be seen, in this hour, the hydrogen production is going to use all the excess. However, the optimal option is to increase the combined cycles to produce the maximum installed capacity of hydrogen which is directly stored.

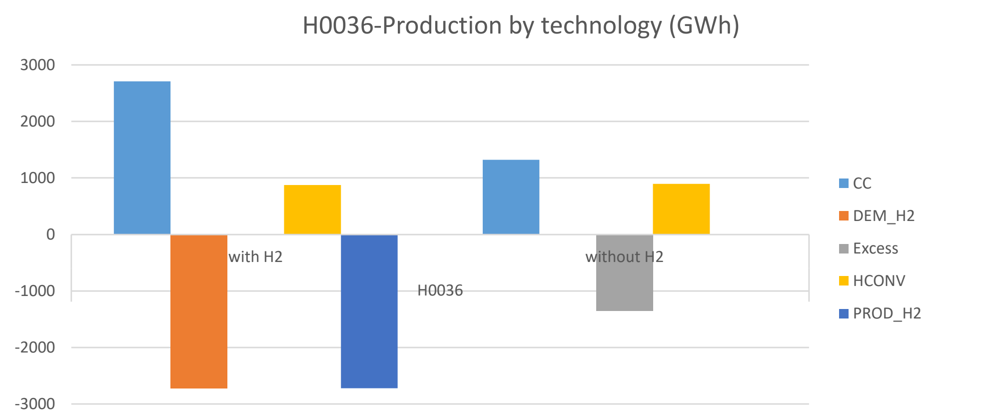

Figure 21. Production by technology (H0036). Source: Own elaboration

To sum up, this scenario gave the opportunity to validate the model in order to test different cases. The main ideas that can be extracted from these cases are that the hydrogen produced comes firstly from the excess because it is "free" energy. However, if more hydrogen quantity is needed, the combined cycles will provide the extra electricity needed. In addition, depending on the moment, the model may select to store, to cover the demand or to do both attending to the optimal hours in order to minimize the objective function. Nevertheless, it never uses hydrogen stored to supply the demand because as it has been analyzed is an inefficient option.

Furthermore, including hydrogen in the power system does not have a big impact in the average power price. In fact, as it has been inferred, it can help to reduce the difference between peak and off-peak price what will give stability and efficiency to the actual power system. The hydrogen storage facility helps to manage demand. It allows to reduce peak zones, increase off-peak zones, translate peaks to valleys and helps to flatten the curve.

4.2.2 CAPACITIES SCENARIO

This scenario analyzes the impact of hydrogen production and storage capacity. Two cases were simulated. The first one, with less hydrogen production installed capacity and the second one with less hydrogen storage installed capacity.

From a production point of view, it is important to indicate that the same technologies that were constant in the validation scenario, continue being constant. As a reminder, these technologies were: wind, solar, solar thermal, nuclear, conventional hydraulic, cogeneration and pumping. The reasons are explained in section 4.2.1.

In Figure 22, it can be observed the technologies that change its production from one case to the other. Initially, it is important to indicate that even with less production, the model does not use hydrogen from the storage to supply the hydrogen demand. In addition, in the scenario with less production, even if sufficient storage capacity is available to store, the model is not storing (see Figure 23). It is using the available hydrogen production capacity to supply the external hydrogen demand. With a limited hydrogen production capacity and without storing, the excess consumed is lower and therefore, it needs to use more combined cycles in order to supply the electricity demand.

The case with less storage capacity, allows the model to store a little hydrogen quantity. However, as it can be seen, even the lowest storage capacity gives flexibility to the system. It helps to reduce the combined cycles production, the average price, and the excess. In addition, again, this hydrogen stored is only used to produce electricity (see Figure 23).

Furthermore, as it can be seen in Figure 23, in the case with less production capacity, the model does not store hydrogen.

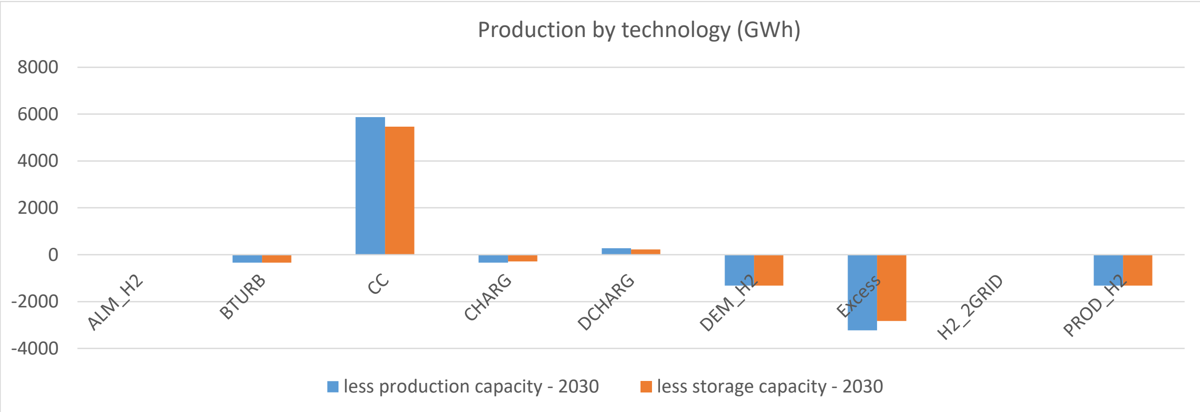

Figure 22. Production by technology. Source: Own elaboration

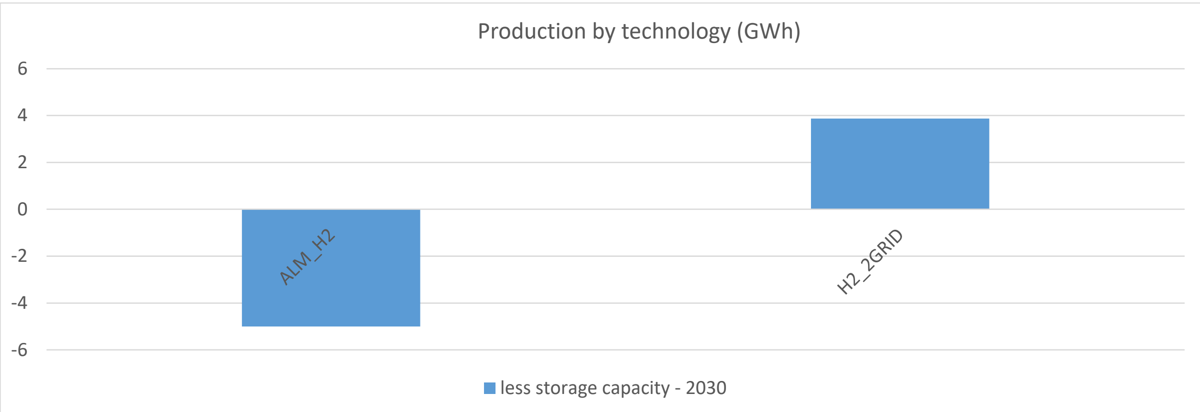

Figure 23. Storage behavior. Source: Own elaboration.

Furthermore, it is also interesting to analyze in this case how it is the hourly excess behavior. As it has been observed in Figure 24, in the case with less production, the model is not storing so the excess is practically constant. When it changes, is because pumps or batteries are using it. However, introducing a little capacity changes the excess curve. As it can be inferred, the excess hourly evolution (see Figure 24) is contrary to the price hourly evolution (see Figure 25). When the prices are higher, the model uses excess in order to reduce the average price. On the other hand, when the prices are in an off-peak area it is not so necessary to use that excess.

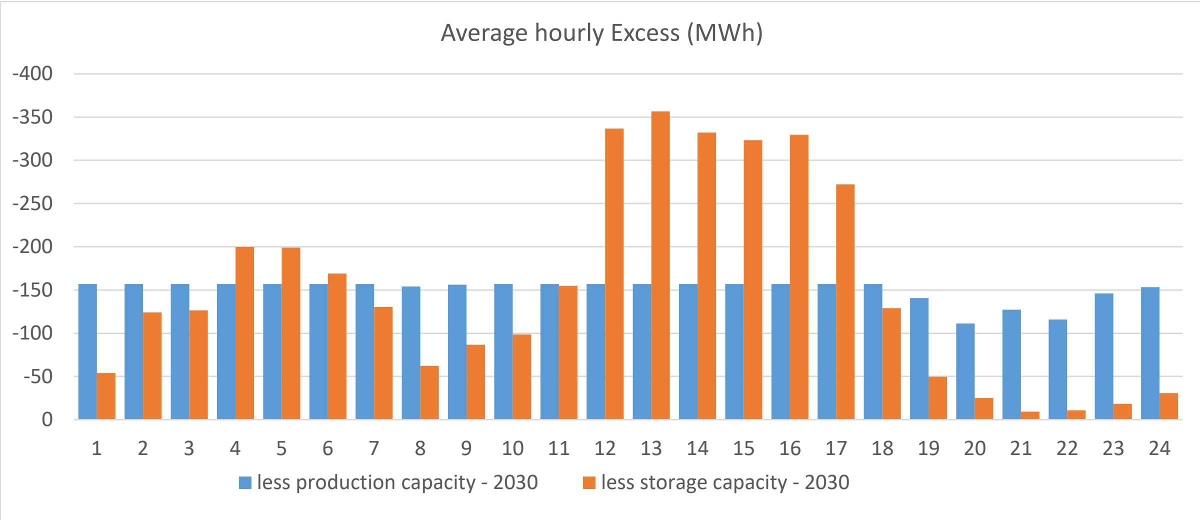

Figure 24. Average hourly Excess. Source: Own elaboration

From Figure 25, it can be observed that even a little storage capacity, helps to flatten the curve. In addition, it slightly reduces the peak. As it has been mentioned, it reduces the differences between peak and off-peak zones. Furthermore, having storage helps to decrease the average annual price even if the difference is not too high. This last conclusion can be observed in Figure 26.

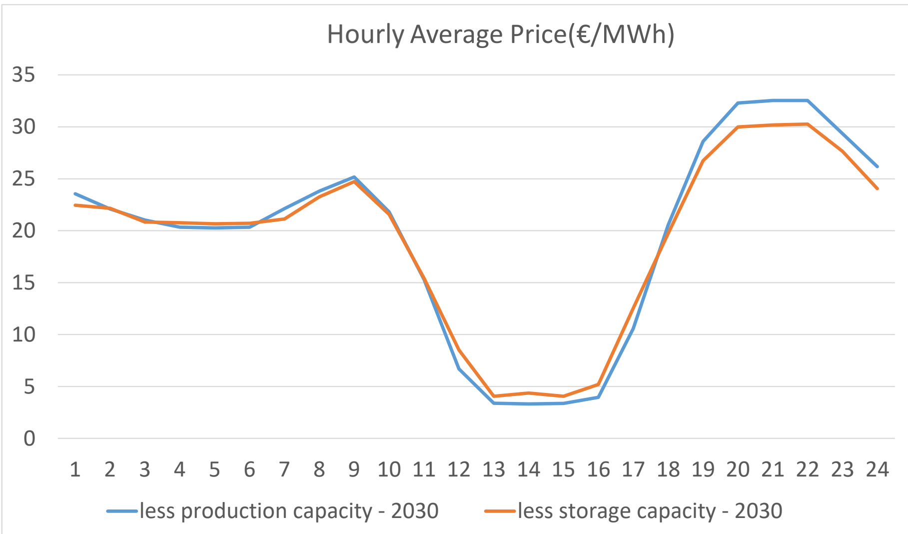

Figure 25. Hourly Average Price. Source: Own elaboration

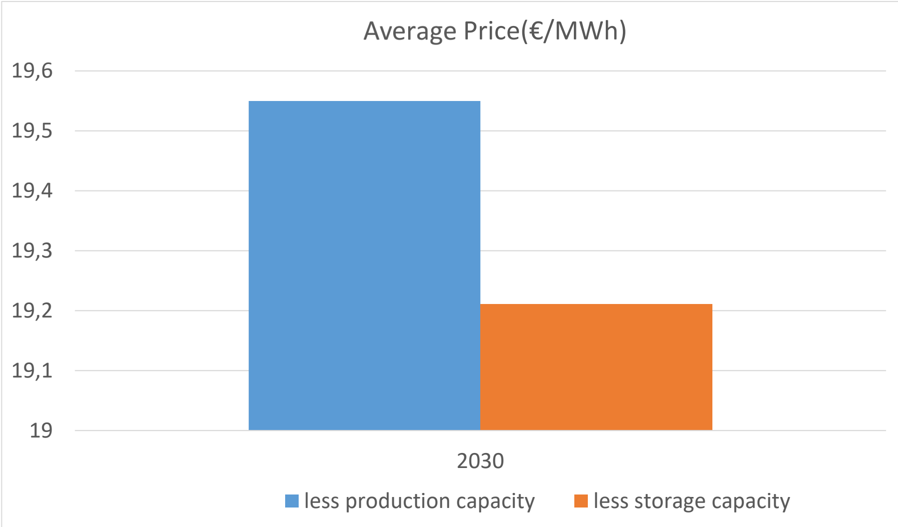

Figure 26. Average Price. Source: Own elaboration

On the other hand, some representative hours are going to be analyzed. The objective is to determine how the model behaves, knowing that the energy balance is made each hour.

Starting with the 1009th hour (see Figure 27), it can be observed that with a little capacity to produce, the model needs to produce in more hours in order to cover the demand. However, if it can store, the model is more flexible and does not need to produce in hour where it is not cost-effective.

Furthermore, in the scenario with less production, as it needs to cover the demand in that hour, it will need to increase the combined cycles to be able to meet the demand. This increase in the production of combined cycles will provoke that in that hour the matching price is going to be higher, as it can be observed in Figure 28.

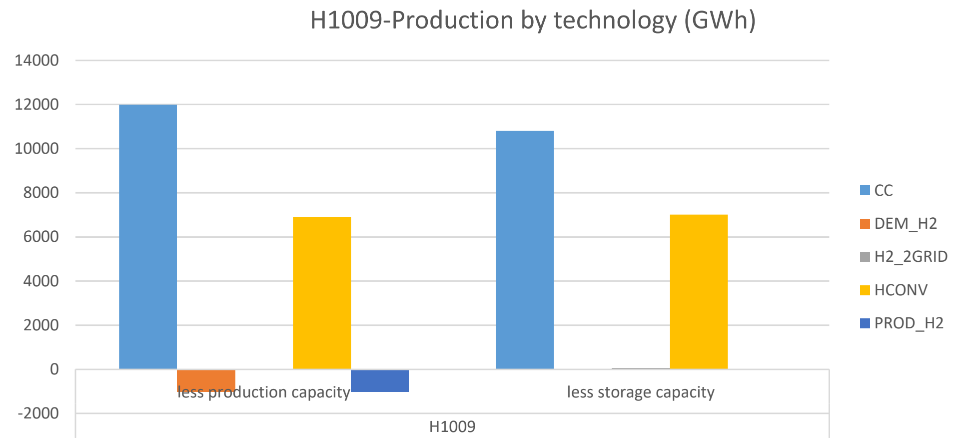

Figure 27. Production by technology (H1009). Source: Own elaboration

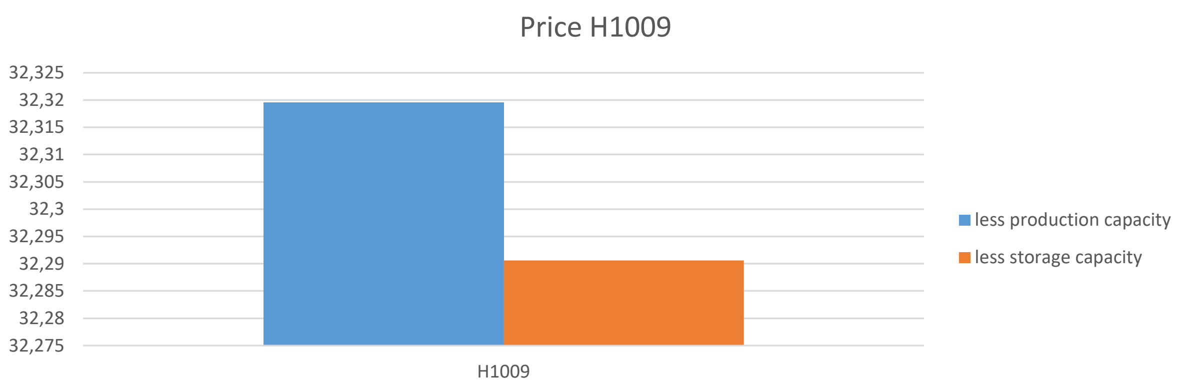

Figure 28. Price (H1009). Source: Own elaboration

Finally, the last hour in being analyzed is the 12th hour (see Figure 29). This hour is interesting because the behavior of the model is virtually identical. With less production capacity, the model will produce its maximum and will use it to supply the demand. The remaining excess will be used to charge the battery.

On the other hand, the case with less storage capacity is doing the same than the case with less production capacity. However, as it has more installed capacity to produce, it will use it up to the maximum. It will use this hydrogen to cover the demand. The remaining excess will be used to charge the battery but as a secondary objective.

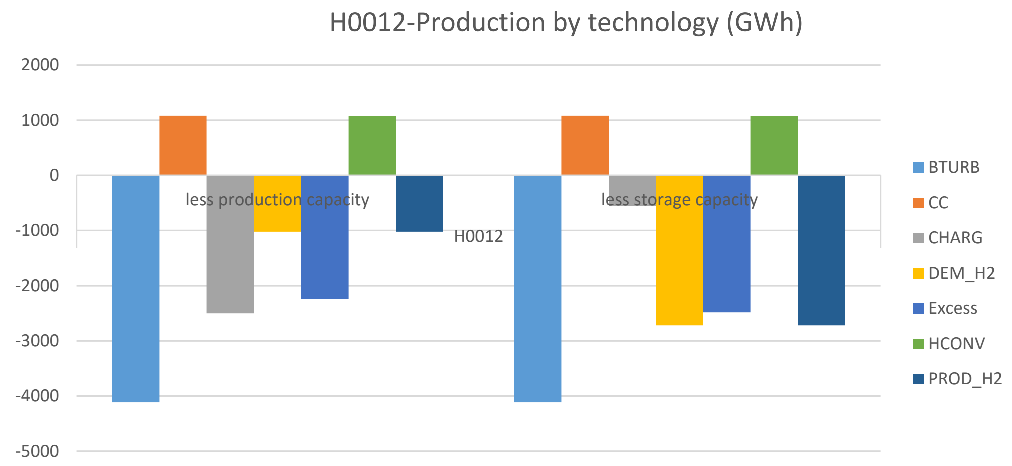

Figure 29. Production by technology (H0012). Source: Own elaboration

In conclusion, from this scenario what can be inferred is that even a little hydrogen storage increases the flexibility to the power system. It allows to have more control over the combined cycles production, the average price or the excess consumption. Furthermore, reducing the hydrogen production capacity only changes when the hydrogen is going to be produced because the model will continue without storing and will focus on meeting the external hydrogen demand. With a little production capacity, the model prioritizes to supply the external demand than storing it. In addition, as it has been observed in Figure 24 and Figure 25, with larger storage capacity, the excess behavior changes and evolves according to the prices.

4.2.3 PRICES SCENARIO

The objective of this scenario was to analyze the model decision in order to store or produce, attending to the variable cost associated to each action.

Firstly, analyzing the production in Figure 30, both cases produce the same quantity per technology. It is important to highlight that in none of the cases the model decides to store. Hence, it is producing what is going to be consumed. This is due to the high production and storage prices introduced. If the production cost increases significantly, the model will only produce the exact quantity that is needed. Producing more means raising the final cost exponentially which is inefficient. By his side, if the storage cost is high, occurs the same, because it will produce what is necessary. Therefore, the two cases will react equally.

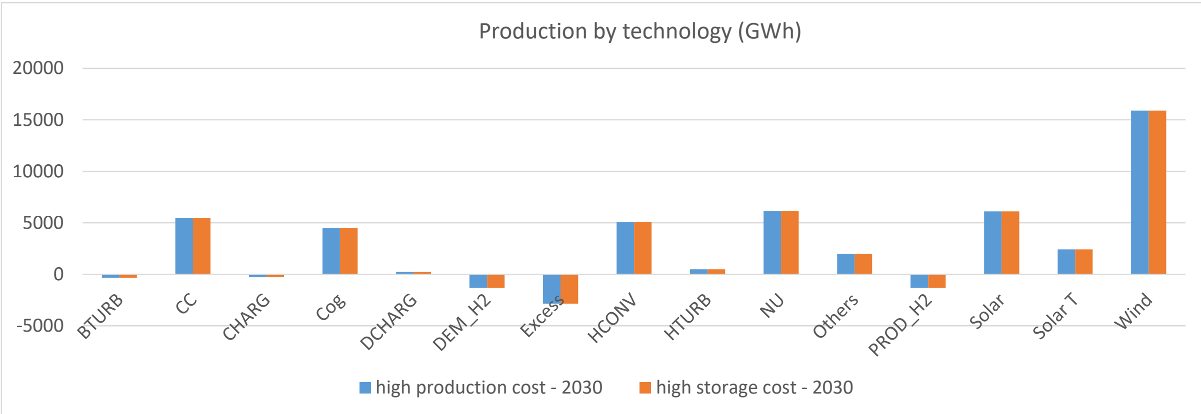

Figure 30. Production by technology. Source: Own elaboration

Furthermore, as the production does not change, the prices will react the same way. In Figure 30 and Figure 31, the price curve is the same for the two cases and therefore, the average price is also equal. In addition, it is interesting to analyze that even with high producing cost, the average annual price is similar than with lower costs. However, this analysis will be made in more detail in 7.

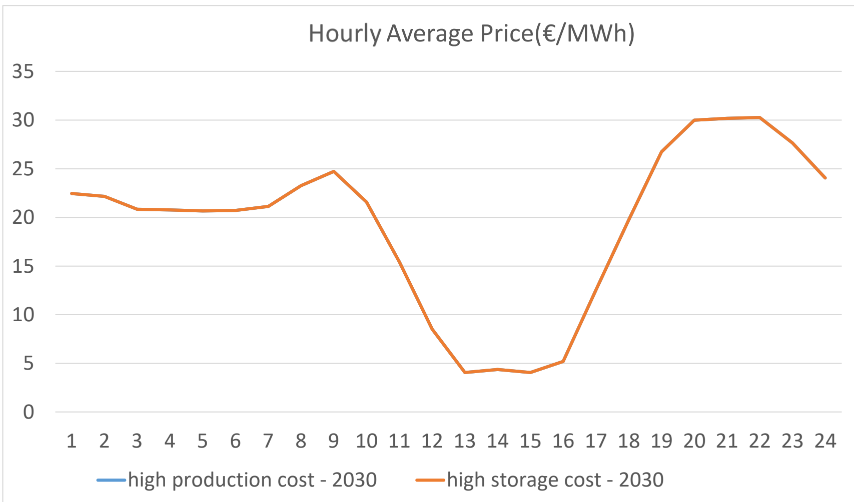

Figure 31. Hourly Average Price. Source: Own elaboration

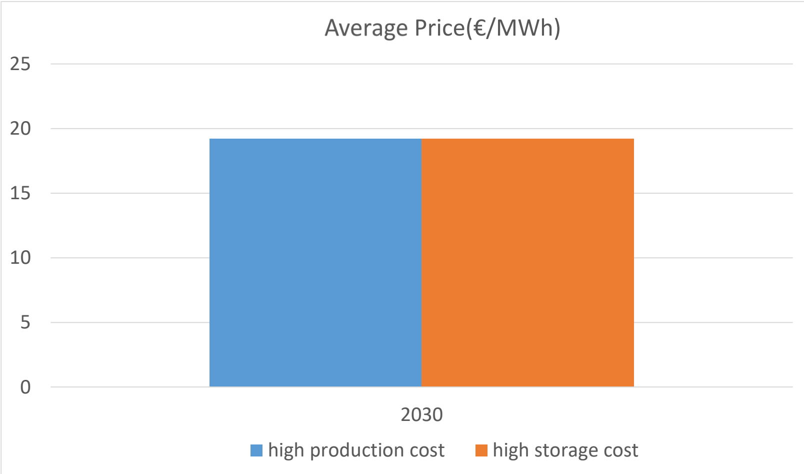

Figure 32. Average Price. Source: Own elaboration

In conclusion, this scenario allows to confirm that with high production costs, storage has no sense because it will increase exponentially the final price even if there are hours where electricity price is zero. This cost is not related to the electricity price but to the electrolyzer utilization cost and producing to store means using more the electrolyser. To store hydrogen, it needs to be produced and if this action is expensive, it will produce the quantity that is strictly required.

4.2.4 STORAGE SCENARIO

As it has been described in 4.1.4, this scenario is focused on analyzing the most cost-effective hydrogen storage. The first case considers compressed storage. It has a good efficiency but has a high cost. The second one, uses liquified storage which is less efficient but has a lower cost. Both cases consider the same storage installed capacity.

Regarding the annual production, as it has been done in the scenarios analyzed before, the technologies that are not represented in Figure 33 is because they do not change from one case to the other. As a reminder, these technologies are Wind, Solar, Solar Thermal, Nuclear, Conventional Hydraulic, Cogeneration and Pumping.

Analyzing Figure 33, the changes from one case to the other are practically nonexistent. However, with liquid storage the system is going to produce more hydrogen. Therefore, the excess and combined cycles consumption will be greater than with compressed storage in order to supply the difference between the hydrogen produced with each storage method.

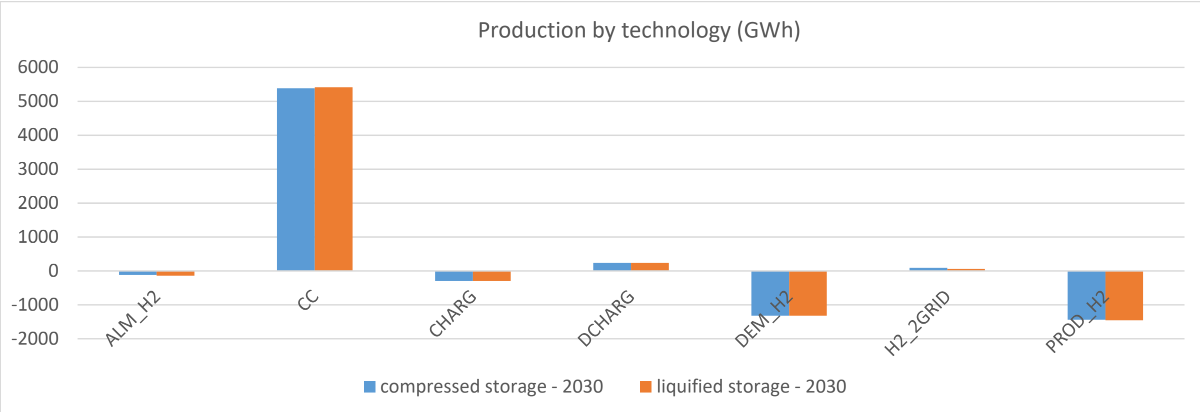

Figure 33. Production by technology. Source: Own elaboration

The most notable difference is in the storage behavior (see Figure 34). Even with a worse efficiency, the model stores more hydrogen with liquified storage. The difference in the stored quantity can be provoked by the significant difference that exists between the storage cost of the two processes. Therefore, as liquified storage has a lower cost, the model decides to store more hydrogen even considering that the efficiency is lower.

However, the hydrogen that is used later to produce electricity is less than with compressed hydrogen. This is because the liquid storage efficiency is significantly worse, so in the hydrogen extraction more energy will be lost.

In addition, it is interesting to indicate that with liquified storage the system not only store more hydrogen but also charge more the battery as it is reflected on the Figure 33. This could be because the storage efficiency is worse and the system needs more energy in order to supply the electricity demand.

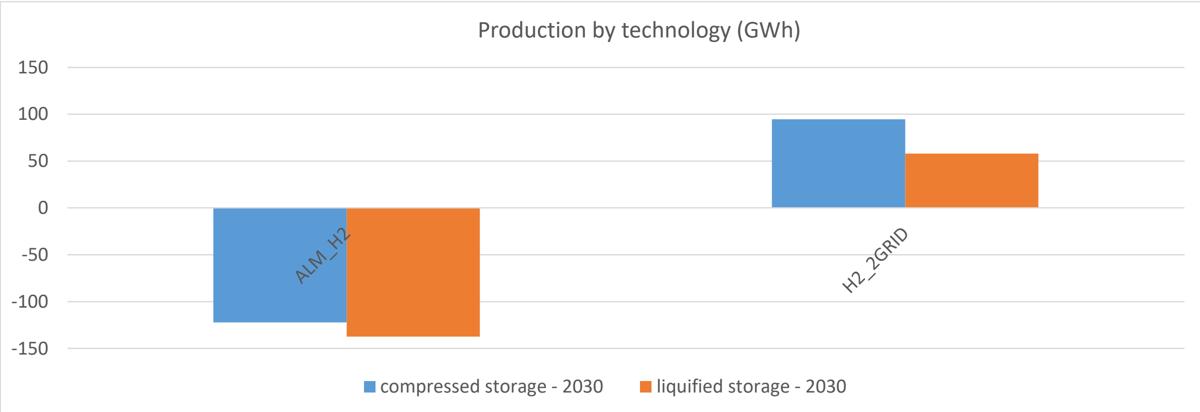

Figure 34. Storage behavior. Source: Own elaboration

On the other hand, the profile of the price curve must be analyzed (see Figure 35). It can be inferred that the hourly behavior is the same for the two storages specially in valley areas. Therefore, it seems reasonable that the production by technology does not present big changes. The differences that have been noted in the productions, may have been due to the slight deviation in the curve price from one case to the other. Furthermore, the little variation in the hourly profile can be noted in the average price as it is reflected in Figure 36. For compressed hydrogen the electricity price is 19,84 €/MWh and for the liquified hydrogen, the price is 19,46 €/MWh. There is not a big difference, but it may be enough to choose one method over another.

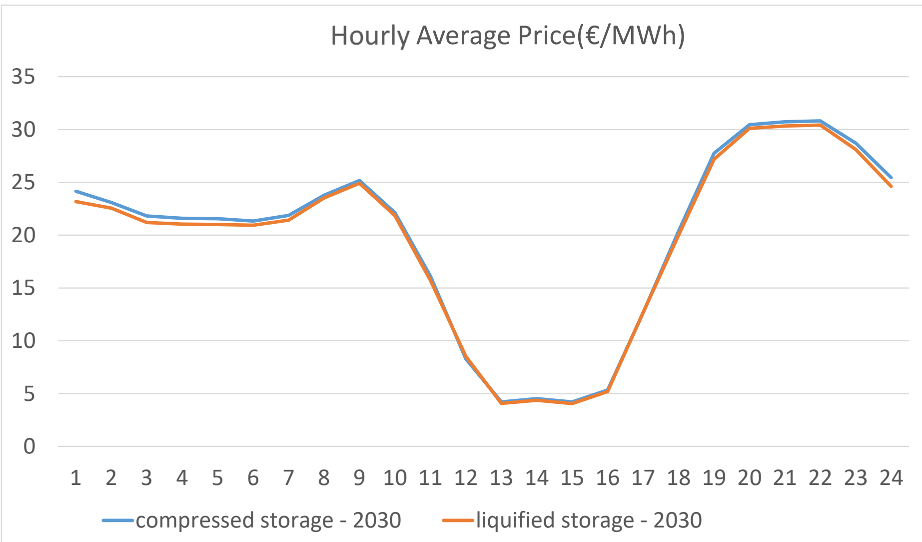

Figure 35. Hourly Average Price. Source: Own elaboration

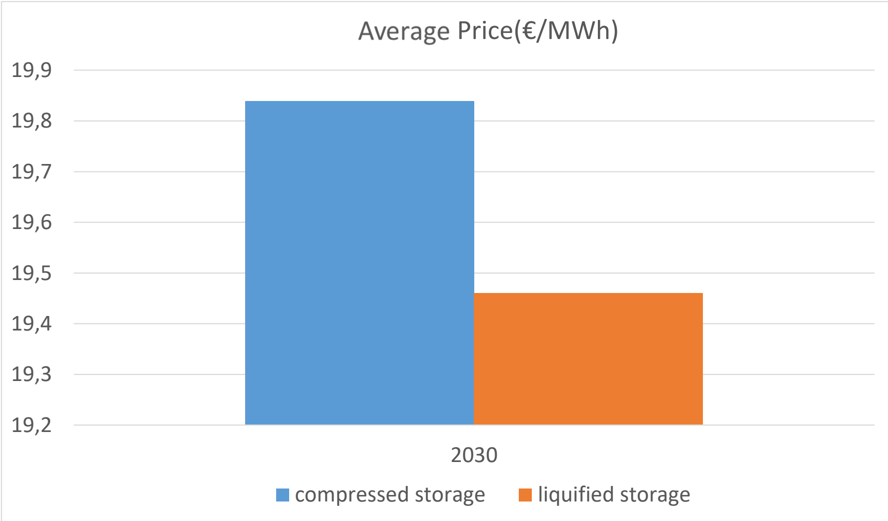

Figure 36. Average Price. Source: Own elaboration

Finally, some representative hours will be analyzed. The hours 828 and 827 are going to be examined together because its profile can be seen as complementary. It is interesting to analyze in Figure 37 that for the first hour (828), with liquified hydrogen, the model decides to store. However, with compressed storage, the decision changes, and the model does not store and decides to pump. This could be provoked by the difference between the compressed storage cost and the pump cost, being the second one lower. However, the pump cost compared with the liquid storage cost seems to be greater and therefore, the system selects to store. Nevertheless, even if the quantity pumped (compressed case) and stored (liquified case) is the same, the excess consumption is greater in the liquified storage. This excess difference is also reflected in the hydraulic production that is lower when more excess is consumed.

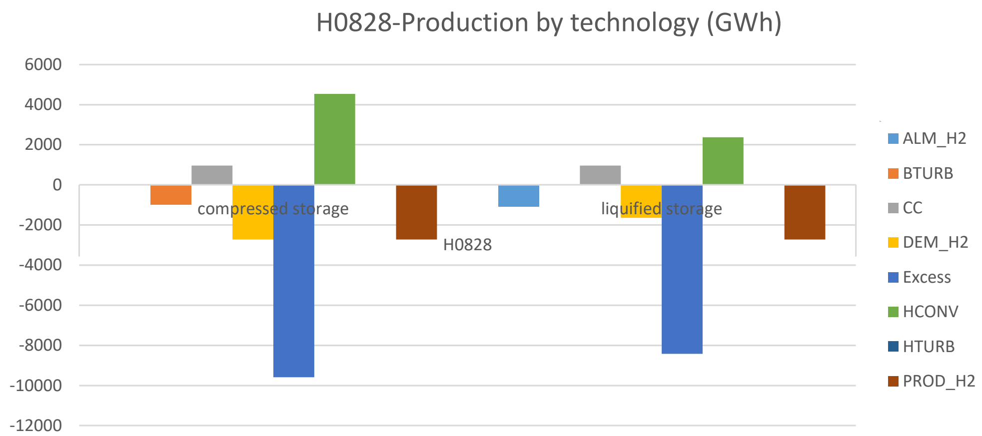

Figure 37. Production by technology (H0828). Source: Own elaboration

By his side, the hour 827 (see Figure 38) does the opposite of the 828th hour. With liquified storage, the model decides to pump, increases hydraulic production, and uses less excess. With compressed hydrogen, the model stores, uses less hydraulic and more excess. However, what is interesting is that these two hours are not the only ones where this occurs. There are more pair of hours where this happens such as 1045th -1046th. These hours have in common that in both situations, with compressed and liquified hydrogen, the marginal price for those hours is 0 €/MWh. Therefore, both situations are just as cost-effective.

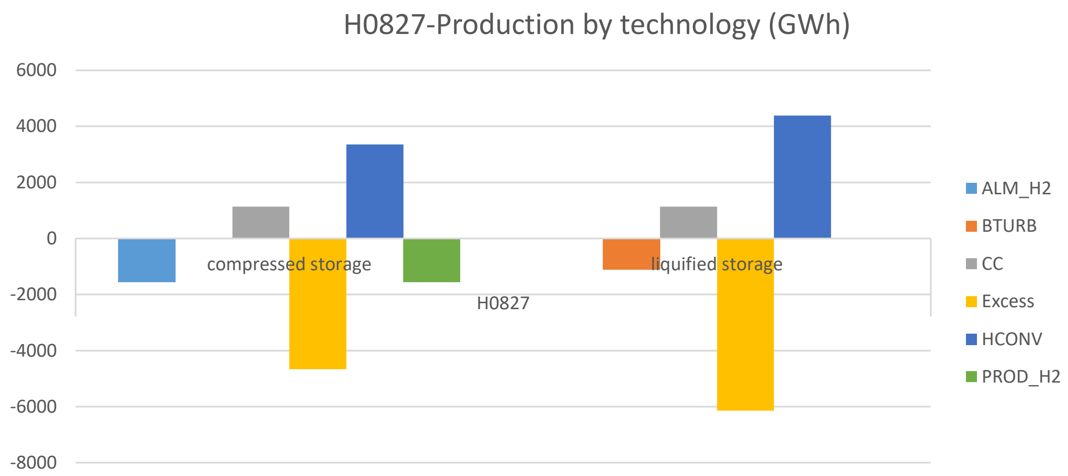

Figure 38. Production by technology (H0827). Source: Own elaboration

The 1081th hour (see Figure 39) has been highlighted because the model decides in both situations to store hydrogen. However, the production of the other technologies are different depending on the case. It can be inferred that, even producing and storing the same hydrogen and covering the same demand, with liquified storage, the model increases its hydraulic production. By his side, with compressed hydrogen, the model prefers to give this surplus using the battery because it's a cheaper option.

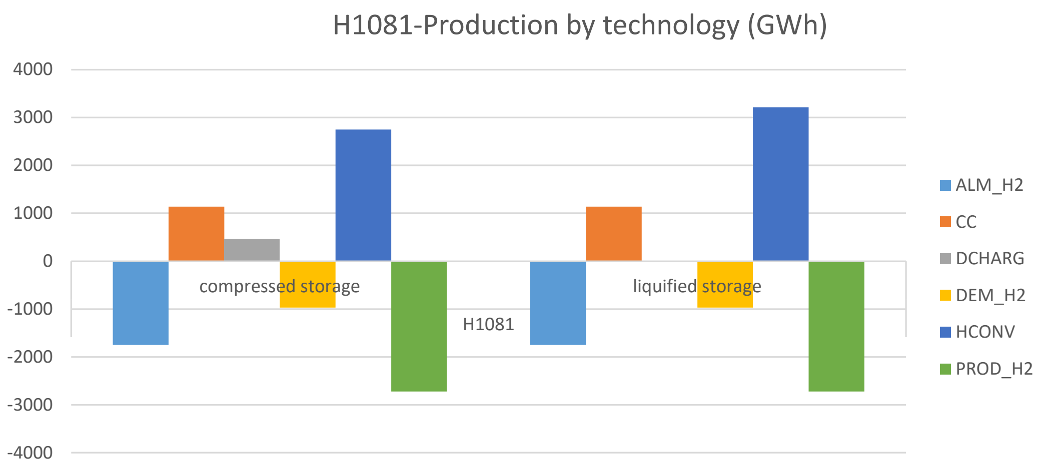

Figure 39. Production by technology. Source: Own elaboration

In conclusion, analyzing the type of storage, it can be concluded that the advantages of liquifed storage is the reduction in costs. However, with this type, the quantity of hydrogen that can be harnessed is lower even when the quantity stored in greater. Therefore, depending on the objective (reducing costs or extracting more hydrogen), one option will be better or the other.

5. SUSTAINABLE DEVELOPMENT GOALS

In this chapter, the environmental impact of the project will be analyzed considering the different Sustainable Development Goals, [50], (see Figure 40) that have being determined by the United Nations. This section will focus on the main goals that this project looks to accomplish.

Figure 40. Sustainable Development Goals. Source: United Nations

From the 17 sustainable development goals this project has special linkages with the objectives focused on the climate change and the decarbonization context. The goals identified that has relation with the Green Deal and with an economy based on renewable energy are:

- **Goal 13. Take urgent action to combat climate change and its impacts.**
  To achieve this goal, it is important to integrate the climate change measures in the different national plans or strategies. As well as improving awareness-raising and institutional capacity on climate adaptation and early warning.
  The Green Deal established the necessity of limiting the global warming in 1,5ºC. To reach it, it is required that CO2 emissions decrease around 25% for 2030 and net zero emissions in 2070. Having these objectives in mind, green hydrogen seems to be one of the key elements to reach them in the decarbonization transition.

The creation of a Hydrogen Council transmits the importance of hydrogen as a driver for the climate change.

However, it is interesting to highlight the role of hydrogen in international and national strategies. Starting with the European Union with its Hydrogen Strategy, [2], which determines a three-path roadmap. The targets are from now to 2024, 6 GW of electrolysers installed, and 1 million tonnes of green hydrogen produced; during 2025 to 2030, the installed capacity have to increase to 40GW, and the production will be 10 million tonnes. Lastly, for 2030 and beyond, the hydrogen may become an intrinsic part of the integrated energy system.

In Spain, following the structure set by EU, the Hydrogen roadmap, [3], that is aligned with its National Integrated Energy and Climate Plan 2021-2030 stands out that for 2024, 600 MW of electrolysers will be installed. For 2030, the number will increase up to 4 GW.

This project looks to analyze the impact that these scenarios will have in the power system. CEVESA enables to study the CO2 emissions and the electricity prices impact that including green hydrogen will have in the power sector. Even if the prices will be greater than a scenario without hydrogen, it is important to weight the role that it has in the CO2 emissions. Furthermore, it is interesting to analyze the option of store the hydrogen and how the prices will evolute taking it in consideration.

In addition, the Spanish capacity to produce green hydrogen because of the installed capacity of wind and solar makes this scenario attractive to the national economy. This could allow Spain to become a reference in terms of renewable energy deployment.

- **Goal 7. Ensure access to affordable, reliable, sustainable, and modern energy for all.**

  To achieve this goal, the objectives for 2030 are to increase substantially the share of renewable energy in the global energy mix and to double the global rate of improvement in energy efficiency.

The PNIEC, [4] collects these concepts. It also includes objectives as 42% of renewable in end-uses, a 39,5% of improvement in the energetic efficiency and a 74% of renewables in power sector.

In this context, including hydrogen in the actual economy models would provoke the optimization of the renewable energy.

One of the main characteristics of green hydrogen is that it can be stored. As it has been analyzed in 2.2.3, the objective is to produced hydrogen in the periods with excess of renewable energy that cannot be stored and to use it in the moments when it is necessary. In such a way, it will increase the security of supply. It will also provoke that wind and solar energy that today is, would be used. Furthermore, using hydrogen for power-to-gas applications will also help to increase the renewable impact as it will decarbonize the gas sector that is one of the most powerful in Spain.

To reach these targets, the hydrogen roadmap, [3] establishes objectives for 2030 as 25% of hydrogen industrial demand from renewable sources or, in mobility, to include a float of 150 bus, 5000 light and hard vehicles, and 2 hydrogen trains.

This project looks to analyze the impact that this new demand and the ambitious renewable share will have in the future power system. It will allow to intuit if the future electricity prices will be competitive with the traditional technologies that are not aligned with the decarbonization context the country is experiencing.

- **Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.**

  To achieve this goal, it is necessary to develop sustainable infrastructures to support economic development and to promote inclusive and sustainable industrialization by 2030.

  This objective is aligned with the goal 13. The investments for electrolysers installation as it is stayed in the hydrogen roadmap or in the European union hydrogen strategy is looking to develop a sustainable and solid structure of green hydrogen production.

  Furthermore, the projects that are investigating new ways of producing hydrogen is also helping to ensure this infrastructure. To find new ways of producing hydrogen as SOEC or PEM technologies that will be more affordable and more effective, will help to settle the hydrogen economy in the actual system.

By his side, this project looks to analyze the hydrogen economy using PEM technology and to investigate how the evolution of the actual cost of this technology affects the cost of electricity. However, the actual model is opened to make different tests using a variety of technologies as SOEC or the more mature one, Alkaline.

In the following page, a resumé of what have being stay out in this chapter is included.

SDG dimension	SDG Identified	Role	Goal
Biosphere	SDG 13: Climate Action. Take urgent action to combat climate change and its effects (noting the agreements adopted in the forum of the United Nations Framework Convention on Climate Change)	Primary	By 2030, decrease CO2 emissions on a 25% for achieving in 2070 net zero emissions. At the same time, the European Commission expects that renewable hydrogen will be deployed at large scale.
Society	SDG 7: Affordable and clean energy. Making access to energy affordable and compromised with global decarbonization	Primary	Making green hydrogen competitive with gas in the electricity market to provoke the appearance of a virtual floors where generators will decide to produce clean hydrogen obtaining incomes instead of selling energy at lower prices.
Economy	SDG9: Industry, Innovation and Infrastructure. Develop resilient infrastructure, promote inclusive and sustainable industrialization, and encourage innovation	Secondary	Increasing the investments for clean hydrogen to achieve by 2030 at least 40 GW electrolysers to produce 10 million tonnes of renewable hydrogen. Furthermore, to continue investigating new technologies as PEM or SOEC electrolysers

Table 19. SDG dimension summary. Source: Own elaboration

6. PROFITABILITY ANALYSIS

In this section is specified the costs associated to the elaboration of this document as well as the costs related to the equipment and licenses needed to provide the information and analysis required.
The costs are decomposed in the following groups:

- Workforce
- Equipment
- Licenses

The value of the costs associated to the purchase of the material needed for this research coincide with the retail prices provided by each manufacturer for personal uses. Each value is duly referenced.

The workforce will be divided in engineer, supervisor, and technicians consulted. It has been divided attending the nature of the tasks performed or proposed. The tasks were the conceptual development, the development direction, and the building of the system/model, respectively. The following table specified the cost associated to the workforce for certain working hours.

Workforce type	Quantity (Hours)	Cost per hour	Total Cost
Engineer	400	25 €	10.000 €
Supervisor	20	60 €	1.200 €
Technician	40	60 €	2.400 €
Total			13.600 €

Table 20. Workforce costs. Source: Own elaboration

It is considered that the equipment employed for the project will be amortized in four years. In the table below the costs associated to this research are disaggregated:

Concept	Price
HP Envy Notebook, [51]	1.274 €
Ipad Pro 128 GB, [52]	1.199 €
Total (4 years)	2.473 €
Annually amortizable	618 €

Table 21. Equipment Costs. Source: Own elaboration

The following table will show the costs related to the licenses used in the project:

Concept	Price
Office 365 License, [53]	69 €
GAMS License, [54]	537,60 €
Total	607 €

Table 22. Licenses costs. Source: Own elaboration

Hence, the total cost for this one-year project is reflected in the table 7:

Cost Type	Cost
Workforce	13.600 €
Equipment	618 €
Licenses	607 €
Total	14.825 €

Table 23. Project Cost. Source: Own elaboration

7. CONCLUSIONS

The panorama has been set out, and the plan for the energetic transition has been established. However, Spain must start its implementation if it wants to be a benchmark in climate neutrality as it is said in the Spanish roadmap, [3].

After a careful analysis of the hydrogen value chain, it can be concluded that the role of hydrogen on a circular economy can be as an energy storage, incorporated on the gas pipeline or, in the electricity sector, giving more flexibility to the electrical network by, for example, profiting from the renewable electricity surplus. Hydrogen offers a great breadth to the operator of the electrical system both to offer resilience and to offer flexibility to big scale.

Considering the scenarios analyzed, it can be inferred that hydrogen production must come from energy excess to be competitive with the conventional technologies. However, when the energy excess is not sufficient to supply the external hydrogen demand, the combined cycles will increase its production. This last resource will drive prices up because the energy price matching is marked by combined cycles.

Furthermore, hydrogen storage gives flexibility and stability to the actual power system. It helps to reduce the difference between peak and off-peak prices. However, the system only stores when the hydrogen production capacity is not limited or if the production prices are not too high. Otherwise, the production would be only destinated to supply the hydrogen demand.

It is important to indicate that, as the model has been approached, supplying the demand using stored hydrogen is inefficient. Therefore, in none of the cases does this situation occur.

Analyzing the average electricity prices obtained, it has been observed that introducing hydrogen in the power balance increases the average electricity price. However, the difference between using hydrogen or not is not too big. Hydrogen gives flexibility to the system and being able to store it helps to decrease the final price. The prices obtained in the different cases were around 20€/MWh which is a considered price in other studies as [16]. This electricity price and a 30% reduction on the electrolysers costs will drift to the appearance of a virtual floor in the electricity market, a threshold below which prices will not fall. This floor price is key when making long-term hourly price forecasts and giving the right price signals to renewable projects' investors.[16].

However, the model simulated does not include transportation, therefore, for future studies, it would be interesting to analyzed how transportation will affect the model proposed, in order to understand how a decentralized model would work and to take into consideration the possible delays that would occur.

In addition, simulating longer scenarios would give a better perspective of the hydrogen implementation in the future power system, as well as, analyzing Spain and Portugal as a unique system. Another field of expansion would be using investments in hydrogen production and storage capacities in order to analyze the optimal installed capacities for the expected future hydrogen demand. However, the weekly optimization that was introduced, makes difficult to carry out this implementation.

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