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UNIVERSIDAD PONTIFICIA
ICAI

MASTER IN THE ELECTRIC POWER INDUSTRY

MASTER'S THESIS

ECONOMIC MODELS TO OPTIMIZE GREEN HYDROGEN PRODUCTION WITH A PV FARM IN SPAIN. CASE STUDY FOR A SOLAR 50MW SITE WITH AN H2 ELECTROLYZER ON SITE.

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To my family

To my friends

Acknowledgment

First of all, I would like to thank Comillas Pontifical University - ICAI - for the teaching and values that were transmitted throughout the years I have spent within its walls. Without a doubt, all the experiences I have had have made me a better person, and above all a better professional capable of facing any challenge that comes my way.

Secondly, I would like to express my most sincere gratitude to my director, professor and also mentor Daniel Fernández Alonso, who trusted me from the beginning, becoming an unconditional pillar in the development of my professional carrier.

Lastly, and most important, this journey would not have been possible without the unconditional love and support of my family, with special mention to my parents, who have been my greatest support and who have kept me going at times when I did not even believe in myself.

To each and every one of you, thank you!

Laura Ruiz Lozano

$18^{th} July, 2021$

Internship at ENGIE Spain

Engie S.A. is a French multinational electric utility company, which operates in the fields of energy transition, electricity power and gas trading generation and distribution, natural gas, nuclear, and any sources of renewable energy. It is one of the few players in the sector to develop expert skills in both upstream and downstream activities.

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¿Qu'est-ce que l'on brûlera à la place du charbon si celui-ci venait à manquer? De l'eau répondit Pencroft. L'eau, décomposée en ses éléments par l'électricité.

Oui mes amis, je crois que l'eau sera un jour employée comme combustible, que l'hydrogène et l'oxygène qui la constituent, utilisés isolément ou simultanément, fourniront une source de chaleur et de lumière inépuisables. L'eau est le charbon de l'avenir.

Jules Verne
"L'île mystérieuse" (1874)

Contents

List of Figures

List of Tables

Abstract

SUMMARY

Hydrogen is not a primary source of energy but an energy carrier. Green hydrogen will be key to eliminate greenhouse gas emissions, responsible for climate change, as well as other pollutants linked to segments such as transport, energy generation and the industrial sector.

This Master Thesis is aimed at reviewing in depth the state of the art of green hydrogen and its production technologies. Furthermore, an understanding of hydrogen economics and the strategic impact in the energy sector will be carried out in order to be able to elaborate a simplified robust financial model to analyze the expected profitability of PV farms investment that includes an H_2 electrolyzer.

Key words - electrolyzer, hydrogen plant, electrolysis, green hydrogen, decarbonization, energy transition.

I - INTRODUCTION

Renewable energies are clean, inexhaustible, and increasingly competitive sources of energy. They differ from fossil fuels mainly in their diversity, abundance, and potential for use in any part of the planet, but above all in that they do not produce greenhouse gases. The growth of renewable energies is unstoppable, as reflected in the statistics provided annually by the International Energy Agency (IEA).

Large utilities must face this new green reality and for this reason it is now time to explore different market alternatives and possibilities to extract the highest economical profit from a green power plant, in this regard, power batteries and H_2 production acting as an energy vector.

The Spanish Council of Ministers has approved the "Hydrogen Roadmap: a commitment to renewable hydrogen" [Esp20]. With this plan, the Government is promoting the deployment of this sustainable energy vector, which will be key for Spain to achieve climate neutrality, with a 100% renewable electricity system, no later than 2050.

The development of renewable hydrogen will encourage the creation of innovative industrial value chains in the country, technological knowledge, and the generation of sustainable employment, contributing to the reactivation towards a green economy with high added value.

I-A GREEN HYDROGEN

Currently, the environmental classification of hydrogen goes as follows: grey hydrogen (from fossil fuels), blue hydrogen (from fossil fuels with carbon capture) and green hydrogen (from renewable resources). This classification goes according to the production methodology from which the hydrogen is obtained. The following pie chart represents the primary resources of hydrogen production.

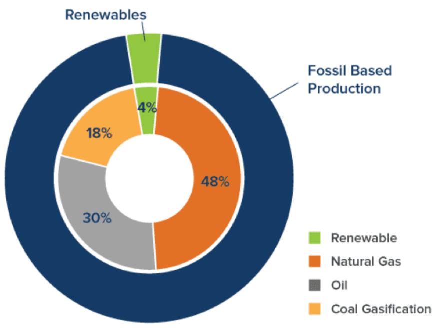


Figure 1. Primary sources of hydrogen production. Source: [Bal08].

When hydrogen is obtained from renewables energies (electrolysis, biomass, etc.) is known as green hydrogen. This new way of obtaining pure hydrogen without emitting greenhouse gasses to the atmosphere allows massive storage of electricity produced by renewable energies, thus offering a solution to compensate for their intermittency and make their production as profitable as possible. Renewable hydrogen has become the key to unlock the full potential of renewables and enable the emergence of a low-carbon energy system.

There exists three main technologies of electrolyzers: alkaline electrolyzer cells (AEC), proton exchange membrane (PEM) electrolyzer, and solid oxide electrolyzer cells (SOEC). A more in depth study will be carried out in order to determine which technology is more suited for the installation adjacent to a solar PV generation plant.

I-C - HYDROGEN ECONOMY

When talking about the future of hydrogen, many scenarios should be taken into account as it is subjected to a lot of uncertainty. These scenarios will evolve as technologies improve deriving in a reduction of the production costs.

The second largest production of H_2 comes from natural gas reforming SMR - Steam Methane Reforming. For this reason, in order to compare and understand the green hydrogen outcome prices, the SMR process will be used as a benchmark for green hydrogen.

To have a more precise conception of how much would it cost to produce hydrogen with natural gas (SMR), with a price of 5$/MMBTU the price of the hydrogen produced will be around 1$/kg. When speaking about the process of electrolysis, the final price is highly dependent on the price of electricity and the renewable technology used.

A parity in prices will be observe in the near future. From 2030 to 2050, renewable hydrogen will start to be price-competitive with grey hydrogen.

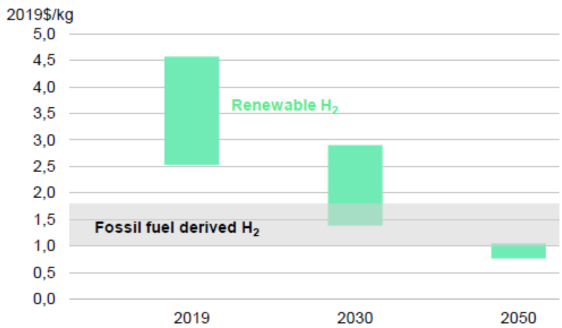


Figure 2. Drop in green hydrogen prices [NEF20].

For a further understanding of the final price of green hydrogen, the levelized cost of hydrogen - LCOH method - will be used. The LCOH is a methodology used to account for all the capital and operating costs of producing hydrogen and therefore enables different production routes to be compared on a similar basis.

LCOH	Utilization rate									
Electricity market price €/MWh	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0	6.47	3.24	2.16	1.62	1.29	1.08	0.92	0.81	0.72	0.65
10	7.04	3.81	2.73	2.19	1.87	1.65	1.50	1.38	1.29	1.22
20	7.62	4.38	3.31	2.77	2.44	2.23	2.07	1.96	1.87	1.80
30	8.19	4.96	3.88	3.34	3.02	2.80	2.65	2.53	2.44	2.37
40	8.77	5.53	4.45	3.91	3.59	3.38	3.22	3.11	3.02	2.94
50	9.34	6.11	5.03	4.49	4.16	3.95	3.80	3.68	3.59	3.52
60	9.92	6.68	5.60	5.06	4.74	4.52	4.37	4.25	4.16	4.09
70	10.49	7.25	6.18	5.64	5.31	5.10	4.94	4.83	4.74	4.67
80	11.06	7.83	6.75	6.21	5.89	5.67	5.52	5.40	5.31	5.24
90	11.64	8.40	7.32	6.78	6.46	6.25	6.09	5.98	5.89	5.81

Figure 3. Levelized cost of hydrogen 2020.

II - METHODOLOGY

When determining the optimal electrolyzer to be installed adjacent to a solar PV plant, a technical and economic study must be carried out.

II-A - TECHNICAL STUDY

The technical study of the plant is oriented to determine the optimum output power of the hydrogen plant to maximize the available resources of the solar plant and, at the same time, minimizing the plant's costs.

First of all, the power generated by the plant needs to be known. Here is a graph that depicts the variation in generation from June and December.

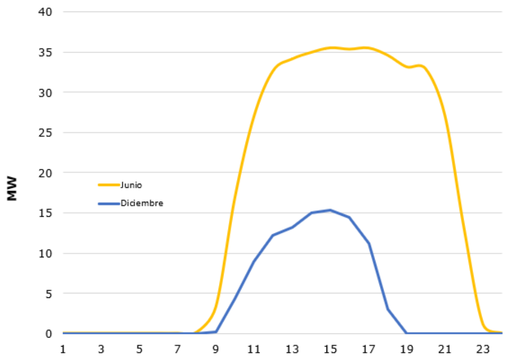


Figure 4. Power generation curve comparative: June and December.

The total annual production of energy from the PV plant is 92.77 GWh. In addition, it returns the hourly production of the solar plant for all days of the year. In this way it is possible to evaluate the energy produced on a monthly basis.

In order to establish the optimal size of the electrolyzer, a study of different power ranges for the hydrogen plant has been carried out. The possible ranges were set in accordance to the AC nominal power of the generation plant - 39.2 MW. The slots where divided in into 39, starting with a capacity of 1MW up to an electrolyzer of 39MW.

The next steps are to determine the energy consumed by each slot, and the hydrogen produced, in kg.

In order to be able to establish the correct value for CAPEX and OPEX of the electrolyzer at the reference year at which the project will be started, the least square approximation was computed. Other cost to take into account is the water required for the electrolysis process.

Finally, in order to set the optimal capacity of the electrolyzer, the way to proceed is to determine the difference in total costs and hydrogen production between the studied capacity and the previous one. The idea of doing it like this is to be able to obtain the lowest variation in price, with the largest variation in hydrogen production within the different capacities. This will provide the lowest marginal cost, resulting in the optimal electrolyzer capacity.

$$min \frac{TC_i - TC_{i-1}}{H_{2i} - H_{2i-1}}$$

The optimal solution for the hybrid configuration is an electrolyzer with a 12MW of installed capacity, where the absolute minimum can be found - 0.856€/kg.

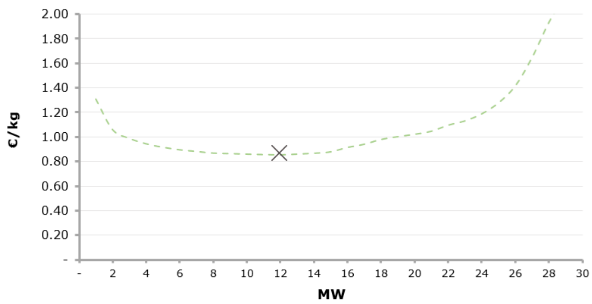


Figure 5. Electrolyzer's marginal costs according to the different hydrogen plant capacities.

II-B - ECONOMIC STUDY

For analyzing the economic viability of the project, the electrolyzer and the solar plant must be taken into account.

The economic study can be approached from different perspectives, but the one used in this Model is the one with which the Net Present Value (NPV) is obtained from the investment and operation of the solar and hydrogen plant.

The economic study with an 8% WACC results in a final price of hydrogen of **7.00€/kg**. This was obtained making the NPV equal to zero.

IV - CONCLUSIONS

The production of green hydrogen from electrolysis will become one of the most important pillars in the decarbonization of the economy. Its versatility for a variety of end-uses such as production of electricity, transport, heating fuel, and many other industrial applications makes it a key asset in the energy transition.

The results show in a practical way the main data extracted from the review of the state of the art. On an industrial scale, there is a large gap of approximately €5/kg between the cost of obtaining gray hydrogen and that of obtaining green hydrogen. Therefore, in order to achieve full industrial development of the technology, support mechanisms are needed, either via subsidies or any other form of injection of money. Only a balance of costs will encourage a complete technological shift from grey to green hydrogen in the different industrial applications that hydrogen is currently used for: fertilizers, mobility, etc.

IV-A - BASE CASE CONCLUSIONS

- The optimal design for the electrolyzer adjacent to a PV generation plant nowadays is not competitive enough.
- The installation of batteries is strongly dependent on the year in which they are installed.
- The lack of a competitive and regulated market from which to extract a hydrogen price makes it difficult to analyze the feasibility of this type of project.

IV-B - FUTURE DEVELOPMENTS

- Encourage knowledge and technological development on the production, storage and use of hydrogen.
- Adaptation of gas structures for energy storage and transport.
- Future green hydrogen demand will drive the development of a new market, with new restrictions, displacing conventional fuels.
- Oxygen capture and storage technologies.
- An adequate hydrogen regulation must be established.

Resumen

RESUMEN

El hidrógeno no es una fuente de energía primaria, sino un vector energético. El hidrógeno verde será clave para eliminar las emisiones de gases de efecto invernadero, responsables del cambio climático, así como otros contaminantes ligados a segmentos como el transporte, la generación de energía y el sector industrial.

Esta Tesis de Máster tiene como objetivo revisar en profundidad el estado del arte del hidrógeno verde y sus tecnologías de producción. Además, se llevará a cabo una comprensión de la economía del hidrógeno y del impacto estratégico en el sector energético, con el fin de poder elaborar un modelo financiero robusto y simplificado para analizar la rentabilidad esperada de la inversión en parques fotovoltaicos que incluyan electrolizadores para la producción de H_2.

Palabras clave - electrolizador, hidrógeno verde, electrólisis, descarbonización, transición energética

I - INTRODUCCIÓN

Las energías renovables son fuentes de energía limpias, inagotables y cada vez más competitivas. Se diferencian de los combustibles fósiles principalmente en su diversidad, abundancia y potencial de uso en cualquier parte del planeta, pero sobre todo en que no producen gases de efecto invernadero. El crecimiento de las energías renovables es imparable, como reflejan las estadísticas que ofrece anualmente la Agencia Internacional de la Energía (IEA por sus siglas en inglés).

Las grandes empresas deben hacer frente a esta nueva realidad verde y, por ello, ha llegado el momento de explorar las diferentes alternativas del mercado y las posibilidades de extraer el mayor beneficio económico de una central eléctrica verde, en este sentido, las baterías eléctricas y la producción de H_2 actúan como vector energético.

El Consejo de Ministros español ha aprobado la "Hoja de ruta del hidrógeno: una apuesta por el hidrógeno renovable"[Esp20]. Con este plan, el Gobierno impulsa el despliegue de este vector energético sostenible, que será clave para que España alcance la neutralidad climática, con un sistema eléctrico 100 % renovable, a más tardar en 2050.

El desarrollo del hidrógeno renovable fomentará la creación de cadenas de valor industriales innovadoras en el país, el conocimiento tecnológico y la generación de empleo sostenible, contribuyendo a la reactivación hacia una economía verde de alto valor añadido.

I-A HIDRÓGENO VERDE

Actualmente, la clasificación medioambiental del hidrógeno es la siguiente: hidrógeno gris (procedente de combustibles fósiles), hidrógeno azul (procedente de combustibles fósiles con captura de carbono) e hidrógeno verde (procedente de recursos renovables). Esta clasificación va en función de la metodología de producción de la que se obtiene el hidrógeno. El siguiente gráfico representa los principales recursos de producción de hidrógeno.

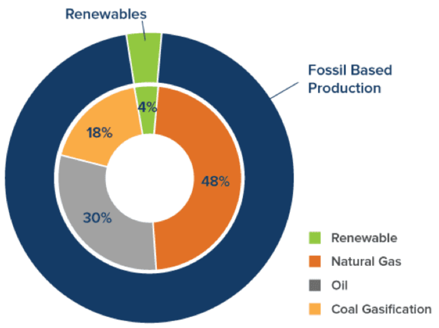


Figura 6. Fuentes primarias de producción de hidrógeno. Fuente: [Bal08].

Cuando el hidrógeno se obtiene a partir de energías renovables (electrólisis, biomasa, etc.) se conoce como hidrógeno verde. Esta nueva forma de obtener hidrógeno puro sin emitir gases de efecto invernadero a la atmósfera permite el almacenamiento masivo de la electricidad producida por las energías renovables, ofreciendo así una solución para compensar su intermitencia y rentabilizar al máximo su producción. El hidrógeno renovable se ha convertido en la clave para liberar todo el potencial de las energías renovables y permitir la aparición de un sistema energético bajo en carbono.

Existen tres tecnologías principales de electrolizadores: las células de electrolizadores alcalinos (AEC), los electrolizadores de membrana de intercambio de protones (PEM) y las células de electrolizadores de óxido sólido (SOEC). Se llevará a cabo un estudio más profundo para determinar qué tecnología es más adecuada para la instalación adyacente a una planta de generación solar fotovoltaica.

I-C - ECONOMÍA DEL HIDRÓGENO

Cuando se habla del futuro del hidrógeno, hay que tener en cuenta muchos escenarios, ya que está sometido a mucha incertidumbre. Estos escenarios irán evolucionando a medida que las tecnologías mejoren, lo que derivará en una reducción de los costes de producción.

La segunda mayor producción de H_2 proviene del reformado de gas natural SMR (Steam Methane Reforming). Por esta razón, para comparar y comprender los precios resultantes del hidrógeno verde, se utilizará el proceso SMR como referencia de precios.

Para tener una idea más precisa de cuánto costaría producir hidrógeno con gas natural (SMR), con un precio de 5$/MMBTU el precio del hidrógeno producido será de alrededor de 1$/kg. Si hablamos del proceso de electrólisis, el precio final depende en gran medida del precio de la electricidad y de la tecnología renovable utilizada.

En un futuro próximo se observará una paridad de precios. De 2030 a 2050, el hidrógeno renovable empezará a ser competitivo en precio con el hidrógeno gris.

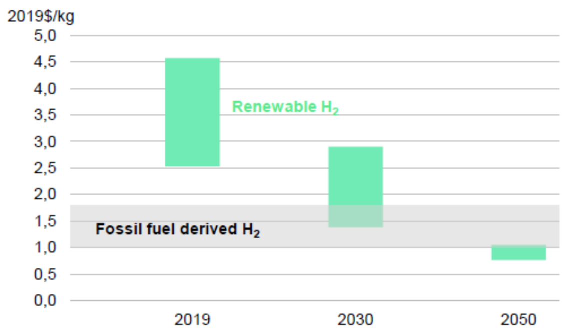


Figura 7. Caída de los precios del hidrógeno verde [NEF20].

Para comprender mejor el precio final del hidrógeno verde, se utilizará el método del coste nivelado del hidrógeno (LCOH). El LCOH es una metodología que se utiliza para contabilizar todos los costes de capital y de explotación de la producción de hidrógeno y, por tanto, permite comparar diferentes rutas de producción sobre una base similar.

LCOH	Utilization rate									
Electricity market price €/MWh	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0	6.47	3.24	2.16	1.62	1.29	1.08	0.92	0.81	0.72	0.65
10	7.04	3.81	2.73	2.19	1.87	1.65	1.50	1.38	1.29	1.22
20	7.62	4.38	3.31	2.77	2.44	2.23	2.07	1.96	1.87	1.80
30	8.19	4.96	3.88	3.34	3.02	2.80	2.65	2.53	2.44	2.37
40	8.77	5.53	4.45	3.91	3.59	3.38	3.22	3.11	3.02	2.94
50	9.34	6.11	5.03	4.49	4.16	3.95	3.80	3.68	3.59	3.52
60	9.92	6.68	5.60	5.06	4.74	4.52	4.37	4.25	4.16	4.09
70	10.49	7.25	6.18	5.64	5.31	5.10	4.94	4.83	4.74	4.67
80	11.06	7.83	6.75	6.21	5.89	5.67	5.52	5.40	5.31	5.24
90	11.64	8.40	7.32	6.78	6.46	6.25	6.09	5.98	5.89	5.81

Figura 8. Coste nivelado del hidrógeno 2020.

II - METODOLOGÍA

A la hora de determinar el electrolizador óptimo que debe instalarse junto a una planta solar fotovoltaica, hay que realizar un estudio técnico y económico.

II-A - ESTUDIO TÉCNICO

El estudio técnico de la planta está orientado a determinar la potencia óptima del electrolizador para maximizar los recursos disponibles de la planta solar y, al mismo tiempo, minimizar los costes.

En primer lugar, es necesario conocer la potencia generada por la planta. A continuación se muestra un gráfico que representa la variación de la generación entre junio y diciembre.

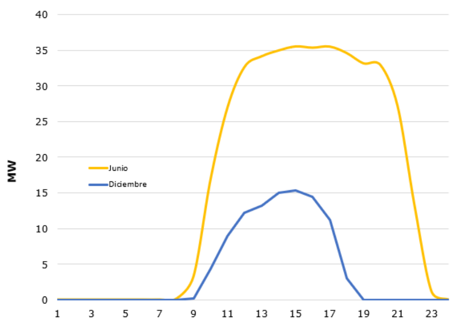


Figura 9. Comparativa de la curva de generación de energía: Junio y diciembre.

La producción total anual de energía de la planta fotovoltaica es de 92,77 GWh. Además, devuelve la producción horaria de la planta solar para todos los días del año. De este modo, es posible evaluar la energía producida mensualmente.

Para establecer el tamaño óptimo del electrolizador, se ha realizado un estudio de diferentes rangos de potencia para la planta de hidrógeno. Los rangos posibles se establecieron de acuerdo con la potencia nominal de CA de la planta de generación - 39,2 MW. Los rangos se dividieron en 39, empezando por una capacidad de 1MW hasta un electrolizador de 39MW.

Los siguientes pasos son determinar la energía consumida y el hidrógeno producido - en kg - por cada potencia de electrolizadores.

Para poder establecer el valor correcto de CAPEX y OPEX del electrolizador en el año de referencia en el que se iniciará el proyecto, se ha llevado a cabo el cálculo a través de la aproximación de mínimos cuadrados. Otro coste a tener en cuenta es el agua necesaria para el proceso de electrólisis.

Finalmente, para fijar la capacidad óptima del electrolizador, se procede a determinar la diferencia de costes totales y de producción de hidrógeno entre la capacidad estudiada y la anterior. La idea de hacerlo así es poder obtener la menor variación de precio, con la mayor variación de producción de hidrógeno dentro de las diferentes capacidades. De esta forma se obtendrá el menor coste marginal, dando como resultado la capacidad óptima del electrolizador.

$$min \frac{TC_i - TC_{i-1}}{H_{2i} - H_{2i-1}}$$

La solución óptima para la configuración híbrida es un electrolizador con una capacidad instalada de 12MW, donde se puede encontrar el mínimo absoluto - 0,856€/kg.

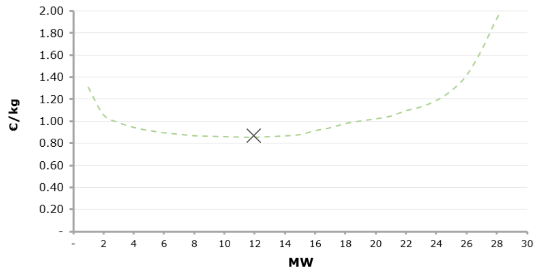


Figura 10. Costes marginales del electrolizador según las diferentes capacidades de las plantas de hidrógeno.

II-B - ESTUDIO ECONÓMICO

Para analizar la viabilidad económica del proyecto hay que tener en cuenta el electrolizador y la planta solar.

El estudio económico puede abordarse desde diferentes perspectivas, pero la utilizada en este Modelo es aquella con la que se obtiene el Valor Actual Neto (VAN) de la inversión y operación de la planta solar y el electrolizador.

El estudio económico con un WACC del 8 % da como resultado un precio final del hidrógeno de **7,00 €/kg**. Esto se ha obtenido haciendo que el VAN sea igual a cero.

IV - CONCLUSIONES

La producción de hidrógeno verde a partir de la electrólisis se convertirá en uno de los pilares más importantes de la descarbonización de la economía. Su versatilidad para diversos usos finales, como la producción de electricidad, el transporte, el combustible para calefacción y muchas otras aplicaciones industriales, lo convierten en un activo clave en la transición energética.

Los resultados muestran de forma práctica los principales datos extraídos de la revisión del estado del arte. A escala industrial, existe una gran diferencia, de aproximadamente 5 €/kg, entre el coste de obtener hidrógeno gris y el de obtener hidrógeno verde. Por lo tanto, para lograr el pleno desarrollo industrial de la tecnología, se necesitan mecanismos de apoyo, ya sea mediante subvenciones o cualquier otra forma de inyección de dinero. Sólo un equilibrio de costes fomentará un cambio tecnológico completo del hidrógeno gris al verde en las diferentes aplicaciones industriales para las que se utiliza actualmente: fertilizantes, movilidad, etc.

IV-A - CONCLUSIONES CASO BASE

- El diseño óptimo del electrolizador adyacente a una planta de generación fotovoltaica hoy en día no es lo suficientemente competitivo.
- La instalación de baterías depende en gran medida del año en que se instalen.
- La falta de un mercado competitivo y regulado del que extraer el precio del hidrógeno dificulta el análisis de la viabilidad de este tipo de proyectos.

IV-B - DESARROLLOS FUTUROS

- Fomentar el conocimiento y el desarrollo tecnológico sobre la producción, el almacenamiento y el uso del hidrógeno.
- Adaptación de las estructuras de gas para el almacenamiento y el transporte de energía.
- La futura demanda de hidrógeno verde impulsará el desarrollo de un nuevo mercado, con nuevas restricciones, que desplazará a los combustibles convencionales.
- Debe establecerse una regulación adecuada del hidrógeno.
- Tecnologías de captura y almacenamiento de oxígeno.

1

Introducción

The measure of intelligence is the ability to change
Albert Einstein (1879–1955)

The aim of this first chapter is to put into context the main motivations of the project in a way of introducing the topics that will be further developed in this Master Thesis.

1.1. Motivation

Renewable energies are clean, inexhaustible, and increasingly competitive sources of energy. They differ from fossil fuels mainly in their diversity, abundance, and potential for use in any part of the planet, but above all in that they do not produce greenhouse gases - causing climate change - or polluting emissions. Moreover, their costs are steadily decreasing, while the general trend of fossil fuel costs is the opposite, regardless of their economic volatility.

The growth of renewable energies is unstoppable, as reflected in the statistics provided annually by the International Energy Agency (IEA). According to IEA forecasts, the participation of renewables in the global electricity supply will increase from 26% in 2018 to 44% in 2040, and they will provide 2/3 of the increase in electricity demand recorded in that period, mainly through wind and photovoltaic technologies.

The European and Spanish energy sector is waiting for a rainfall of billion EUR within the 2020/2030 period, following different regulations to foster the Energy Transition and the decarbonization of the society within the next decade. The post Covid-19 pandemic context, and the expected economic recovery to be mostly driven by the green renewable industry will doubtless accelerate the penetration of green energy. Renewable production has already started to evolve towards a more sophisticated energy management technology. As an example, the Spanish Government has committed in early 2021 up to 38 billion EUR public subsidies for energy transition industrial projects. These projects will have to be extremely aligned with the requests of the EU Next Generation Funds: showing strong capabilities in terms of technical and digital innovation, cohesion between many different local industries and support to local (mostly rural areas) deployment.

Large utilities must face this new green reality and for this reason it is now time to explore different market alternatives and possibilities to extract the highest economical profit from a green power plant. In this regard, power batteries and H2 production acting as an energy vector (it can be stored or directly supplied to a final consumer) are excellent arbitration opportunities with respect to the classical strategy of selling 100% of the production to a wholesale market. As stated above, European, and Spanish renewable support schemes seem to really prioritize those projects offering different storage alternatives on top of the “standard” green energy production.

This Master Thesis is aimed at reviewing in depth the state of the art of batteries and H_2 production technologies. Furthermore, an understanding of hydrogen economics and the strategic impact in the energy sector will be carried out in order to be able to elaborate a simplified robust financial model to analyze the expected profitability of PV farms investment that includes either storage and/or H2 electrolyzers. The final document is aiming at summarizing what an energy investor must master.

1.2. Spanish regulatory framework

1.2.1. Hydrogen Roadmap: a bet on renewable hydrogen

The Council of Ministers has approved the "Hydrogen Roadmap: a commitment to renewable hydrogen" [Esp20]. With this plan, the Government is promoting the deployment of this sustainable energy vector, which will be key for Spain to achieve climate neutrality, with a 100% renewable electricity system, no later than 2050. The development of renewable hydrogen will encourage the creation of innovative industrial value chains in the country, technological knowledge, and the generation of sustainable employment, contributing to the reactivation towards a green economy with high added value.

The document, whose development is contemplated in the Integrated Energy and Climate Plan (PNIEC by its acronym in Spanish) 2021-2030, includes 60 measures and sets national targets -aligned with the European Hydrogen Strategy- to 2030. Among others, 4 gigawatts (GW) of installed capacity of electrolysers, a minimum of 25% of hydrogen consumption by industry must be renewable and implementation of hydrogen plants, trains and heavy transport vehicles propelled by this product.

The achievement of the 2030 targets set out in the Roadmap will make it possible to reduce greenhouse gas emissions by 4.6 million tonnes of CO2 equivalent (CO2eq). Finally, the Roadmap anticipates a vision of what the role of hydrogen will be in the next three decades, in which Spain seeks to lead a national project towards a decarbonized economy, in such a way as to promote the innovative value chain, the applied knowledge of the industry, the development of pilot projects throughout the national territory and support for areas of just transition.

The potential of hydrogen

Hydrogen is not a primary source of energy, such as the sun or wind, but an energy carrier, i.e. a manufactured product that is capable of storing energy so that it can be released gradually. If renewable energies are used in its manufacture, the hydrogen obtained will be considered “green hydrogen” or “renewable hydrogen”.

The Roadmap identifies this energy vector as a key sustainable solution for the decarbonization of the economy and the development of industrial and RD value chains, thus becoming one of the levers of economic reactivation linked to the energy transition, together with other areas such as renewable deployment, sustainable and connected mobility or the energy refurbishment of buildings.

Opportunities for Spain

In this sense, the Roadmap identifies the opportunities that the promotion of national production and the application of renewable hydrogen represent for Spain.

Firstly, the commitment to renewable hydrogen will activate the development of value chains. New opportunities open up for the generation of sustainable employment and economic activity in areas such as the manufacture of electrolyser assemblers, fuel cells, components (electronics, control, automotive, mechanical), vehicles, shipyards, pressure tanks, h2 dispensers or renewable hydrogen production plants, as well as their management, large-scale storage solutions, hydrogen transport equipment or mobility services based on renewable hydrogen.

This strengthening of the value chain will be accompanied by greater Spanish energy R&D&I, which will also become a pillar for sustainable economic development. In this respect, the Spanish Science, Technology and Innovation Strategy 2021-2027 includes among its strategic lines of national RD the application of renewable hydrogen in industry and as a resource for climate change and decarbonization.

Green hydrogen will be key to the path the country has embarked on to eliminate greenhouse gas emissions, responsible for climate change, as well as other pollutants linked to segments such as transport, energy generation and the industrial sector. In fact, the Roadmap highlights the potential of renewable hydrogen to decarbonize sectors or processes with greater decarbonization complexity, such as air transport or industrial processes that require high temperatures.

In addition, the document highlights its potential to accelerate renewable deployment in Spain, with the associated positive effects that a greater presence of renewable energies in the system has on electricity prices and industrial competitiveness. In this area, the Roadmap underlines its role in the development of smart grids and, especially, to store renewable energy on a large scale and seasonally, providing manageability to the system. This deployment will be in line with the Storage Strategy, the draft of which is currently being prepared by MITECO.

These two factors, according to the Roadmap, will make hydrogen one of the main assets to make Spain one of the European powers in renewable generation. To this must be added the implementation of other technologies, such as those included in the Roadmap for the development of offshore wind and marine energy in Spain, also in the drafting phase, which will bring about a radical change to the current energy paradigm, consolidating a 100% renewable electricity system by 2050 at the latest.

Another aspect highlighted by the Roadmap is the potential of renewable hydrogen to favor the decarbonization of isolated energy systems, with special attention to island territories.

Objectives to 2030

The Roadmap sets out national objectives for the promotion of renewable hydrogen to 2030 and, on the basis of these, outlines a vision to 2050, when Spain will have to achieve climate neutrality and have a 100% renewable electricity system. The objectives are consistent with the targets set by the European Commission in its Hydrogen Strategy. They are as follows:

- Production: 4 GW of installed electrolysis capacity - the renewable hydrogen production system using clean energies and water - which represents 10% of the target set by the European Commission for the EU as a whole. In addition, as an intermediate milestone, it is estimated that by the year 2024 it would be possible to have an installed capacity of electrolysers of between 300 and 600 MW.
- 25% of industrial hydrogen consumption will be of renewable origin by 2030. At present, industry uses practically all of the 500,000 tonnes of hydrogen consumed annually in Spain. Most of the product used is hydrogen of fossil origin (or grey hydrogen), i.e. it uses natural gas as a raw material in its production. For every kilogram of renewable hydrogen that replaces an existing consumption of non-renewable hydrogen, 9 kg of CO2 are avoided in the atmosphere.
- In terms of mobility, by 2030, a fleet of at least 150 buses; 5,000 light and heavy-duty vehicles; and 2 commercial train lines powered by renewable hydrogen are foreseen. Similarly, a network of at least 100 hydrogen dispensers and hydrogen-powered handling machinery should be implemented in the first 5 ports and airports.

Based on these targets, the Roadmap anticipates the changes that will occur in the hydrogen economy beyond 2030 and up to 2050. The document highlights that, once this decade is over, there will be an acceleration in the production and application of renewable hydrogen in Spain, which will be fully competitive with other production technologies. This fact will facilitate the expansion of renewable hydrogen consumption in sectors that are difficult to decarbonize and in new applications, including maritime and air transport, and high temperature industrial energy processes. Finally, due to its potential as a producer, the Roadmap foresees that Spain could become an exporter of renewable hydrogen to the rest of Europe.

Figure 1.1. Main objectives for 2030.

60 measures

The document proposes a set of 60 measures, grouped into four areas of action. Firstly, it includes actions of a regulatory nature that include, among others, the introduction of a system of guarantees of origin to ensure that the hydrogen has been produced from 100% renewable energy. A second chapter is dedicated to sectoral measures to encourage the use of renewable hydrogen and the start-up of projects in areas such as industry, energy and mobility.

On the other hand, the Roadmap includes measures of a transversely nature to promote awareness of the potential of renewable hydrogen in society as a whole; and, lastly, it addresses the promotion of RDI linked to these technologies.

Among other measures, the Roadmap will promote the design of financial instruments to support Spanish industry, which is an intensive hydrogen consumer, in adapting its processes and infrastructures to the continuous supply of renewable hydrogen. Likewise, the current hydrogen consumption poles will be identified, promoting and encouraging the creation of "hydrogen valleys"; and the constitution of Industrial Hydrogen Committees will be promoted together with autonomous communities, local administrations, hydrogen consumers and promoters of renewable hydrogen production projects.

Likewise, measures are included to foster the national development of large power electrolysers (100 MW), as well as to promote their mass production and the application of new materials; and to promote RDI along the hydrogen value chain, so that Spanish science and companies can participate in its development, which will allow the creation of knowledge and competitive advantages, including the Spanish automobile industry, and railway, maritime and air transport. In this respect, an exclusive line of financing will be created for projects in the renewable hydrogen value chain in the successive State Plans for Scientific and Technical Research and Innovation.

Moreover, new renewable hydrogen production energy nuclei will be promoted to help prevent rural depopulation and to achieve the objectives of the demographic challenge, with special attention to the regions of just transition.

The Roadmap concludes by identifying the different financing instruments for its deployment, which include the EU Next Generation funds and the Clean Hydrogen Alliance, created by the European Commission. The document also includes an annex with hydrogen projects identified in Spain.

1.2.2. Energy storage strategy: keys to ensuring security and economy of supply

On February 9th, the Spanish Council of Ministers, at the proposal of the Ministry for Ecological Transition and the Demographic Challenge (MITECO), approved the Energy Storage Strategy [Esp21a], which will support the deployment of renewable energies and will be key to guaranteeing the security, quality, sustainability and economy of supply.

The Strategy, which forms part of the set of actions aimed at achieving the objectives established in the PNIEC and the Long-Term Decarbonization Strategy 2050, establishes 10 lines of action and 66 measures aimed at promoting the deployment of storage and boosting the competitiveness of the industry in its value chain, in order to achieve the objectives, set to reach a storage capacity of 20 GW in 2030 and 30 GW in 2050, considering large-scale and distributed storage. In this sense, energy storage systems are key to guaranteeing the transition to an emission-neutral economy and the effective integration of renewable energies into the system, as they allow energy to be stored at times when there is a surplus in order to use it when renewable resources are scarce, or demand is high.

In relation to renewable hydrogen, the Strategy establishes the following measures:

- Promotion of green hydrogen.
- Development of Power-to-X.
- Thermal storage potential.
- Support for R&D&I in hydrogen value chain technologies.

1.3. Recovery, transformation and resilience plan

Within the global objective of zero emissions by 2050, this component aims to position Spain as a technological benchmark in the production and use of renewable hydrogen, creating innovative value chains.

This energy vector has a high potential in those end uses where it is the most efficient solution, such as hydrogen-intensive industry and high-temperature processes, long-distance heavy transport, maritime transport, rail transport or aviation. In addition, the quality of energy vector gives it great potential as an instrument for energy storage and sectoral integration.

Currently, the lack of projects on a sufficient scale in Spain and its cost differential with respect to other fuels prevents the necessary technical and regulatory development to take advantage of this potential. However, it will be a necessary tool to displace other fuels and decarbonize sectors where electrification or substitution by direct renewable uses is unfeasible, as envisaged in the Long Term Strategy 2050.

The objective is to create a favorable environment for the development and deployment of renewable hydrogen as a key energy vector for the future, around an innovative industrial value chain and knowledge based on SMEs, by supporting technology transfer and the development of new lines of business.

Spain has the opportunity to position itself as a technological reference in the production and use of renewable hydrogen, leading a country project towards a decarbonized economy, by promoting the hydrogen value chain through the creation of technology clusters and pilot projects at a regional scale, the promotion of industrial innovation, support for fair transition zones and the availability of renewable energy at competitive prices. [Esp21b]

For this reason, an estimated total investment of **1.555 M€** will be allocated to renewable hydrogen, and will be developed through 4 main lines:

a) Measures to support SMEs and technology centers,

b) Sectoral integration that spatially concentrates large-scale production, transformation and consumption,

c) Development of pioneering projects,

d) Integration of the national value chain into the community value chain.

This grant corresponds to a 2,2% of the total monetary amount intended to boost the recovery plan between 2021-2023. However, a greater investment will be needed in order to achieve the 4GW if electrolyzers up until 2030.

A study carried out by Iberdrola revealed that in order to achieve the objective of 4GW by 2030, an investment of approximately 9.000 M€ will be necessary. Currently the objective for 2025 is to have installed 600 MW.

1.4. Decarbonization of the economy and energy transition

At this point, several essential questions arise for the definition of the energy transition roadmap. It must address the needs of all sectors, including industry, transport, residential, services and others. These needs require both electrical and thermal energy. However, the greater prospect of growth in renewable sources leads us to foresee a greater increase in electricity generation than thermal generation, despite fluctuations and intermittencies. To compensate for these drawbacks and ensure an adequate energy supply to the grid, the introduction of renewable sources entails a high probability of excess generation over the course of a year, as the penetration of these sources increases. (see Figure 1.2).

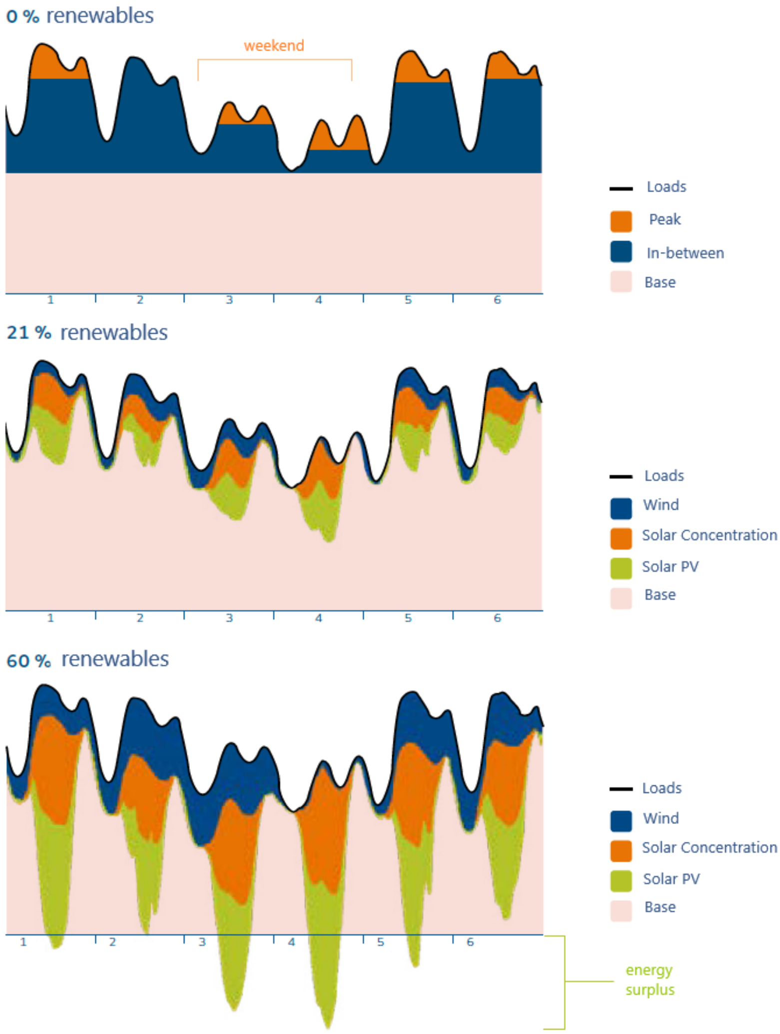


Figure 1.2. Increase in excess power generation as a function of the percentage penetration of renewables in the power grid. Source: Fundación Naturgy [MAG20].

This excess needs to be harnessed, but to do so, the electrical energy must be stored. There are different options (see Figure 1.3):

- using physical principles such as the use of potential energy in hydraulic systems, or mechanical energy in pressurized air systems, or,
- the use of chemical molecules as energy carriers, either based on electrochemical batteries (for example, using lithium or other redox pairs), or based on simple molecules such as hydrogen or synthetic methane (capable of being stored as a gas), or more complex molecules (capable of being stored as liquids, from methanol to synthetic gasoline), which are technically possible but have very different levels of efficiency and are still under investigation.

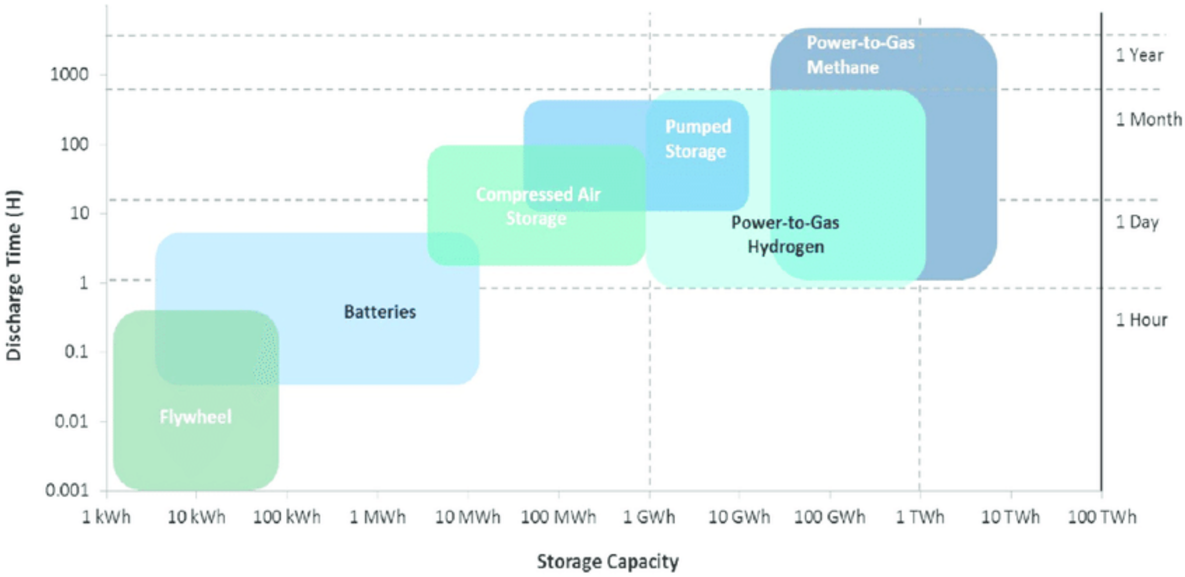


Figure 1.3. Energy storage capacity of different technologies.

Given that the capacities of electrochemical batteries do not currently reach the technical performance required, and their costs are not yet comparatively competitive, the use of simple chemical molecules in the form of gas is a clear alternative, with the added value that in most countries there are already infrastructures available for their storage as renewable gas. This conversion of electrical energy into chemical energy, in the gas phase, is known as Power-to-Gas and is the clearest alternative for powering renewable electricity sources with the ability to store energy in the form of gas. The only system capable of storing electrical energy massively and for long periods of time is hydrogen (see Figure 1.3). If the gas infrastructure already in place is used, several GWh can be stored for months or even years. If necessary, syngas, derived from hydrogen, allows further expansion of storage capacity due to greater compatibility with the infrastructure and higher energy density.

Aspects related to the transport of energy in the form of gas should also be highlighted. Usually, the largest installations of renewable sources are not close to the areas of consumption, so the transport of energy must be considered. In this respect, the comparison between an electricity grid and a gas pipeline leaves no room for doubt. If we wanted to transport energy 100 km, the average cost is estimated to be around 200 €/kW for the power line and only 10 €/kW for the pipeline, 20 times. Hydrogen therefore emerges once again as a clear alternative. [MAG20]

1.5. ENGIE - zero carbon

The ambition of ENGIE is to be the leader in the Zero Carbon Transition and to accompany its customers (industrials, local authorities) in their path towards decarbonization. Engie provides turnkey solutions for the customers with an "as a service approach", to help the customers to rethink their current equipment with decarbonized solutions, involving support for the financing part.

H_2 and more specifically Green H_2 plays a key role in the decarbonization solutions to reach the COP21 Paris objectives (limit the increase of temperature under 2°C and reduce CO2 emissions)

Two main levels should be activated to reach decarbonization:

- Act on the energy efficiency side – consume less
- Increase the part of renewable in the energy mix (objective of ENGIE is to build and install 9GW by 2021 – in addition to the 24 GW existing one)

One characteristic of renewables is their intermittency : production subject to wind and sun and overproduction curtailed if not consumed.

At ENGIE, it is firmly believe that hydrogen is the missing link to unlock the full potential of renewables and carbon-free energy solutions:

Main usages for renewable hydrogen:

- **Decarbonize industrial processes already using Hydrogen as a feedstock** (refinery, chemistry sector, ammonia production, . . .)
- **Mobility usages**: particularly adapted to complement electric solutions in particular for heavy mobility when long distances have to be managed or heavy power capacities are needed (trains, heavy mobility, trucks, fleet of vehicles, maritime)
- **An energy storage medium**, able to store intermittent renewable electricity over longer periods, thus supporting flexibility in the energy system and security of supply for consumers.
- **An essential component of sector coupling**: Renewable electricity can be transformed in green hydrogen and synthetic methane (Power-to-gas) allowing to optimize the use of existing gas networks and underground storage, thus contributing to a cost-efficient energy transition.

At ENGIE , the objective is to be front-runner to develop the renewable hydrogen market.

The way that ENGIE wants to make change is by partnering with early adopters - customers that are already engaged in concrete actions to decarbonize their process. The co-creation and co-development of concrete projects to limit the CO_2 emissions is carried out by the implementation of renewable H_2 solutions.

The main objective of Engie is to build the hydrogen economy, by scaling-up and providing global solutions to decarbonize territories.

2

Hydrogen: the game-changer in the new European Green Deal

Whatever you can do or dream, begin it.
Johann Wolfgang von Goethe
(1749–1832)

This chapter describes the technologies with the greatest current relevance and future potential for mass production of hydrogen: production from natural gas and by electrolysis. It also presents the definition of coloured hydrogen, established from the energy source and production process described here.

2.1. Hydrogen as an energy carrier

Hydrogen is not an energy source but an energy carrier, having many similarities with electricity. There exists various energy sources and technologies from which electricity and hydrogen can be produced. The applications that both have are infinite, being a very versatile product. When addressing the use of hydrogen or electricity, no pollutants are produced (greenhouse gases, sulphur oxides, etc.). When hydrogen is used in a fuel cell, the only sub-product emitted is water. Despite the advantages of hydrogen and electricity, if these where produced from fossil fuels they can have a high CO_2 intensity upstream. For this reason, when hydrogen is produced from coal, oil or natural gas, the technology needs to be equipped with CCUS (Carbon Capture, Use and Storage). [GT19]

Hydrogen is one of the safest fuels. Its safety is comparable to that of natural gas. For this reason, it has been used worldwide for decades in conventional applications in the chemical and petrochemical industry, and also as a fuel before natural gas took over this market. Currently, more than 160 million tons are produced worldwide, of which more than 90% are for industrial use, whether for ammonia production, in refineries, in foodstuffs, in glass manufacturing or in the metallurgical. Hydrogen production in Europe is around 11.5 million tons per year. It is therefore a commodity, a commodity that additionally serves as a fuel, whether for fuel cells, engines or gas turbines. It can also be transported and stored, both as compressed hydrogen and in combination with other molecules such as ammonia or methanol.

The production, transport, storage and uses of hydrogen continue to be developed in anticipation of its use in new areas that will give rise to large markets driven by new regulations to address climate change and the energy transition. Some of these areas may be: the mobility sector and the storage of renewable electric energy in fuels or Power-to-X.

In summary, hydrogen, and hydrogen-based products such as synthetic methane, constitute a pathway for the energy transition to replace the use of fossil fuels, which currently account for 75% of primary energy, with renewable sources. Their use should not only make it possible to largely replace the current use of natural gas, some 350 TWh/year, but also opens up enormous prospects for market expansion based on the introduction of hydrogen in heavy land transport, rail, river and light sea transport and even in light air transport. This increases the future potential of the hydrogen market in Spain, bearing in mind the current available infrastructures of the gas industry.

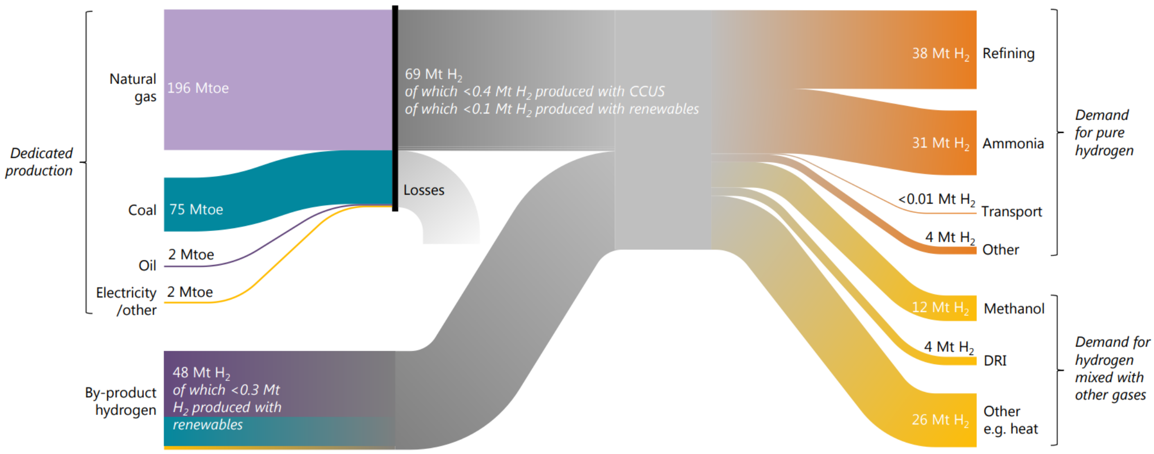


Figure 2.1. Today's hydrogen value chain. Source: IEA [GT19].

2.2. Environmental classification of hydrogen

2.2.1. Grey hydrogen

The term grey hydrogen is used to define hydrogen that is generated from fossil resources and releases the carbon dioxide produced during the reforming reaction into the atmosphere. The term black hydrogen can also be used when referring to hydrogen obtained from coal, and brown hydrogen when it is generated from lignite (a type of coal) [IEA19] , although the most common term for all fossil hydrogen is grey hydrogen.

Grey hydrogen is the most widely consumed hydrogen in Europe, obtained in large natural gas reformers. However, 95% of the hydrogen currently produced does not use carbon dioxide capturing. Emissions during the process amount to about 9 kg CO_2eq/ kg of hydrogen produced, plus an additional 25% from the supply of the raw material, in this case natural gas. Without going into detail on the different reforming technologies, grey hydrogen production can be considered to have emissions in excess of 10-11 kg CO_2eq/kg H_2 generated. Of the process emissions, 2/3 come from the reforming chemical reaction itself plus the displacement reaction, and 1/3 from the burning of fuel to obtain the temperature required for reforming. The emissions of this process are not at all in line with climate targets. By way of comparison, the combustion of 1 kg of gasoline generates about 3-4 kg of CO_2 [IEA19].

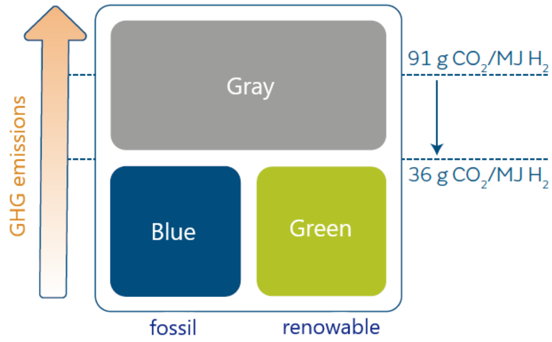


Figure 2.2. Classification of hydrogen according to its environmental impact and origin.

Grey hydrogen is defined, according to the CertifHy [FCH] recommendation, as "hydrogen generated from non-renewable sources that emits more than 4.37 kg CO_2eq/kg H_2 (36.4 CO_2eq/MJ)". To minimize its environmental impact, the method of obtaining hydrogen must incorporate a carbon dioxide capture process, which would transform it into blue hydrogen, or else produce green hydrogen directly.

2.2.2. Blue hydrogen

In the production of blue hydrogen, much of the carbon dioxide emissions are captured. The concept of blue hydrogen can also incorporate hydrogen obtained from natural gas pyrolysis, sometimes referred to individually as turquoise hydrogen.

Blue hydrogen is defined as: "hydrogen generated from non-renewable sources that emits less than 4.37 kg CO_2eq/kg H_2 (36.4 CO_2eq/MJ)". [FCH]

As shown in Figure 2.2, the 36.4 CO_2eq/MJ maximum emissions represent a 60% reduction compared to the current reference process. This maximum emission value is the same for blue hydrogen as for green hydrogen. Therefore, it can be stated with certainty that blue hydrogen is a low-carbon fuel, or at least as low as green hydrogen. It should be noted that all processes, even the greenest, have associated emissions, whether in the construction, transport, operation or dismantling phase of the facilities where they are obtained.

The most relevant process for obtaining blue hydrogen is by reforming natural gas with carbon dioxide capture. This will be explained in more detail in Section 2.3: *Production methodologies*.

However, the very definition of blue hydrogen does not exclude other processes from fossil fuels that have scope for significantly reducing emissions, such as [Cer15]: reforming or pyrolysis of natural gas; electrolysis with non-renewable electricity (nuclear, natural gas, mix); gasification (coal, mixed waste, plastics); thermal cracking (naphtha); or chlorine production (non-renewable electricity).

2.2.3. Green hydrogen

Green hydrogen is defined as low-carbon hydrogen obtained from renewable sources. The technical definition of green hydrogen is: "hydrogen generated from renewable sources that emits less than 4.37 kg CO_2eq/ kg H_2 (36.4 CO_2eq/MJ)"(i.e. 60% GHG emissions saving requirement relative to a fossil fuel comparator of 91 g CO_2eq/MJ H_2. [FCH]

In this sense, green hydrogen must meet these two premises: come from renewable sources and have a low environmental impact. It is important to note that the difference between blue and green hydrogen is that one comes from fossil sources and the other from renewable sources, but the definition of both does not imply any difference in the impact on GHG emissions. In other words, both hydrogens are obtained with low carbon dioxide emissions, although in the case of blue hydrogen the captured CO_2 has to be managed, while in green hydrogen this is avoided and it also has a higher emissions reduction potential than blue hydrogen. Obviously, both aspects determine the production costs, aspects that will be dealt with in future chapters.

The concept of green hydrogen was created specifically for the production of hydrogen from water electrolysis and renewable electricity, in clear contrast to the current process of production from fossil resources and with high environmental impact.

The potential for green hydrogen production through electrolysis is very high, since it can be obtained in any facility that has a system that generates renewable electricity (wind, solar, hydro, geothermal) and has water. Green hydrogen therefore contributes to the wider deployment of these renewable sources. Electrolysis allows the storage of wind energy and solar radiation, and no dependence on polluting power plants. The benefits of green hydrogen are well known, as is the fact that the main obstacle is its production cost, although, as noted below in Chapter 3, these costs are falling rapidly.

2.3. Production methodologies

Hydrogen is the most abundant element in the Universe, but on Earth it is very difficult to find in its fundamental state. Its presence is usually accompanied by other elements to form various molecules. The most common are organic compounds, such as hydrocarbons, and water, in association with oxygen.

Hydrogen production technologies are wide-ranging, as it can be produced from a variety of primary sources, but the largest source is hydrocarbons, especially natural gas. The following figure shows the contribution of each primary source to hydrogen production.

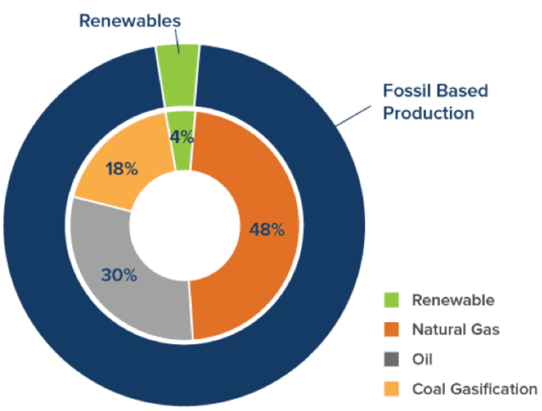


Figure 2.3. Primary sources of hydrogen production. Source: [Bal08].

2.3.1. Steam reforming

Natural gas reforming is based on decomposition of the methane molecule to give rise to hydrogen and carbon oxides (CO and CO_2). This process requires a combination of three conditions [US20b]: high temperature (700 - 1100 ° C), the presence of a catalyst (nickel-based), and the presence of an oxidizing agent (water and/or air).

There are three production methods depending on the oxidizing agent:

- Water vapor: steam reforming.
- Oxygen or air: partial oxidation.
- A combination of both: autothermal reforming.

The oxidizing agent most commonly used in the natural gas reforming process is steam reforming, known as the Steam Methane Reforming process (SMR) [IEA17], and basically consists of two reactions. The first is the partial decomposition of methane into carbon monoxide (CO) and water (H_2O), which takes place at high temperatures and consumes a large amount of energy. The second is the water-gas shift, which is used to increase the amount of hydrogen generated, which is slightly exothermic and takes place at lower temperatures.

Regardless of the oxidizing agent, the current overall hydrogen production process is based on 4 stages in series (see Figure 2.4): natural gas desulfurization, reforming, gas displacement and hydrogen purification. Of these, the central unit of the process is the reformer, but before entering the reformer, the natural gas undergoes a desulfurization process, in which more than 99% of the sulfur contained in the conventional gas is removed. After the desulfurization stage, a H_2S-clean gas is obtained.

Once cleaned, the natural gas is mixed with water vapor, the temperature is increased to about 700-900°C and it is introduced into a nickel-based catalytic bed. Once the syngas mixture (CO and H2) is achieved, it is passed to the displacement unit to convert the carbon monoxide (CO) to carbon dioxide (CO_2) and increase the amount of final hydrogen.

The product obtained from the reforming is a mixture of carbon dioxide (CO_2) and hydrogen (H_2), with traces of methane (CH_4) and carbon monoxide (CO). To obtain a pure hydrogen stream, a final stage of purification, i.e. separation of the other compounds from the synthesis gas, must be carried out.

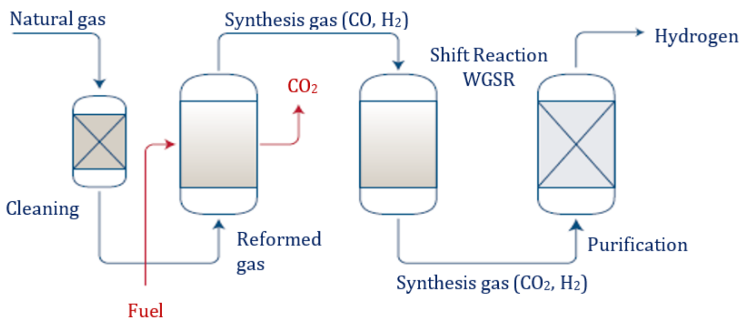


Figure 2.4. Steam reforming industrial process.

The stoichiometry of the reaction indicates that the final product consists of 4 moles of H_2 for each mole of CO_2. However, hydrogen has a very low molecular weight so in the natural gas reforming process it is produced more unwanted by-product (carbon dioxide) than the desired product (hydrogen), with the impact on greenhouse gas emissions that this represents.

Thus, it is estimated that for each ton of hydrogen, 9-11 tons of carbon dioxide are emitted [Bon10]. Worldwide, the generation of hydrogen from natural gas involves emissions of 630 Mt per year. From these devastating figures comes the general interest in sequestering the carbon dioxide from the reforming process rather than emitting it into the atmosphere.

Hydrogen obtained from fossil methane is classified as grey and blue depending on whether or not the process incorporates carbon dioxide capture.

2.3.2. Pyrolysis

Methane gas pyrolysis is an emerging technology that allows the decomposition of methane into hydrogen and carbon. This process is also known as thermal cracking of methane or methane decomposition, and some authors call the hydrogen produced as turquoise. Unlike reforming, pyrolysis does not use any oxidizing agent such as water or oxygen. Thus, no chemical compounds containing oxygen in their structure are added and promote the production of carbon oxides (CO_2 or CO). [HHK09]

$$CH_4(g) \longrightarrow 2H_2(g) + C(s)$$

The process is endothermic and takes place at very high temperatures of 800-1.200°C. The reaction produces two moles of hydrogen for every solid carbon molecule. The removal of solid carbon from the reactor generates an important technological challenge, key for the viability of the process since it can block both the pores of the catalyst and the hydrodynamics of the reactor itself. To overcome this challenge, the literature proposes the use of metals or molten salts that are stable at high temperatures of the order of 1200°C. [GDB97]

In this process, methane is injected into a bubbling reactor and decomposes into the liquid phase. The carbon produced has a lower density and floats on the surface of the molten liquid, which prevents deactivation of the catalytic liquid and promotes the separation of the carbon. The carbon would be obtained in a pure form and could be used in various applications as pigments or polymers [BAS21]. It is also proposed to obtain the necessary energy for the reaction by means of electric current instead of thermal current, favoring the origin of the energy to be renewable. In any case, it is important to mention that these technologies are still under development.

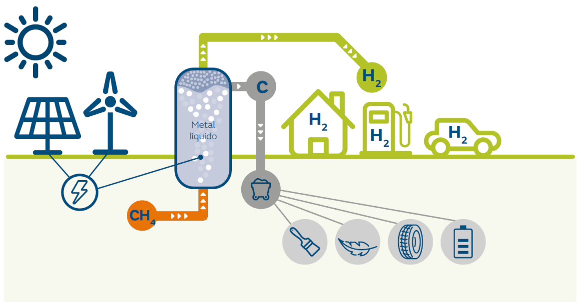


Figure 2.5. Hydrogen production from natural gas pyrolysis. Source: Fundación Naturgy [MAG20].

2.3.3. Electrolysis

The Greek expression "lysis" means decomposition or breakdown, so electrolysis describes a process in which electrical energy is the main source for the chemical reactions involved, resulting in molecular breakdown. In the case of water electrolysis, by applying a voltage and a direct current to water, the dissociation of water molecules (H_2O) into hydrogen (H_2) and oxygen (O_2) is induced, which are released in a gaseous state. An electrolyser is therefore an electrochemical device that converts electrical energy into chemical energy, in some cases also combined with thermal energy as it does not work at room temperature [LTK14].

When hydrogen is obtained from renewables energies (electrolysis, biomass, etc.) is known as green hydrogen. This new way of obtaining pure hydrogen without emitting greenhouse gasses to the atmosphere allows massive storage of electricity produced by renewable energies, thus offering a solution to compensate for their intermittency and make their production as profitable as possible. Renewable hydrogen has become the key to unlock the full potential of renewables and enable the emergence of a low-carbon energy system.

Currently, there exists three main technologies of electrolyzers: alkaline electrolyzer cells (AEC), proton exchange membrane (PEM) electrolyzer, and solid oxide electrolyzer cells (SOEC). Some of the main techno-economic characteristics of these three technologies can be seen in Table 2.1.

Stack	**AEC**	**PEM**	**SOEC**
Electrolyte	KOH	Polimeric membrane	solid oxide
Electric charge carrier	OH^-	H^+	O_2^-
Voltage (V)	1.75 - 2.4V	1.6 - 2.0 V	1.2 - 1.3 V
Operating temperature (ºC)	60 - 80	50 - 80	650 - 1,000
Operating pressure (bar)	1 - 30	30 - 80	1
Efficiency (kWh/Nm^3)	4.3 - 5.5	4.5 - 5.4	3.2 - 3.7
Efficiency (%, LHV*)	63 - 70	56 - 60	74 - 81
Power consumption at rated capacity (kWh/kg)	51	55 - 70	40 - 41
CAPEX (€/kW)	750	1,200 - 2,000	4,500 - 12,000
OPEX (€/(kg/day)/year)	32	58	225 - 600

*LHV = Lower Heating Value.

Table 2.1. Summary of the main characteristics of different types of electrolyzers

Alkaline Electrolysis Cells - AEC - is the most mature of the three technologies, being the most commercial one too. Since the 1920s, this technology has been used in the production of hydrogen within the chlorine and fertilizers industry. Historically, in counties with important hydro resources electrolyzers with a capacity of up to 165MWe were built, however due to the emergence of natural gas and methane reforming for hydrogen production, these where decommissioned in the 1970s. Alkaline technology is distinguished for having low capital expenditures due to the electrolyte used - KOH. This technology is less responsive to the entrance of energy, limiting the efficiency of the electrochemical reaction, resulting in lower production of hydrogen compared to the other technologies.

Proton exchange membrane electrolyzer - PEM - was first introduced by General Electric, around the 1960s, to tackle the technical problems that the AEC technology presented. They represent the second most used technology in water electrolysis, and they use as an electrolyte pure water, avoiding subsequent recycling of the potassium hydroxide electrolyte, as happened with the alkaline electrolyzer. The material used for the electrodes is platinum or iridium, making the technology more costly than AEC, however it has greater versatility and faster response time, making it ideal for incorporation with renewable energy resources (wind and solar). Regarding its size, the PEM electrolyzer is relatively small. The proton exchange membrane electrolyzer goes from a minimum load of 0% up to 160% of its design capacity, meaning that it can be overloaded for a short period of time if the power electronics of the system are designed accordingly. It presents a shorter lifetime and are less developed than other technologies.

Solid Oxide Electrolysis Cells - SOEC - represent the least mature of the three main water electrolysis technologies for this process, but the one with the best efficiency. SOECs have a low material cost as it uses ceramics as the electrolyte material. They need high temperatures to operate, needing a heat source (solar thermal, geothermal or nuclear power plants,). The main advantages of SOEC systems are their high energy efficiency, and that they can operate in reversible mode (RSOC), both in electrolysis mode (SOEC) and in fuel cell mode (SOFC) similar to a battery but that can generate energy using different fuels such as hydrogen, hydrocarbons, alcohols, among others (see Figure 2.6).

It can also be used for co-electrolysis of steam and carbon dioxide to create gas mixtures (hydrogen along with carbon monoxide) in order to future conversions into synthetic fuels [GT19]. One big challenge that SOEC technology needs to overcome is the degradation of the materials due to the high temperatures of operation.

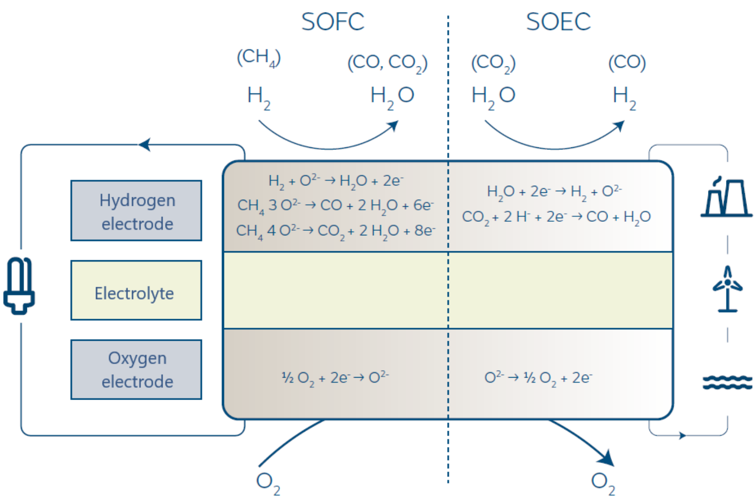


Figure 2.6. Schematic of a solid oxide system operating in fuel cell mode (SOFC) and in electrolyzer mode (SOEC). Source: Fundación Naturgy [MAG20].

2.4. Electrolyzers

As mentioned previously, every electrolyzer present a very similar configuration, however each one has their specific components. Hereunder, a general scheme of a typical AEC and PEM configurations are represented.

2.4.1. Alkaline Electrolysis Cells - AEC

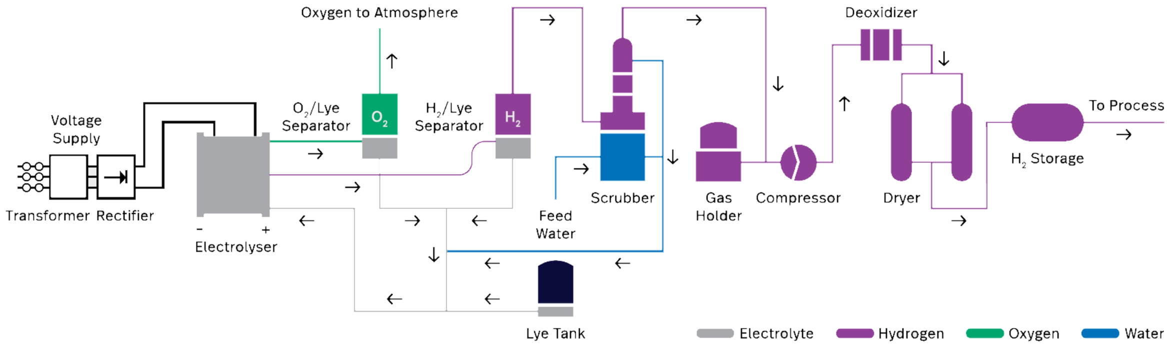


Figure 2.7. Atmospheric alkaline hydrogen plant diagram. Source: NEL.

It is noted that the two main inputs are energy from the electrical system (in this project from the solar plant) and water. It is particularly important to mention the fact that oxygen is released into the atmosphere instead of being trapped for later use in various applications, such as aerospace. In addition, another waste that has not been considered is the dirty water unusable for electrolysis.

The following table shows the main features for the production of hydrogen:

AEC Specifications	Units	Value
Minimum production capacity	%	15
Maximum production capacity	%	100
DC power consumption	kWh/Nm^3	3.8 - 4.4
O_2 - Content in H_2	ppm	< 2
Contenido H_2O en H_2	ppm	< 2
Purity	%	> 99.999
Operating temp.	ºC	80 ºC
Electrolyte	% KOH	25

Table 2.2. Potential energy injected into the system with AEC technology

The specific energy consumption for this type of electrolyzers allows the performance of these elements to be determined. Knowing that 3kWh are required to generate 1Nm3 of hydrogen, a range of yields of 68.2% and 78.9% can be determined. Therefore, the average yield is set at 73.6%.

2.4.2. Proton exchange membrane electrolyzer - PEM

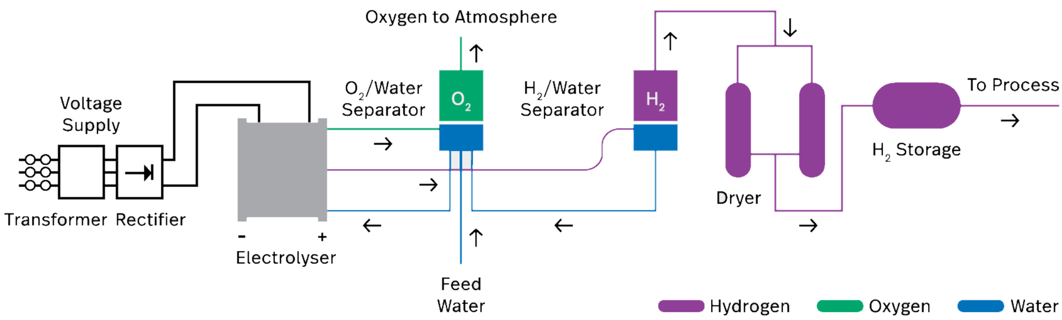


Figure 2.8. Proton exchange membrane hydrogen plant diagram. Source: NEL.

The following table shows the main features for the production of hydrogen:

PEM Specifications	Units	Value
Minimum production capacity	%	0
Maximum production capacity	%	100
DC power consumption	kWh/Nm^3	4.8
O_2 - Content in H_2	ppm	< 1
Contenido H_2O en H_2	ppm	< 2
Purity	%	> 99.9995
Operating temp.	ºC	58 ºC
Electrolyte		Proton Exchange Membrane

Table 2.3. Potential energy injected into the system with PEM technology

2.4.3. Electrolyzers' cost

The objective of this project is to study the technical and economic pre-feasibility of installing a hydrogen plant adjacent to a solar plant. For this purpose, the most important aspects for modeling such a system are the costs of the plant itself. These costs will determine the appropriate optimization of resources and, consequently, the determination of the plant capacity.

For this purpose, the hydrogen plant costs have been extracted from the report prepared by Roland Berger for *Fuel Cells and Hydrogen Joint Undertaking* [Nav17] in which the different "green hydrogen" production scenarios are studied. The unit costs included in this report are represented for the years 2017 and 2025, so an interpolation or extrapolation for the different years will be necessary. Interestingly, the capital and operating costs are strongly dependent on the economies of scale.

The costs (CAPEX and OPEX) are shown in the following tables:

CAPEX

		AEC		PEM	
Capacity (MW)	Units	2017	2025	2017	2025
1	€/kW	1.200	900	1.500	1.000
5	€/kW	830	600	1.300	900
20	€/kW	750	480	1.200	700

Table 2.4. Initial CAPEX for AEC and PEM technologies.

OPEX

		AEC		PEM	
capacity (MW)	Units	2017	2025	2017	2025
1	% CAPEX	4	4	4	4
5	% CAPEX	3	3	3	3
20	% CAPEX	2	2	2	2

Table 2.5. Initial OPEX for AEC and PEM technologies.

On the following graphs, it can be observed the price trend that is expected for both technologies up until 2050.

The one on the left depicts how alkaline technology is expected to fall up to 43% to 2030 based on current China production costs, or even 90% in countries not being China.

On the other hand, the right graph represents not only the cost reduction, but also how the average order will increase to 2030. Proton Exchange Membrane technology is expected to experience a reduction in its cost of around 60%, given relative immaturity versus alkaline electrolyzers. Its is expected to be more focused on space-restricted applications with variable renewable in the short-term. (information extracted from *BoA - Thematic Investing Hydrogen primer* [IBH20])

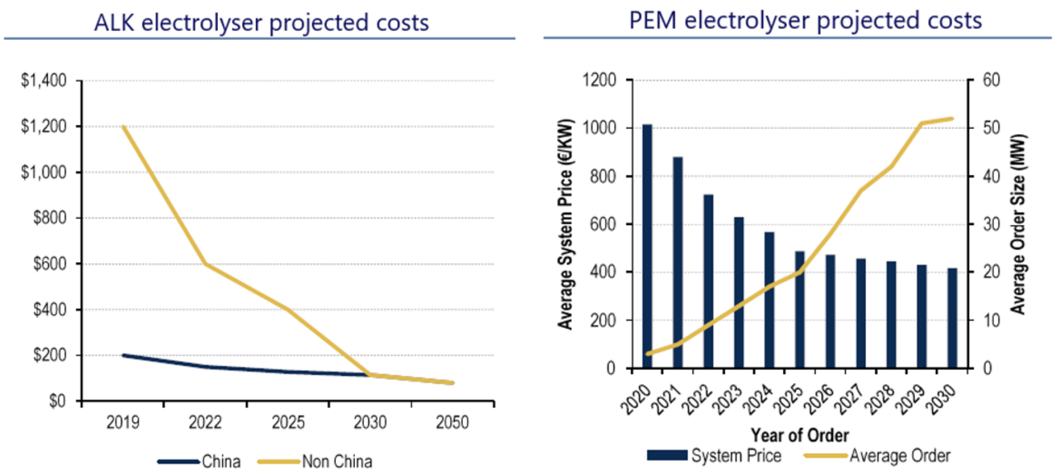


Figure 2.9. Future projections on electrolyser's costs. [IBH20].

2.5. Storage and distribution

2.5.1. Storage

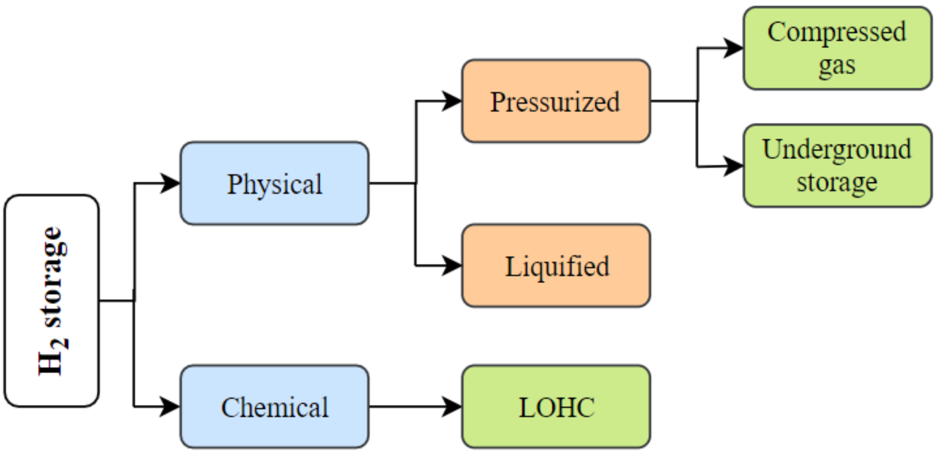


Figure 2.10. Hydrogen storage possibilities.

2.5.1.1. Compressed gas

It is currently one of the simplest, most common and efficient storage technologies in use. High pressure hydrogen is stored in cylindrical tanks made of high strength materials to ensure durability.

Commonly used cylinders are 50L and can be purchased commercially from 10, 30, 200, 250, 350, 700 and 900 bar. For stationary applications (no lay-out restriction) storage pressures are typically less than 80 bar.

ISO 11439:2013 defines the use of high pressure cylinders:

- **Type I**: All-metal construction, usually steel.
- **Type II**: Mainly steel or aluminum reinforced with a polymeric fiber sheath. The metal vessel and composites share approximately the same structural load.
- **Type III**: Metal casing (typically aluminum) with a full carbon fiber composite shell. Composite materials support all structural loads.
- **Type IV**: Non-metal construction. Carbon fiber or a hybrid carbon fiber/glass composite wound over a thermoplastic polymer coating.
- **Type V**: Construction without thermoplastic polymer, but completely made of composite materials.

Type	I	II	III	IV	V
Operating pressure (bar)	175 (Al) 200 (steel)	263 (Al/glass) 300 (steel/carbon)	300 (Al/glass) 440 (Al/aramid) 700 (Al/carbon)	900	900
Aplication	stationary	stationary	mobile	mobile	mobile

Table 2.6. Different types of high pressure cylinders according to ISO 11439:2013

2.5.1.2. Underground storage

Natural gas has been stored underground since 1916 and much of the experience is directly applicable to hydrogen.

Today, there are already 23 salt caverns being used for natural gas or hydrogen storage in the UK. In France, there are at least 15 subway storage sites for natural gas, either in salt caverns or in aquifers, for a total available capacity of 110 TWh, i.e. approximately 30% of its current annual demand.

Most of the existing subterranean storage facilities for natural gas have maximum operating pressures in the range of 70 to 170bar, although there are facilities operating at both extremes, from a low pressure of 10 bar to a maximum of more than 270 bar.

Some of the most commonly used are:

- **Porous Medium:**
  Porous rock strata, usually sand or sandstone, 150-900m below the surface, sufficiently porous to provide a reasonable storage volume and sufficiently permeable to provide an adequate rate of injection and withdrawal; the rock must have a cover of adequate thickness, covering the reservoir.

  In addition, it must be a dome-shaped geological structure, which provides structural closure to limit vertical and lateral movement of gas, along with a water/gas reservoir at the bottom that prevents downward movement of gas.

- **Natural gas reservoirs or depleted oil fields:**
  The oldest, most widespread and most economical mode of subterranean storage is reinjection of gas into existing, partially depleted fields.

- **Aquifers:**
  Similar fields can be developed by converting the natural aquifer into gas storage reservoirs by injecting gas to displace water from part of the aquifer.

- **Salt caverns**:
  Subterranean hydrogen storage in salt caverns is a technically feasible option for large-scale electricity storage, but requires suitable geology and public acceptance.

  Construction costs of salt caverns decrease significantly with size, with investments for brownfield caverns ranging from 40-60 €/m^3 for volumes of 500,000 m^3.

2.5.1.3. Liquified

Hydrogen can be stored in liquid form at -253°C and 1 bar. It has the advantage of having a higher volumetric energy density and operating at atmospheric pressures.

It is usually used in medium demand (5-20 ton/day) and high purity applications (e.g. aerospace fuel). Liquid H_2 storage tanks can be from a few liters (laboratory applications) up to 3,800m^3 as in NASA.

Losses due to BoG (Boil-of-Gas) are in the order of 0.1 to 1 [%/day] depending on the size stored.

Its main disadvantage lies in the energy cost of liquefaction: 10-12 kWh/kg H_2 or approximately 30-36% of the lower calorific value. The liquefaction process is CAPEX intensive.

The cost of liquefaction (for 5-20 ton/day) is of the same order as that of SMR production: 1-2 USD/kg.

	Liquid	**Gas (300bar)**
Density	70.85 g/L	20.77 g/L
Volumetric energy density	2.36 kWh/L	0.69 kWh/L
Mass energy density	33 kWh/kg	33.3 kWh/kg

Table 2.7. Hydrogen properties according to its physical state

2.5.1.4. Liquid Organic Hydrogen Carriers - LOHC

Liquid organic hydrogen carriers (LOHCs) are organic compounds that can absorb and release hydrogen; therefore, LOHCs can be used as a hydrogen storage medium. The method by which this absorption and release process is achieved is based on chemical reactions.

As an example of LOHC, any unsaturated compound will do, since all of them can absorb hydrogen in a hydrogenation phase. However, although there are a large number of theoretically viable alternatives, work is still underway to improve their economic viability, safe handling and the amount of hydrogen transported in the liquid (which is estimated to be at least over 6% by weight). [Ben20]

2.5.2. Distribution

The widespread use of hydrogen will require an extensive new infrastructure to produce, distribute, store and dispense it as an automotive fuel or for power generation. Depending on the source from which hydrogen is produced and the form in which it is distributed, there are many alternative infrastructures.

Hydrogen can be transported as a compressed gas, as a cryogenic liquid or as a solid in a metal hydride. The most economical method of transport will depend on the quantity and distance transported. Hydrogen, currently, for industrial use, is transported as a gas at low pressure (8-20 bar) or high pressure (200-350 bar) or as liquid hydrogen, through pipelines or by road via tankers and cryogenic tanks and a small amount by ship or rail. [BV05]

2.5.2.1. Compressed H2

Gas pipelines

Today, several hydrogen pipeline networks are used to distribute large quantities (aprox. 10,000$Nm3$/h) of gaseous hydrogen to the industrial market. Their lengths range from 500m to more than 100 km. The main players are Air Liquide, Air Products, Linde and Praxair.

Hydrogen pipeline networks are estimated at around 1600km in Europe and 1100km in North America. Most of the pipelines are located where large quantities of hydrogen are consumed in the refining and petrochemical sectors. Overall, these pipeline lengths are small compared to the global natural gas transportation pipeline system, which would exceed 2,000,000 km.

The operating pressure of hydrogen pipelines is generally less than 100 bar and the diameter of the pipelines generally ranges from 10mm to 300mm. Pipelines used for hydrogen distribution are low carbon, low alloy and low strength steels, such as API X42 steel to reduce embrittlement.

Embrittlement corresponds to the phenomenon where hydrogen interacts with the metal and manages to diffuse and react chemically producing micro-fractures that can end up breaking the material. For safety reasons, most of the pipelines are buried, so the steels are protected by coatings or cathodic protection to avoid corrosion problems. [US20a]

Hydrogen transport through pipelines is the most efficient of all alternatives. Normally there are no compressor stations because friction losses are negligible. A hydrogen pipeline system carries about 30% less energy than a natural gas pipeline system due to the energy density of hydrogen. When addressing the cost, hydrogen piping can vary from $0.3 to $1.5 million dollars, depending on the diameter and installation site.

Ideal for the distribution of large quantities of hydrogen.

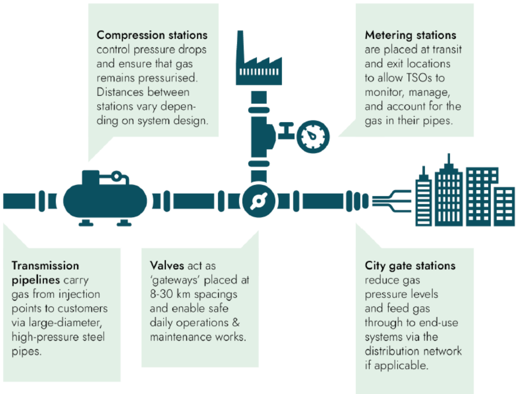


Figure 2.11. Expected gas pipeline structure. Source: [WvdLP20] .

Currently, in Europe, there is being developed the European Hydrogen Backbone with which it is wanted to pave the way to large-scale competitive hydrogen for the European market. By 2030 the project is expected to have a 6.800km pipeline network, and by 2040 around 23.000km (Figure 2.12). This infrastructure will consist of 75% of converted natural gas pipelines with a 25% of new pipeline stretches [WvdLP20].

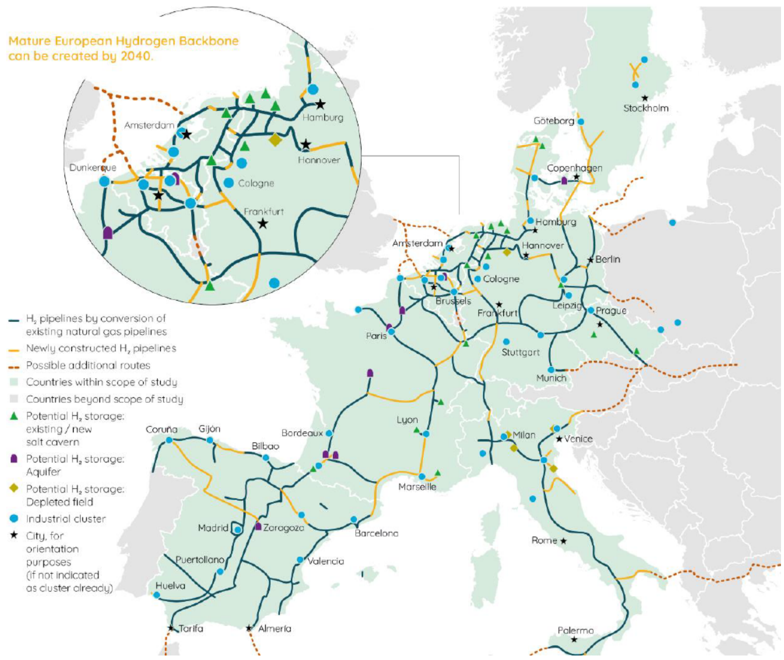


Figure 2.12. 2040 European hydrogen highway. Source: [WvdLP20] .

Road

Compressed gas can be transported using high-pressure cylinders, tank trucks or pipelines. If hydrogen is transported as a gas, it must be compressed at high pressures to maximize tank capacity.

High pressure gas cylinders carry compressed gas up to 40 MPa and store about 1.8kg of hydrogen, but are very expensive to handle and transport.

Tube trailers consist of several steel cylinders mounted on a protective frame. They can be configured to carry between 63 and 460 kg of hydrogen, depending on the number of tubes.

2.5.2.2. Liquefied H2

Pipelines

One idea for transporting liquid hydrogen is through insulated gas pipelines, which would also include a superconducting cable. The liquid hydrogen would act as a coolant for the superconductor that would allow electricity to be transported over long distances without the high losses of today's power lines. The main problem with liquid hydrogen transport would be the specialization in insulation needs and losses due to pumping and re-cooling of the hydrogen along the way.

Road

Hydrogen liquefaction is economically viable when the volumes required are small. Liquid hydrogen is transported using insulated double-walled tanks to prevent flash evaporation of the liquid hydrogen. Some tanks use a liquid nitrogen shield to cool the outer wall of the container to minimize heat transfer.

Tank trucks can carry 360kg-4300kg of liquid hydrogen. Trailers have larger capacities, carrying between 2900kg-9100kg. The BoG (Boil-of-Gas) in trucks is between 0.3-0.6%/day.

Figure 2.13. Liquefied hydrogen transport and storage.

Sea

Barges and deep-sea vessels are also considered for transporting hydrogen over long distances. BoG on ships is estimated at 0.2-0.4%. Canada has developed some ship designs for transatlantic hydrogen transport. All of them are still under development, none have been built yet.

Liquefied H_2 transportation infrastructure has been developed mainly in North America (10 times more than Europe). The break-even distance, were liquefied hydrogen transport is more economical than compressed H_2, is 400km, making LH_2 ideal for long distance transportation. [WvW19]

2.6. Hydrogen Applications

Clean fuel

Hydrogen fuel is one of the most environmentally friendly choice as it is produced with an electrolyser from renewable energy and water. The only emission is water vapour. It's also practical; hydrogen cars can be completely refueled in a matter of minutes and have a range equal to that of gasoline or diesel. The use of hydrogen is becoming one of the most important methods for decarbonizing public, commercial, and heavy-duty transportation.

A typical configuration could be the following one:

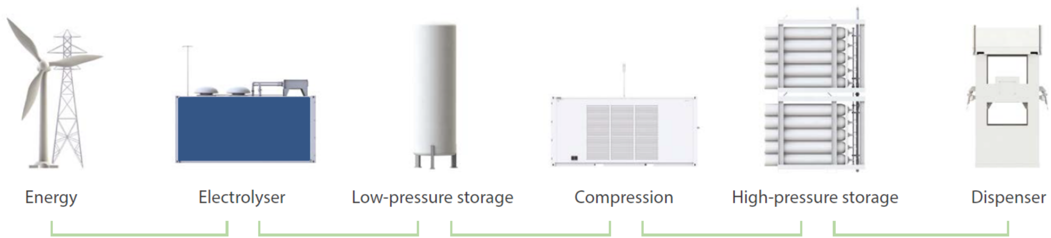


Figure 2.14. Refuelling station solution.

Energy storage

Power-to-Gas energy storage is a modular system that can harvest power from the electricity grid as demand exceeds supply and intermittent renewable generation triggers network reliability issues.

Power-to-Gas is a method of converting electrical energy into chemical energy in the form of hydrogen, which can then be pumped into in the gas network. The gas network has the capacity to store electricity forever, while Power-to-Gas has the capability to store MW to GW for periods ranging from hours to months.

Some typical configurations, depending on the application:

Power-to-gas

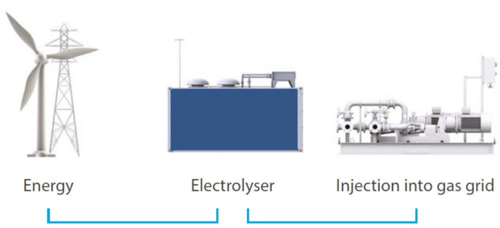


Figure 2.15. Power-to-gas configuration.

Methanation

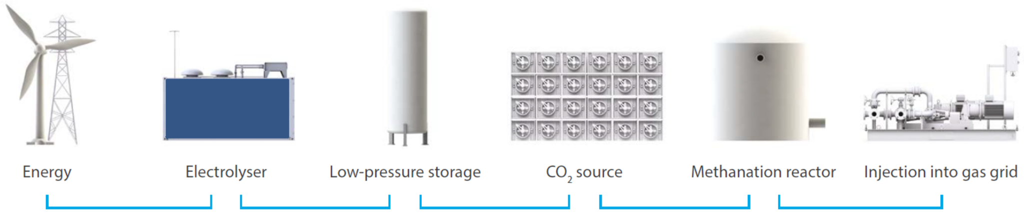


Figure 2.16. Methanations configuration.

Tube trailer filling

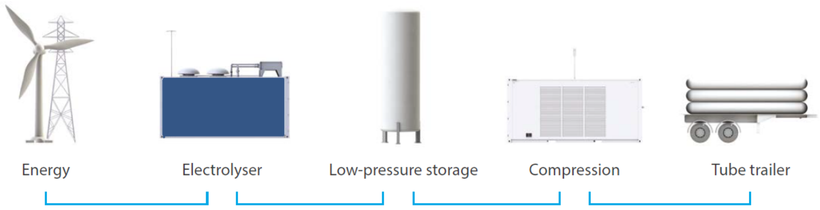


Figure 2.17. Tube trailer filling configuration.

Island system

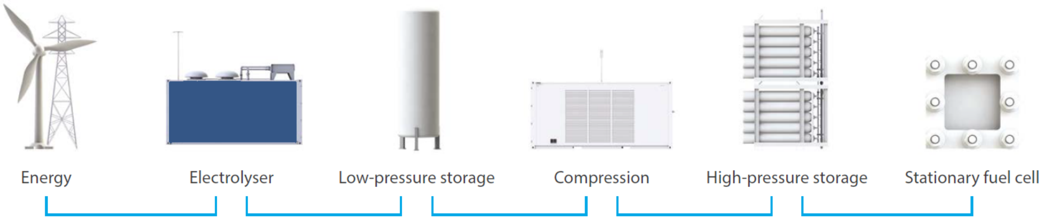


Figure 2.18. Island systems configuration.

Industrial hydrogen

Green hydrogen offers an incentive for the global chemical industry to reduce its dependency on methane while still balancing site energy needs.

Some typical configurations, depending on the industry:

Refineries

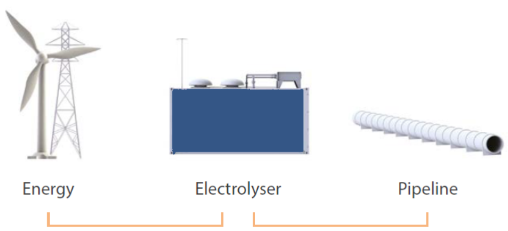


Figure 2.19. Refineries configuration.

Ammonia synthesis

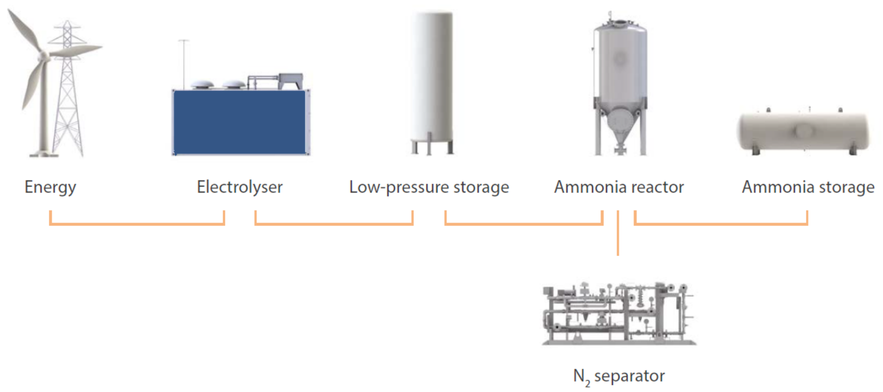


Figure 2.20. Ammonia synthesis configuration.

Methanol synthesis

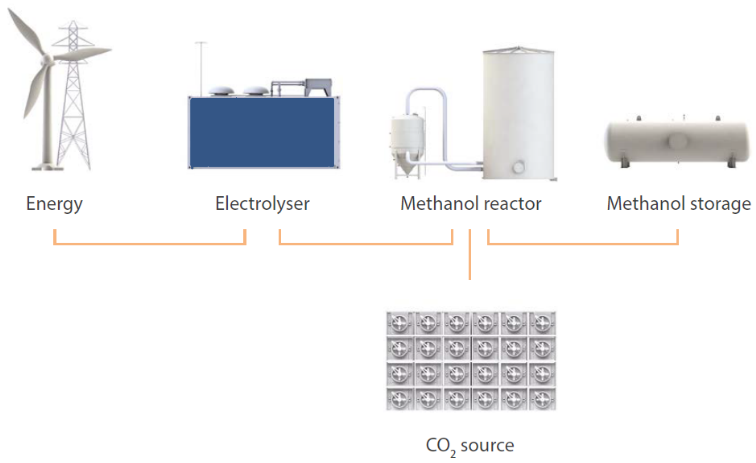


Figure 2.21. Methanol synthesis configuration.

Steel production

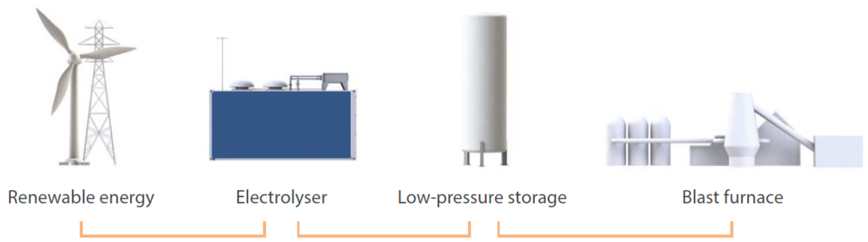


Figure 2.22. Steel production configuration.

3

Main technical-economic indicators for utility applications

In this chapter the main technical-economic indicators for hydrogen production will be reviewed in order to obtain a broader understanding of the hydrogen economy and how to compute a final price for green hydrogen. Some cases will be presented with the intention to picture what was previously explained

3.1. Envisioning hydrogen economy

When talking about the future of hydrogen, many scenarios should be taken into account as it is subjected to a lot of uncertainty. These scenarios will evolve as technologies improve deriving in a reduction of the production costs.

When talking about Europe, the impact of hydrogen will be marginal on companies in 2020-2025. Between 2025-2030, the hydrogen market will experiment a further progress within the refining, chemical and heavy road transport sectors, even improving hydrogen purity in ammonia fertilizers. In the long run, hydrogen could become more accessible to become a fuel for other sectors if electricity prices drop and other end markets take off.

Currently, the annual production of hydrogen is around 70Mt, where more than the 95% comes from hydrocarbons. Although electrolysis will be the key for the development of a green hydrogen economy, currently it only represents 3% of total H_2 production. Around a 38% of hydrogen produced is generated in industrial processes as a by-product, where in many cases is treated as waste and forgotten.

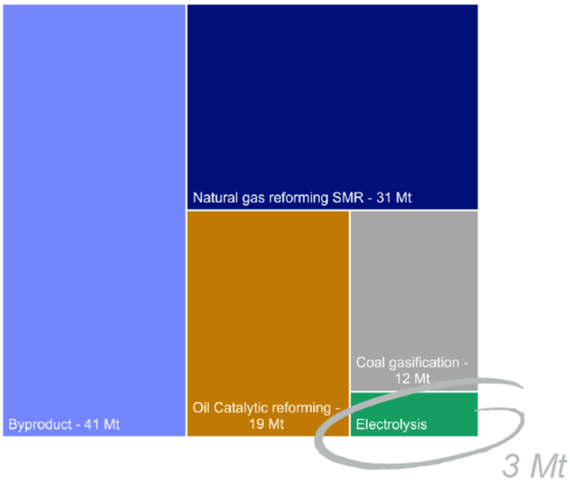


Figure 3.1. Total hydrogen production by sectors - 2020.

As it can be observed in Figure 3.1 the second largest production of H_2 comes from natural gas reforming SMR (with around 31Mt per year). For this reason, in order to compare and understand the outcome prices, the SMR process will be used as a benchmark for green hydrogen.

One of the traditional ways of producing hydrogen, as mentioned previously, is by the process known as Steam Methane Reforming (SMR) (see Section 2.3.1). This process requires electricity, water and pure methane for the production of hydrogen, emitting around 10kg of CO_2 to the atmosphere per kg of H_2 produced. However, the production of hydrogen with electrolysis only needs electricity and water with the only emissions being oxygen. This process is flexible and allows to adjust the load factor accordingly to the availability of the renewable energy source used and this will allow the capture of more renewable technologies into the system.

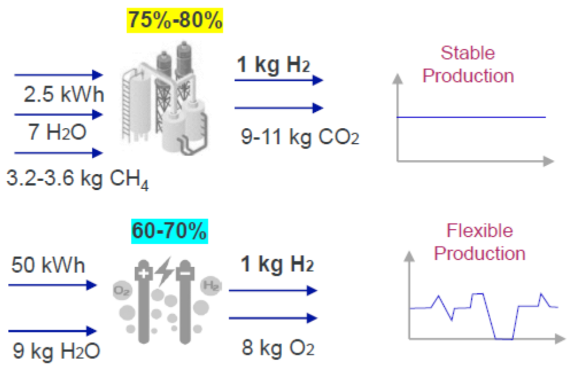


Figure 3.2. Comparison between SMR and electrolysis production of hydrogen.

When comparing the different technologies that coexist in the market, the main driver is the price at which it can be obtain the hydrogen. The price of hydrogen from hydrocarbons is in the range of 1$ to 4$ the kg of H_2, whereas green hydrogen scales up to reach a price around 10$/kg H_2.

To have a more precise conception of how much would it cost to produce hydrogen with natural gas (SMR), with a price of 5$/MMBTU the price of the hydrogen produced will be around 1$/kg. When speaking about the process of electrolysis, the final price is highly dependent on the price of electricity and the renewable technology used.

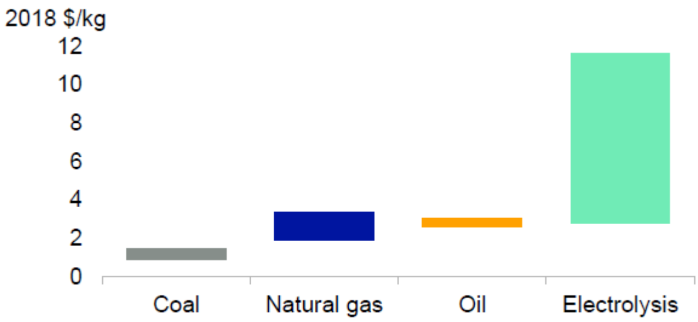


Figure 3.3. Comparison of the different costs of hydrogen from different technologies [NEF20].

The reason why hydrogen is becoming one of the key factors in the energy transition, is its price. As previously mentioned, the final price of green hydrogen depends on the price of electricity. There will be a change in prices over the years thanks to economies of scale and the use of more mature technologies allowing for a significant drop in the final price of hydrogen by 2050. It is expected (as observed in Figure 3.4) a parity of prices by 2030 of green and brown hydrogen. The expected reduction could be also accelerated with the introduction of new measures, as emission taxes, to the production of hydrogen.

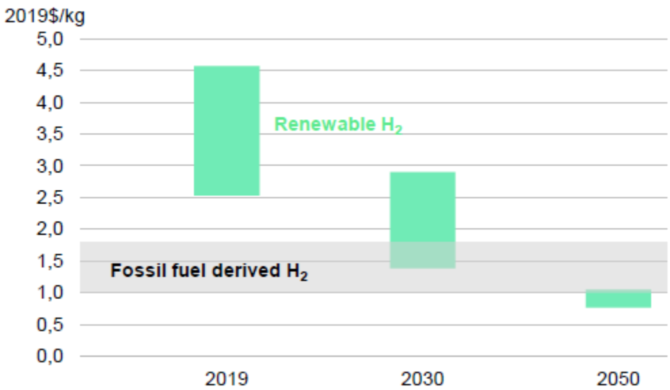


Figure 3.4. Drop in green hydrogen prices [NEF20].

3.1.1. Obstacles to overcome in hydrogen production

- The production of “green hydrogen” represents a medium-term solution for sectors such as the refining industry, the production of fertilizers from ammonia and transport with heavy trucks.

- This solution should prove competitive in the long term to replace other uses such as heating from natural gas, electricity generation, maritime transport, and steel production.

- Competitive hydrogen production requires government policies aimed at accelerating the energy transition and improving its costs significantly: even if this production cost is halved in 2030 to $2/kg (about 1.68€/kg) this would be equivalent to a natural gas cost of about $17.6/MMBtu (about 50.4€/MWh) witch in turn would result in a cost of more than 100€/MWh to produce electricity.

- Finally, hydrogen production could offer a long-term storage solution for the seasonality and intermittency of renewable energies.

Policies and markets must move forward as a whole. In the SP Global Platts article "How Hydrogen Can Fuel The Energy Transition" considers that the candidate and ideal sectors for the development of this green technology are the current hydrogen markets, where there are already projects under development to integrate renewable energies with electrolyzers to produce green hydrogen (i.e Petronor). It is also highlighted that an effective implementation in the sector of ammonia-based fertilizers production is more complex, taking into account the fluctuations in the price of fertilizers in the international markets (i.e. Fertiberia).

Other sectors that could experiment the evolution of their policies and markets beyond 2030, if they work together, are the alternative fuels in internal combustion engines, home heating and finally, in industrial sectors where this substitution of the already existing technologies entails a great challenge.(Figure 3.6)

3.1.2. Impact on electricity market prices

Green hydrogen will be one of the key players in the decarbonization of the economy and will play a key role in energy storage and fossil fuel substitution. Its production is expected to bottom-out the electricity market prices and avoid the spillage of renewable energy. If this technology is embraced, Spain has the opportunity to become the main production hub in southern Europe.

Hydrogen has basically two markets. The first is for those industries that use it as a raw material. This is the case of refineries, chemical and fertilizer industries and metallurgical industries. These industries are not expected to see a change in the trend of hydrogen consumption.

On the other hand, there is green hydrogen as a substitute for fossil fuels, mainly gas. Green hydrogen is hydrogen produced from renewable energy sources, which means that it does not emit CO_2 or other greenhouse gases. This is the side of hydrogen with extraordinary growth potential. The total decarbonization of the economy, the European Union's objective for 2050, will require the complete substitution of fossil fuels such as gas or oil and its derivatives.

These fossil fuels currently play a predominant role in sectors such as industry, transport and heating. Decarbonization of these sectors will come in part from electrification. But there are areas where electricity use is inefficient, such as heat generation for industry or heavy and long-distance transport. In these cases, hydrogen is the most suitable emission-free fuel. This is why green hydrogen is referred to as the fuel of the future.

In addition, the possibility of generating electricity directly from hydrogen and oxygen in a fuel cell makes hydrogen a gas capable of storing energy, another essential aspect for the penetration of intermittent and non-manageable renewable energies.

Therefore, the production of green hydrogen is expected to grow exponentially in the coming decades, and its production is expected to have an impact on electricity market prices.

Green hydrogen production and electricity market prices

The production costs of hydrogen to make it competitive with gas are estimated to be around 2€ per kilo of hydrogen, although this will largely depend on the evolution of gas prices and CO_2 emission rights. To produce green hydrogen at these costs using electricity from renewable energy sources, the electricity price should be less than 20€/MWh, depending on how much the amortization costs of the electrolyzers are reduced. However, according to experts, given the drop in the CAPEX of this technology in recent years, it is not unreasonable to expect decreases of 30% to 35% in the coming years.

Similarly, it also seems unlikely that electricity generation costs (LCOE) for technologies such as photovoltaics will fall below 20€/MWh in the near future. All this means that a *virtual floor* will appear in the electricity markets, a threshold below which prices will not fall, since, at that price, generators will decide to produce green hydrogen from which they will obtain income instead of selling the energy on the market at lower prices. This price floor is one of the keys to take into account when making long-term hourly price forecasts and giving the right price signals to investors in renewable projects.

Spillage in renewable electricity production

The production of green hydrogen will not only avoid recurring low prices on electricity markets but will also prevent the dumping of renewable energy. The so-called spillage is all the energy that is produced but does not end up entering the electricity grid because it is surplus. The availability of an alternative such as green hydrogen production will make it possible to avoid wasting excess energy.

Batteries, or other energy storage technologies that may appear in the future, will also be necessary as, together with hydrogen, they will reinforce this floor in market prices and prevent further dumping.

Green hydrogen in the energy transition

For hydrogen to develop its role in the energy transition, it will need the support of the right policies, investments, aid and regulatory changes. If this is the case, Spain has the opportunity to become the main hub for green hydrogen production in the south of the continent for two main reasons. On the one hand, due to the cost of electricity generation, where Spain, thanks to its abundant solar resources, among others, can have more competitive prices than the rest of the markets. And, on the other hand, because the logistical cost of transport has little weight in the final cost of hydrogen when it is produced on a large scale.

If it really does become the largest producer of green hydrogen, experts estimate that up to 10 GW of additional renewable capacity could be needed over and above that proposed in the PNIEC, thanks to hydrogen production.

3.2. Hydrogen value chain

Some of the technologies that contribute to the hydrogen value chain have been explained in Chapter 2. It is very important to take into account the different technologies that appear in the H2 value chain until its final use, but not all of them are always present, this depends on the final use that is going to be given to the gas. The prices that where mentioned previously, only reflect the electricity and production stages, if more stages are required, then the price will increase. Only electricity and production stages are present in all processes, despite their final use.

To set an example, when speaking about hydrogen to be used in the production of fertilizers, this hydrogen does not have to go through all stages of the value chain. If the fertilizer plant is built right next to the electrolyzer, then no need for storage, TD and re-conversion. However, if transportation of the gas is required, then the only stage that could be skipped is the storage one (in case all the hydrogen produced is sent to the factory).

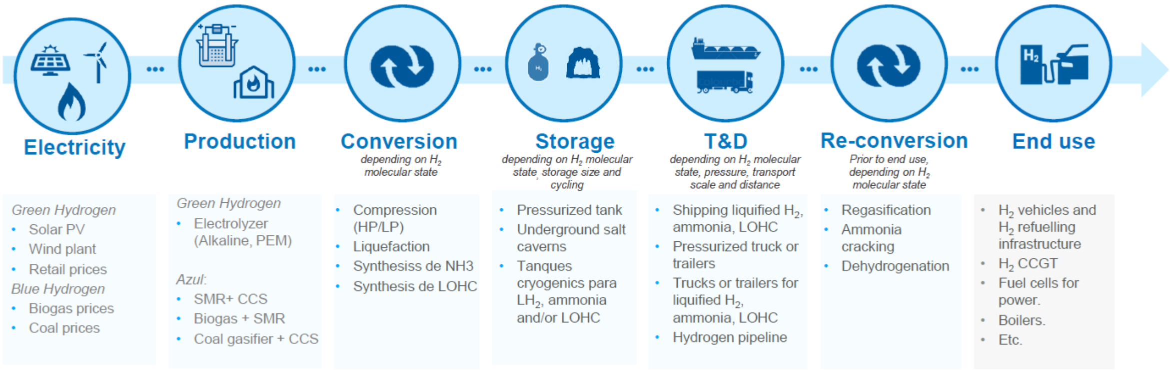


Figure 3.5. Complete hydrogen value chain.

As it can be seen in Figure 3.6, there are different break-even costs for the different application that hydrogen has. On the right, the average and optimal prices for green and blue hydrogen are stated. With this as a benchmark, the different prices for the different applications are plotted in order to have a broader view of current hydrogen prices.

When speaking about mobility, generally this end use relies less on production cost as it requires a longer value chain. For this reason, prices (USD/kg) are more competitive. However, in the H2-DRI steel production, H_2 cost needs to be under 1USD/kg to be competitive in China. Finally, when addressing the hydrogen for heating purposes, prices well below 0.5USD/kg are required to break even in the USA.

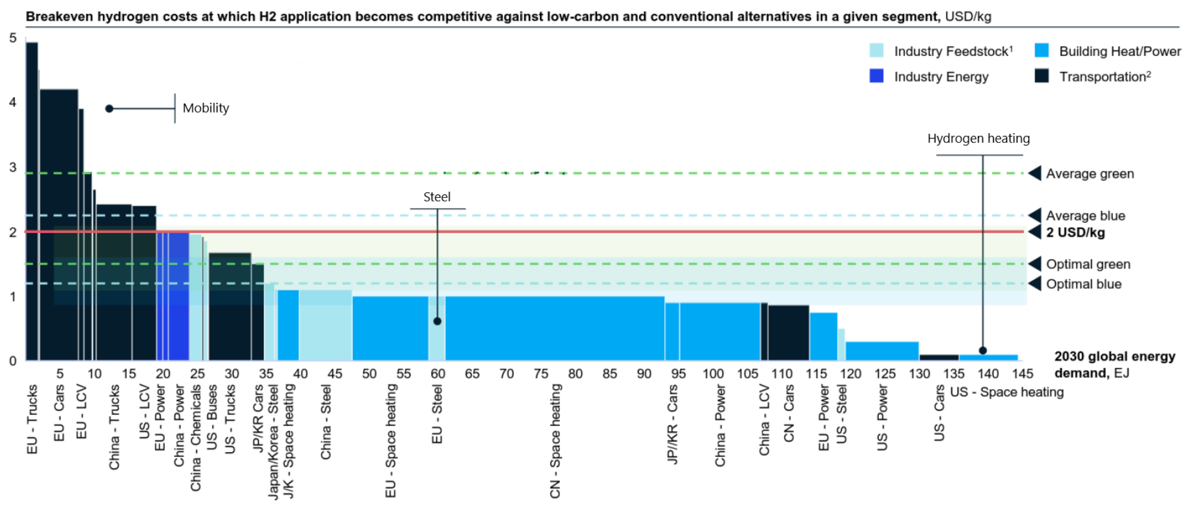


Figure 3.6. Break-even H2 cost per type of application [Hyd20].

3.3. Hydrogen storage

When analysing the complete value chain of hydrogen, storage is essential in order to estimate its final price. For this reason, is important to know how much additional cost it will be added to the cost of production depending on the form of storage required.

There are three main ways of conversion of hydrogen before storage: pressurized, liquefied and chemical compounds.

- Pressurized hydrogen [gas at 50-1000 bar]. The most common one used nowadays as is the cheapest one. After setting the correct pressure, the gas is then stored either in H2 tanks, salt caverns or even pipelines.
- Liquefied hydrogen [liquid at 1bar and -253ºC]. It requires liquefaction plants and storage in H2 cryogenic tanks.
- Chemical compounds. Hydrogen can be also stored in chemical compounds. The most common ones are: ammonia [liquid at -33ºC] or LOHC (Liquid Organic Hydrogen Carriers)

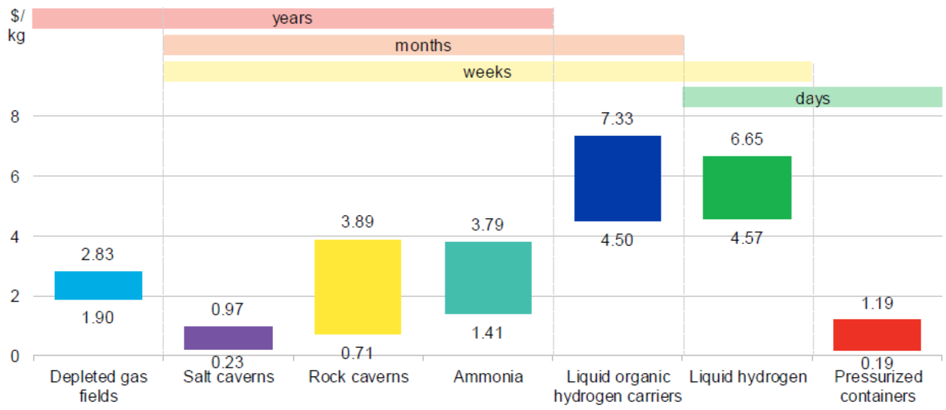


Figure 3.7. Relationship between storage technologies and time span [NEF20].

3.4. Levelized Cost of Hydrogen - LCOH

Now that it was reviewed how prices will evolve in the hydrogen production, an indicative value of its price will be computed taking into account both the cost of generating renewable energy and the utilization rate and efficiency of the electrolyzer. The tool that will be used is the Levelized Cost of Hydrogen (LCOH). Note that the aim of the LCOH is to make comparisons between scenarios, and it should not be used and/or treated as a selling price.

Before going into further details on the LCOH, a note should be made on how the generator curtailment and the LCOE affects the utilization rate of the electrolyzer. As it can be observed in Figure 3.8, the utilization factor of the electrolyzer is directly constrained by the utilization factor of the renewable plant.

In the case of using solar generation, the optimal electrolyzer utilization rate - where there is a 0% generator curtailment and the LCOE multiplier is minimum - is around 30-35%, whereas with wind generation is a bit higher, 40-50%. The correlation between the utilisation factor of the electrolyser and the cost (LCOE multiplier) is asymptotic, and at around 40-50%, for PV generation, it stabilizes. With an utilisation factor of 10%, the costs of using an electrolyser are very high, so we need to reach at least 50% utilisation for prices to stabilize. If the idea is to use PV generation, the PV plant will need to be oversized (as its optimal operating point is 40% max) , resulting in more curtailment and therefore an asset that is not generating at its optimum state will incur higher electricity costs.

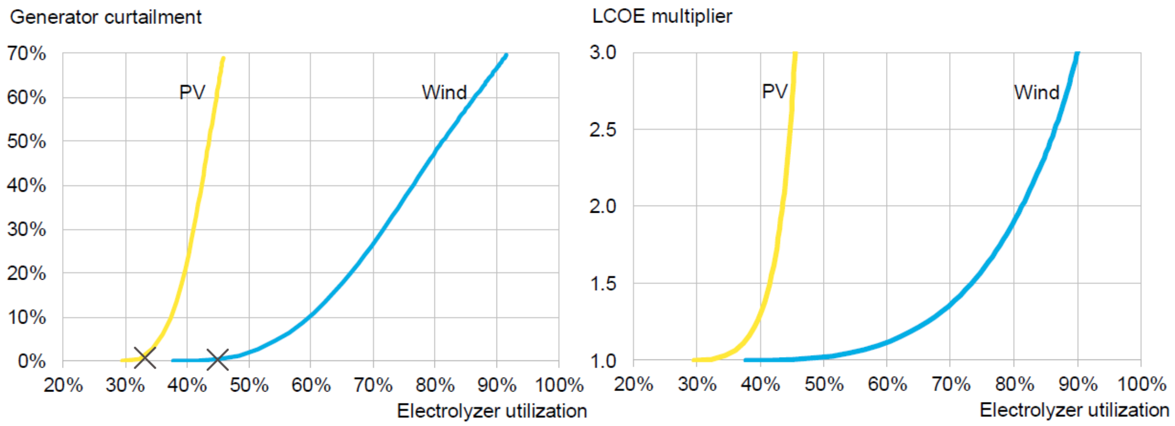


Figure 3.8. Utilization rate vs. Generator curtailment and LCOE for an electrolyzer.
Source: BloombergNEF. Note: The calculation is based on hourly generation data in 2018 for PV and wind plants monitored by the CAISO.

For this reason, a trade-off between these factors need to be taken into account:

- To produce hydrogen with electrolysis connected to the grid at a known cost of electricity. In this situation, the electrolyzer will be working at 100% utilization factor as the generator curtailment or the LCOE have no effect on this scenario (see Figure 3.10). The hydrogen obtained cannot be denominated as pure green hydrogen, as the origin of electricity coming from the grid is not purely renewable.

- When introducing renewable sources, the optimal scenario is to design an oversized hydrogen plant in order to work at the optimal utilization rate depending on the technology used (low generator curtailment and low LCOE multiplier).

  Figure 3.9 tries to represent what was previously stated with a stable production of hydrogen. This is only possible if a PPA compensates the hours where there is no light for the solar generator to work.

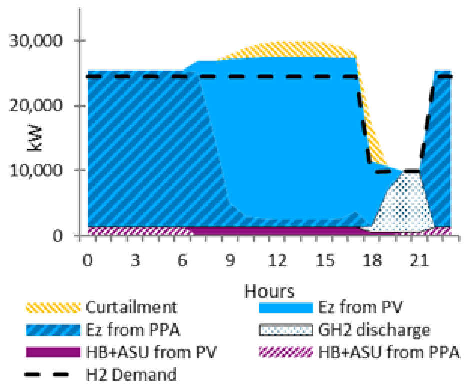


Figure 3.9. Annual average operation of an electrolyzer with PV curtailment.

The levelized cost of hydrogen (LCOH) is a methodology used to account for all the capital and operating costs of producing hydrogen and therefore enables different production routes to be compared on a similar basis. The same methodology is applied for electricity production, energy storage etc.

Note: The LCOH does not include H_2 storage and transport costs which may be required depending upon the application.

$$LCOH_1 = \frac{Annual\, capital\, repayments + O\&M\, Costs}{Annual\, production\, of\, H_2} \tag{3.1}$$

The model is based on a straightforward calculation where the system costs and maintenance are taken into account and then divided by the total amount of hydrogen produced annually.

The initial CAPEX is assumed to be amortized over the assumed economic life of the electrolyzer (20 years) to then determine the annual capital repayments. For this calculation it was used the PMT function (PAGO function in Spanish) in an Excel spreadsheet. This function also considers the real weighted average cost of capital (WACC) that was assumed to be 8%.

$$Annual\, capital\, repayments\, [EUR/kW] = -PMT(WACC, Economic\, life, CAPEX) \tag{3.2}$$

Where:

· WACC = weighted average cost of capital
· Economic life = 20 years
· CAPEX = installed capital price [EUR/kW]

To obtain the annual production of H_2 we need to take into account the hours in a year that the electrolyzer will be producing and the real efficiency of the electrolyzer of converting electricity into kg of H_2.

As we are not considering directly the cost of construction and maintenance of the PV farm that will be feeding the electrolyzer, we will just take into account the price at which the energy produced will be sold in the market, being this energy the one consumed for the production of hydrogen.

$$LCOH_2 = (\frac{Annual\, capital\, repayments + O\&M\, Costs}{UR * 8760} + \frac{EP}{1000 * \eta_e}) * H_2CF \tag{3.3}$$

Where:

· O&M Cost = annual operating and maintenance costs
· UR = utilization rate [%]
· EP = energy price [€/MWh]]
· η_e = electrolyzer efficiency [%]
· H_2CF = conversion factor [kWh/kg H_2]

The conversion factor is taking into consideration the molecular properties of hydrogen; the amount of energy required to obtain 1kg of H_2.

$$1\, kg\, of\, H_2 = 33.3\, kWh$$

LCOH	Utilization rate									
Electricity market price €/MWh	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0	6.47	3.24	2.16	1.62	1.29	1.08	0.92	0.81	0.72	0.65
10	7.04	3.81	2.73	2.19	1.87	1.65	1.50	1.38	1.29	1.22
20	7.62	4.38	3.31	2.77	2.44	2.23	2.07	1.96	1.87	1.80
30	8.19	4.96	3.88	3.34	3.02	2.80	2.65	2.53	2.44	2.37
40	8.77	5.53	4.45	3.91	3.59	3.38	3.22	3.11	3.02	2.94
50	9.34	6.11	5.03	4.49	4.16	3.95	3.80	3.68	3.59	3.52
60	9.92	6.68	5.60	5.06	4.74	4.52	4.37	4.25	4.16	4.09
70	10.49	7.25	6.18	5.64	5.31	5.10	4.94	4.83	4.74	4.67
80	11.06	7.83	6.75	6.21	5.89	5.67	5.52	5.40	5.31	5.24
90	11.64	8.40	7.32	6.78	6.46	6.25	6.09	5.98	5.89	5.81
100	12.21	8.98	7.90	7.36	7.04	6.82	6.67	6.55	6.46	6.39
110	12.79	9.55	8.47	7.93	7.61	7.39	7.24	7.12	7.03	6.96
120	13.36	10.13	9.05	8.51	8.18	7.97	7.81	7.70	7.61	7.54

*** hydrogen price €/kg without taking into account transport, storage and distribution costs*

Figure 3.10. Levelized cost of hydrogen. Case base with a 1200 EUR/kW CAPEX.

On Figure 3.10 the results are represented showing a strong correlation between the utilization rate of the electrolyzer and the electricity market price. The price of hydrogen in €/kg is inversely proportional to the utilization rate and directly proportional to the electricity market price. The case base that represents these numbers is going to be explained in further details in Section 3.5.1 where a simplified configuration of an electrolyzer connected to the grid is analyzed.

As depicted in Figure 3.8, if the electrolyzer is connected directly to a renewable source, the utilisation factor of the electrolyser will be directly constrained by the utilisation factor of the renewable plant. For this reason, in Figure 3.10, we can observe that if the electrolyzer is connected to a solar generation plant, the prices could oscillate from 2.77 € to 3.31 € per kg of hydrogen, whereas if connected to a wind generation plant prices could be between 3.59 € and 3.91 € per kg.

Furthermore, if the reduction of CAPEX expected by 2030 is met and with a more mature technology in solar and wind generation, prices will drop dramatically. This was also evaluated with the LCOH analysis and the following results where obtained:

LCOH	Utilization rate									
Electricity market price €/MWh	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0	2.70	1.35	0.90	0.67	0.54	0.45	0.39	0.34	0.30	0.27
10	3.27	1.92	1.47	1.25	1.11	1.02	0.96	0.91	0.87	0.84
20	3.84	2.50	2.05	1.82	1.69	1.60	1.53	1.49	1.45	1.42
30	4.42	3.07	2.62	2.40	2.26	2.17	2.11	2.06	2.02	1.99
40	4.99	3.64	3.20	2.97	2.84	2.75	2.68	2.63	2.60	2.57
50	5.57	4.22	3.77	3.54	3.41	3.32	3.26	3.21	3.17	3.14
60	6.14	4.79	4.34	4.12	3.98	3.89	3.83	3.78	3.74	3.71
70	6.72	5.37	4.92	4.69	4.56	4.47	4.40	4.36	4.32	4.29
80	7.29	5.94	5.49	5.27	5.13	5.04	4.98	4.93	4.89	4.86
90	7.86	6.52	6.07	5.84	5.71	5.62	5.55	5.50	5.47	5.44
100	8.44	7.09	6.64	6.42	6.28	6.19	6.13	6.08	6.04	6.01
110	9.01	7.66	7.21	6.99	6.85	6.76	6.70	6.65	6.62	6.59
120	9.59	8.24	7.79	7.56	7.43	7.34	7.27	7.23	7.19	7.16

*** hydrogen price €/kg without taking into account transport, storage and distribution costs*

Figure 3.11. Levelized cost of hydrogen. 2030 case with a 500 €/kW CAPEX.

What can be interpreted from the results of Figure 3.11 is that prices will start to be competitive in 2030, fluctuating between 1.25 € to 1.82 € per kg of hydrogen.

The countries best placed to meet this challenge in an accelerated manner will be those that are capable, due to their characteristics, of producing electricity below $20/MWh (= 16.80 €/MWh).

3.5. Case studies

3.5.1. Grid-connected system in continuous operation

The most simple way of producing hydrogen with an electrolyzer is by obtaining the electricity required through the grid. This is a very stable process and requires low maintenance. This will result in stable outcome of hydrogen of 4000 Nm3/h. The configuration is the one as shown in Figure 3.12

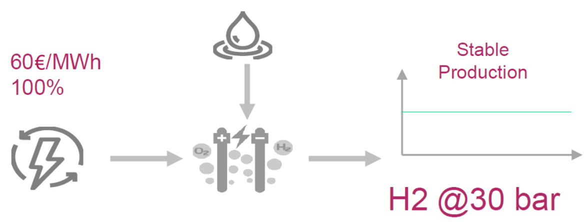


Figure 3.12. Case base configuration.

Hereunder, on Table 3.1, the required input data of the electrolyzer is specified. The technology that was selected for this analysis is a Proton Exchange Membrane electrolyzer, more information about this technology can be found in Section 2.3.3.

NEL M4000 PEM	Nm3/h	4000
Stack efficiency	kWh/Nm3	4.8
Degradation	%/1000h	0.002%
Stack lifetime	hours	50,000
CAPEX	€/kW	1,200
OPEX	%CAPEX	4%

Table 3.1. Income parameters for base case LCOH analysis

With 100% electricity from the grid at a price of 60 €/MWh, it is obtained a price of 4.10 €/kg of H2 (as observed in Figure 3.10). However, if the idea is to compete with the hydrogen produced with natural gas (SMR), these prices are still too high.

This value can be broke down into electricity cost, CAPEX/OPEX and water costs. A more visual understanding of the decomposition of the price can be observed in Figure 3.13 where it can be seen that the electricity price is one of the most determining factors in the final price of hydrogen.

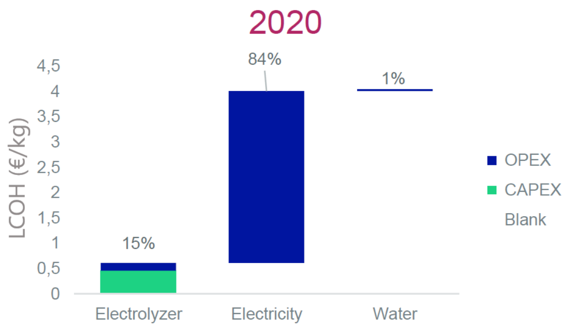


Figure 3.13. Case base cost-related price decomposition.

3.5.2. Grid + solar generation in continuous operation

Now is the case where solar renewable energy is used with much cheaper prices (approx. 20$/MWh). It can be considered also to use a combination of renewables and the grid.

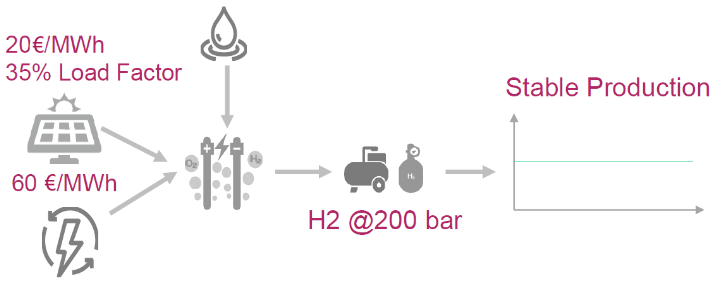


Figure 3.14. Grid + solar configuration.

To keep the study constant, the electrolyser used is the same one as in the base case, so the income parameters are the ones represented in Table 3.1. Computing this configuration, the results obtained where:

- Production price - ~2.80€/kg H2 (Figure 3.10)
- Storage price - ~0.40€/kg. It was assumed that the storage was only necessary for daily periods in pressurized containers (Figure 3.7)

Taking into account these two costs, the final price will be of around 3.20€/kg of hydrogen. This price is much more competitive than the one obtained with just the grid connection (Section 3.5.1). This green hydrogen has the potential of becoming competitive with grey or blue hydrogen with an optimal renewable scenario.

4

Batteries

Battery Energy Storage System (BESS) is a system used to store electrical energy in secondary batteries for later use when needed.

4.1. BESS description

The main components of a BESS ares:

- Energy cells - where the energy is stored
- Power electronics and inverters
- Balance of Plant equipment - transformers, cables, panels, etc.
- IT system grid interface
- Properly equipped container - for utility-scale or grid scale storage system.

There are different layouts in the rendering of the battery cells in the container. For instance, there are containers including the battery cells and power electronics, others including also the transformers. The configuration depends strongly in the technology used by the manufacturers.

Lithium-Ion batteries

Among all electrochemical storage technologies, Li-Ion batteries are the dominant ones nowadays because such batteries present the best KPIs:

- Efficiency - % ratio charged/discharged energy
- Specific energy - Wh/kg
- Specific power - W/kg
- Lightest battery in the market
- Lifetime - number of charges/discharges cycles

These batteries are becoming more and more competitive pricewise as it is a very versatile technology that can be used either for energy-intensive purposes or power-intensive purposes.

Due to this reasons, these kind of batteries can meet different requirements and are going to be even more widespread in many industrial sectors.

Battery lifetime

Regardless of the technology improvements achieved in the latest years, the lifetime of a lithium battery is still dependent on:

- Thermal environment
  Batteries life significantly drops at a high and low temperature extreme, however it can be maximized by maintaining temperature in the range 20-30ºC. This is why containers hosting batteries are provided with HVAC systems that maintain the optimal temperature regardless of the external climate conditions.

- Time
  Batteries normally degrade with time even if they are not used (charged/discharged) at all. Such calendar aging is strongly influenced by the temperature at which batteries are stored.

- How they are charged and discharged
  Usage of batteries (measured as charge/discharge cycles) is the main factor influencing the batteries' aging. With just a few full cycles per day, the degradation curve is not very steep, whereas with many short cycles per day (none of them a full cycle), the aging is accelerated.

Batteries' performance is usually measured using the **c-rate (ratio power/capacity)** over a certain period. Compared to the initial (beginning-of-life) value, the c-rate decreases mainly in function of the three factors listed and explained above.

Typically, battery end-of-life is defined when the battery degrades to a point where only 60% of beginning-of-life capacity is remaining.

Power-intensive and energy-intensive storage

Although Li-Ion batteries are very versatile, they are designed to better fit their main functionalities:

- **Power-intensive:** batteries required to perform services where the power capabilities are more important than the energy capacity – batteries required to inject/withdraw large quantities of power for a relatively short period.

  For instance, a c-rate = 4 means that maximum duration of power discharge is 15 minutes. Typically, power-intensive batteries have a c-rate > 2.

- **Energy-intensive**: batteries required to perform services where the energy capacity is more important than the power capabilities – batteries required to inject/withdraw power for a relatively long period.

  For instance, a c-rate = 0.25 means that maximum duration of power discharge is 4 hours. Typically, energy-intensive batteries have a c-rate < 1.

Those batteries having a c-rate in the range 1-2 are not markedly power-intensive nor energy-intensive.

Producers' market

Given the importance of all the components of the BESS, there exists different manufacturers specialised in each component individually.

1. Energy cells producers: they are mostly concentrated in the Far East. These major corporations are located in South Corea (Samsung), Japan (Toshiba) and China (BYD). Even General Electric, a commonly known manufacturer of energy cells, have given up the production and shifted to a different business model, becoming a system integrator, sourcing from external batteries manufacturers.

2. Power electronics producers: multinational industries or medium-size companies.

3. Software developers: Multinational industries or even SMEs.

4. System integrators: there is an increasing number of system integrators, having these companies partnerships with subcontractors.

Regarding the evolution of lithium-ion battery prices, these have been considerably lowering in the las 5 years owing to the aggressive market strategy by Far East corporations aiming at expanding their market shares in Europe and US. Also, due to the increasing presence of system integrators and consequent increasing competition, and finally to the impulse given by the automotive industry regarding the electric car.

Such trend is expected to continue in the next 5 to 10 years. However, due to the Covid-19 crisis the downward trend in prices has stagnated a bit as a consequence of the difficulties faced in the lithium supply.

4.2. Usages

4.2.1. Service to the grid

Among the grid services usually performed by conventional fossil fuels power stations, the following ones can be easily provided by batteries in order to respond to Transmission System Operators (TSO) needs:

- Voltage regulation: batteries can contribute to the grid frequency stability by injecting reactive power when needed.

- Secondary reserve: batteries can provide this service by injecting/withdrawing power in order to restore the frequency nominal value within a very short time-lapse (a few seconds)

- Tertiary Frequency Regulation: batteries can be operated to reduce the energy imbalances between the coverage of the hourly electricity demand expected by the TSO and the real-time situation, by discharging energy when the system is short and charging energy when the system is long.

Energy-intensive batteries are used to reduce the congestion in certain areas of the grid, particularly those where a large number of wind farms are operating.

4.2.2. Service to market operators

Energy reserves - industries and services

Even in the industrial sector and in the tertiary sector, the energy storage systems respond to many requirements: increase the energy efficiency, reduce the electricity bill, maximise the use of renewable energy (when coupled with RES), contribute to the sustainability and strengthen the corporate "green" image.

Of course, the effectiveness of the implementation of energy storage systems is strongly dependant on the industry production cycles and the company habits: theoretically it is easier to be attained by companies of the tertiary sector.

Renewable Power Generation - time shifting

In the Time Shifting business case the battery is charged buying energy in the hours of the power market with the lowest prices and discharged selling energy in the hours of the highest prices: the operational profile of the battery is determined in order to maximize profits by capturing the largest possible rice spreads.

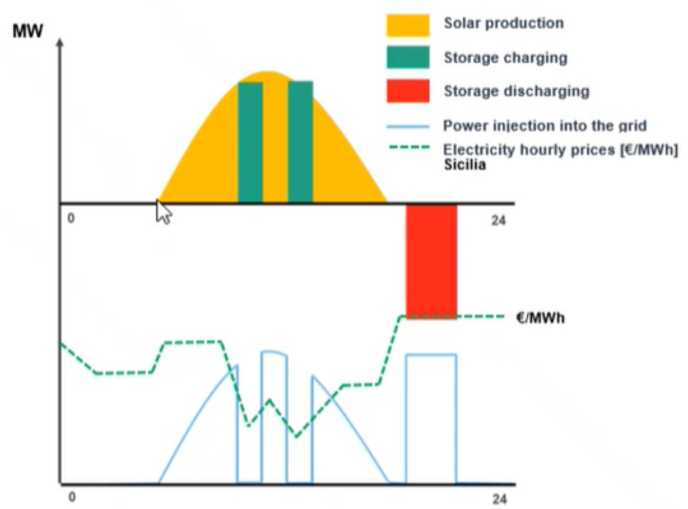


Figure 4.1. Influence of solar production and electricity hourly prices within the charge/discharge of batteries. Source: ENGIE Italy.

The energy storage systems, even when used in this kind of projects, make the management of energy sources at a local or national level more efficient and more environmentally sustainable. In such business case the energy charged in the batteries is injected into the grid in hours of high demand, thus contributing to the reduction of power generation by fossil fuels.

4.3. Costs

The selected BESS for the study, as mentioned previously, is the Li-Ion battery due to its great capabilities. In order to estimate their costs, a report from the National Renewable Energy Laboratory (NREL) has been used. [FRM18]

The costs are broken down by their main components as shown in the table below.

Components	Units	2018
Li-Ion	$/kWh	209
Inverter	$/kW	70
Transformer	$/kW	11

Table 4.1. Battery components costs. [FRM18]

Nowadays, the installation of utility-scale batteries requires a lot of investment in CAPEX. One of the key issues when considering the integration of batteries with renewable energy generation plants is if the Internal Rate of Return (IRR) of the project will be affected positively or negatively.

The revenues that can be accounted with batteries are not enough to compensate the increase in CAPEX that the installation of batteries require. For this reason, the IRR of renewable project will be worsen unless there is a very strong incentive or agreement with market operators or TSOs to invest in these kind of technology.

There is one possibility that must be considered in the long-term as battery lifetime is around 20-30 years. From a strategic point of view, it could become of interest to install these assets to be well positioned for upcoming opportunities, however the decision must come from energy regulators or even the TSO.

Another issue to take into account is the size of the installed batteries. Experience has taught us that investing in small scale batteries is not profitable and so if any investment is to be made, it should be in large batteries.

The following graph illustrates perfectly the cost of batteries according to their use. The one of most interest is the "Storage systems paired with large PV locations" and is the one that it will be considered in the financial study.

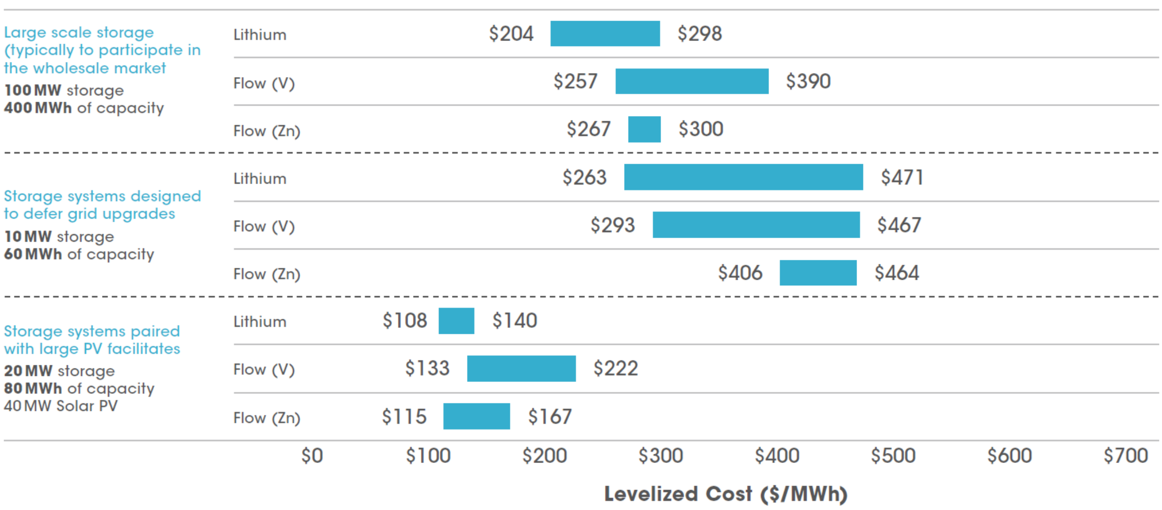


Figure 4.2. Comparison of levelised cost of storage (USD/MWh). Source: IRENA [AB19].

Once discussed the possibility of batteries not being profitable, the financial study will attempt to justify this with numbers. This discussion can be found in **??**.

5

Base case application: 50MW PV farm

This chapter is just a practical implementation case of the different topics studied during the previous chapters. It must define the process to size and design a hydrogen plant adjacent to a solar photovoltaic power plant where the energy for its production is obtained.

In order to carry out the complete study, there are two main sections in which it has been divided: technical and economic study.

5.1. Technical study

To carry out such studies, and especially the technical study, it is necessary to know the components and technical details of the solar photovoltaic plant and the electrolyzer. To this end, this section will be broken down into the following sub-sections, which will go into the above-mentioned aspects in more detail:

- Photovoltaic solar plant
- Electrolyzer design model

5.1.1. Photovoltaic solar plant

The solar plant mentioned in this project has been previously designed and, therefore, an analysis of its reasonableness will not be carried out as it is not the motivation of this project.

The plant to be studied is a 50MW PV generation plant under ENGIE's portfolio. It consists of a ground-mounted plant with an installed capacity of 49.8 MWp distributed over 134,618 modules of 370 Wp each. In order to maximise the collection of solar radiation, the plant has horizontal single-axis trackers consisting of 56 modules each.

In the following table, some of the principal technical characteristics of the PV solar plant are specified.

Parameter	**Units**	**Value**
	Power	
AC Nominal Power	MWac	39.2
AC Max. Power ($\leq 25^oC$)	MWac	45.594
Grid Power Limitation	MWac	44.8
DC Power (STC)	MWdc	49.80866
	PV Module	
Technology		Monocrystalline
Peak Power	Wp	370
Max-Power Voltage	V	39.34
Max-Power Current	A	9.39
Modules per string	#	29
Strings	#	4,642
Modules	#	134,618

Table 5.1. Solar plant data sheet

5.1.1.1. Energy produced in the farm

Once the parameters were introduced in the model, the energy generated by the solar plant was obtained from an actual monitoring of the plant's production. These results are already taking into account the technical characteristics of the plant so no further adjustments were necessary. For a more in-depth understanding of the power generated by the PV plant, the monthly average hourly power curves are included in the Appendix B.

Hereunder, the total production of energy each month is shown. Part of the energy produced in the solar plant will be transformed by electrolysis into hydrogen. Consequently, to know the power generated by the plant at each moment is critical for a correct sizing of the plant.

Month	**Energy (GWh)**
January	3.80
February	6.12
March	7.31
April	7.05
May	10.46
June	11.92
July	11.59
August	10.58
September	8.27
October	7.32
November	5.32
December	3.03
Annual	**92.77**

Table 5.2. Annual energy produced by the solar PV plant

It can be observed in the previous table that the central months (June and July) present the highest production of energy, being these months the ones expected to produce the most hydrogen. On the contrary, January and December are the months with the lowest energy production. In this situation it could be of interest to combine different sources of energy to obtain the quantity of hydrogen desired.

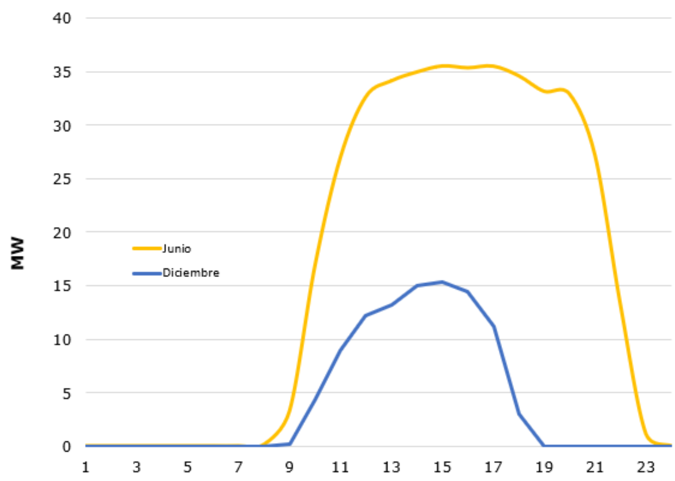


Figure 5.1. Power generation curve comparative: June and December.

5.1.1.2. Cost of solar power plant

The investment in the generation plant has already been incurred, however the order of magnitude for the CAPEX for this solar PV plant is around 700€/kW, including development costs, construction, financial expenses, etc. This is important as they will be used in the final financial model in order to obtain a realistic hydrogen price (€/kg).

5.1.2. Electrolyzer design model

The hydrogen plant under study in this project is focused on the transformation of electricity from an electrical system into hydrogen, which will then be used as an energy vector.

The transformation of electrical energy into hydrogen takes place in the electrolyser, which was presented in more detail in Section 2.4. Hydrogen plants generally consist of separate electrolyser modules, although compact plants are available for specific applications. Specifically, the most suitable electrolyser for the integration along with RES is the Proton Exchange Membrane (PEM) electrolyzer being the one studied in this project. Despite being more costly than the AEC technology, it has greater versatility and faster response time, making it ideal for incorporation with renewable energy resources

The implementation and design of a hydrogen plant adjacent to a solar plant requires a pre-feasibility study in which, initially, the optimum power at which the hydrogen plant should operate is determined by means of a technical analysis. In order to carry out this study, it has been assumed that the energy consumed by the hydrogen plant comes exclusively from the solar plant.

The idea is to determine the optimum output power of the hydrogen plant that maximizes the available resources of the solar plant and, at the same time, minimizes the plant's costs.

Although it is called a technical study, the determination of the optimal capacity of the hydrogen plant is based on the minimization of the marginal costs. In this way, it is possible to determine the optimal state of the system. The marginal cost will be expressed in terms of cost per mass of hydrogen produced (€/kg).

It is therefore particularly important to know the energy consumed by the hydrogen plant, as the costs incurred in the plant as a whole and the amount of hydrogen produced.

5.1.2.1. Energy consumed by the electrolyzer

Once the energy produced by the solar PV plant is determined, the next step is to size the PEM electrolyzer that will be connected to it. As mentioned previously, the hydrogen plant design process is focused on minimizing the marginal cost associated with the production of hydrogen.

In order to establish the optimal size of the electrolyzer, a study of different power ranges for the hydrogen plant has been carried out. As it was mentioned previously, the nominal AC power of the solar plant is 39.2 MWac (Table 5.1), and assuming that the electrolyzer will consume directly the energy produced by the plant, the possible ranges where divided in 39 slots, starting with a capacity of 1MW up to an electrolyzer of 39MW.

In this sense the power and, therefore, the energy consumed by the electrolyzer does not vary linearly.

First, as is logical, the maximum energy that can be consumed by the hydrogen plant is set at 100% of its rated power. Thus, there will be different energy consumption profiles depending on each plant. For plants with low installed power capacity, the proportion of energy consumed is small compared to the total generated, so its utilization is not efficient. On the other hand, when the hydrogen plant installed capacity is high, the amount of energy consumed is significantly higher. However, these situations occur in only a few months of the year, since, for example, for the months of December, a plant with very high power would be oversized by far exceeding the maximum power that the solar plant is capable of generating (see Figure 5.1)

The following graph depicts what is being tried to explain. This said, the 100% represents the 92.77GWh produced by the PV farm, while a 50% means that only halve of the energy produced by the generation plant is being used by the electrolyzer.

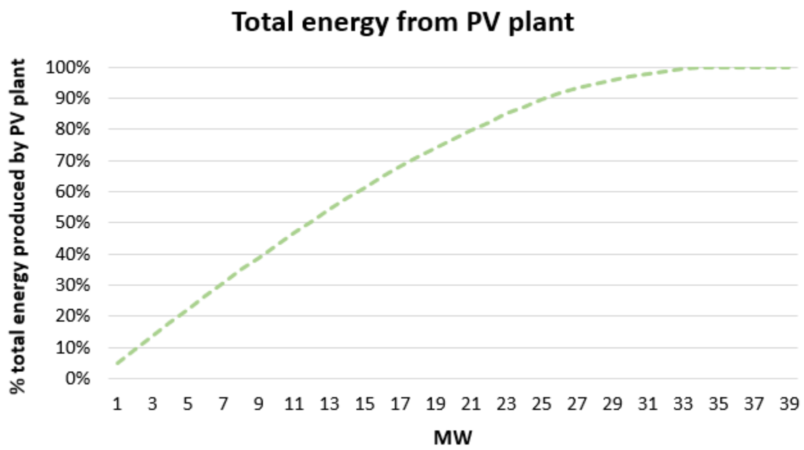


Figure 5.2. Energy consumed according to the different hydrogen plant capacities, represented as a % of the energy generated in the solar PV plant.

5.1.2.2. Hydrogen produced by the electrolyzer

Once the energy consumption of the electrolyser has been determined, depending on the size, the hydrogen production is calculated.

The following table shows the molecular properties of hydrogen, representing the relationship between the energy required to obtain hydrogen and the mass and flow rates. This is important in order to obtain the electrolytic performance of the PEM electrolyzer.

Energy (kWh)	Mass flow rate (kg)	Volume flow rate (Nm3)
1	0.03	0.33

Table 5.3. Relationship between energy consumed for the production of hydrogen

From Table 2.3 it can be obtained that the power consumption is 4.8 kWh/Nm^3, so taking into account this efficiency, and the molecular properties of hydrogen, the electrolytic performance can be calculated.

$$\eta_e = \frac{1}{0.33 * 4.80} = 63.1\% \tag{5.1}$$

Having this in mind, the way of obtaining the amount of hydrogen produced by the plant is:

$$M_{H2} = E_c * f_m * \eta_e \tag{5.2}$$

Where:

- M_{H2} = Hydrogen production [kg or Nm^3]
- E_c = Energy consumed by electrolyzer [kWh/year]
- f_m = Hydrogen flow rate [kg/kWh or Nm^3/kWh]
- η_e = Electrolyzer efficiency [%]

This process is analogous in the case that the desired outcome is the volume generated instead of mass.

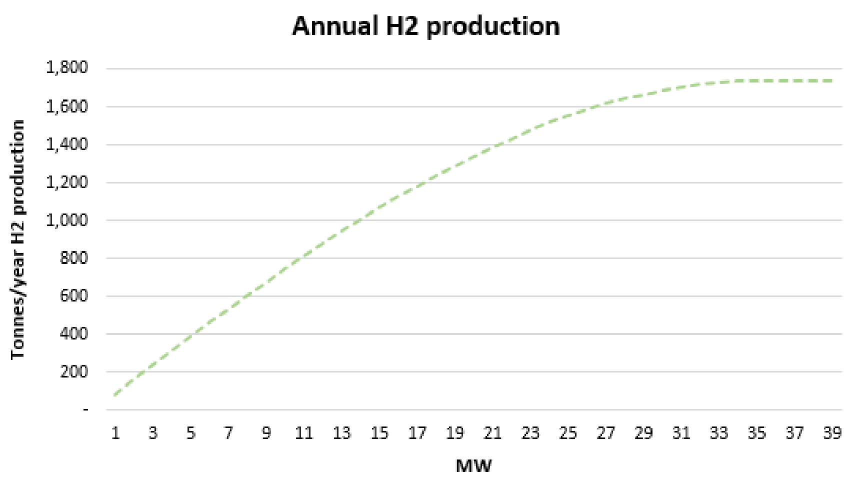


Figure 5.3. Annual hydrogen production according to the different hydrogen plant capacities.

The previous graph compares the yearly hydrogen production with the electrolyzer's capacity. It can be observed that it has a linear behaviour in the lower ranges, however around the 27MW of installed capacity, it starts to flatten. This gives an indication that just because a larger electrolyser capacity is installed, generation will not increase proportionally.

5.1.2.3. Cost of the electrolyzer

Another fundamental input parameter to determine the optimal capacity of the hydrogen plant are the costs incurred. As mentioned in Section 2.4.3 some of the values for CAPEX and OPEX per MW installed were introduced for the years 2017 and 2025.

The reference year at which the project is expected to start is 2022. So, for this reason, in order to be able to establish the correct value for CAPEX and OPEX, the least square approximation was computed.

CAPEX

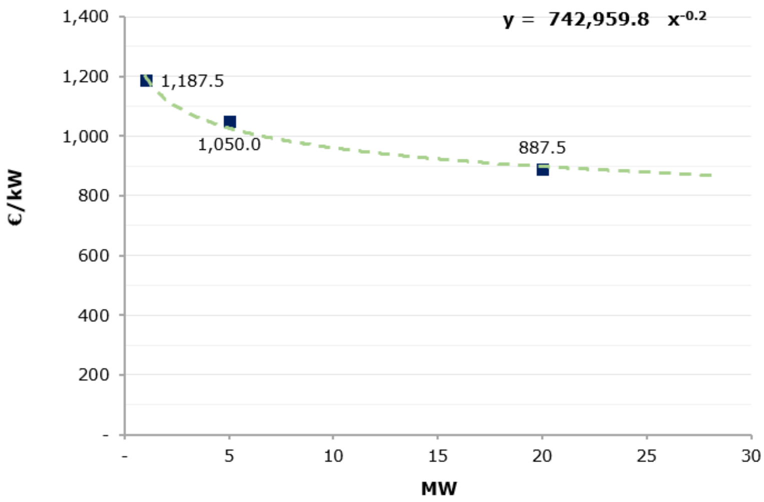


Figure 5.4. CAPEX estimation curve from Table 2.4.

Capacity (MW)	Unit	2022
1	€/kW	1,187.5
5	€/kW	1,050.0
20	€/kW	887.5

Table 5.4. Initial CAPEX of the electrolyzer

OPEX

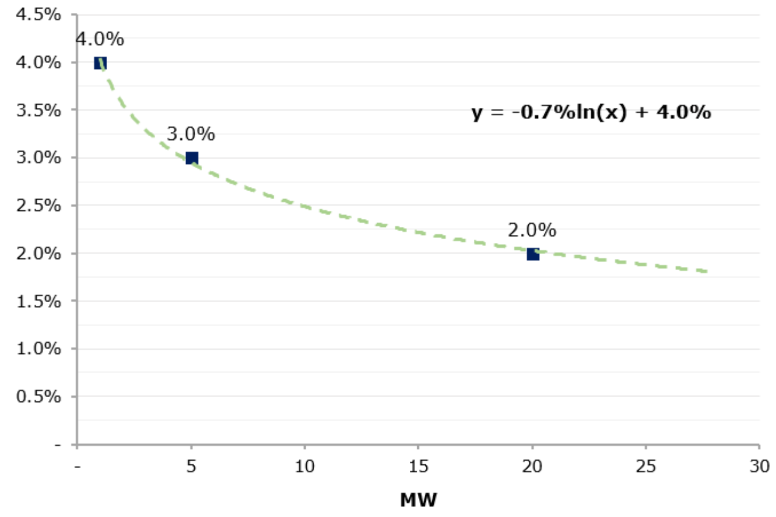


Figure 5.5. OPEX estimation curve from Table 2.5.

Capacity (MW)	Unit	2022
1	% CAPEX	4
5	% CAPEX	3
20	% CAPEX	2

Table 5.5. Initial OPEX of the electrolyzer

WATER COST

Lastly, the water cost is another important factor to consider in the optimization model. It can even be considered as part of the OPEX costs.

It has been set an average price for water 1.84 €/m^3. This price will vary depending on the location of the electrolyzer.

Other aspect to consider is the volume of water required in the electrolysis process. Knowing the stochiometric ratio between moles of water required to produce hydrogen we observe that these only depend on the molecular mass as the mole ratio is 1:1.

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{5.3}$$

The following table presents the masses of the molecules involved in the electrolysis process.

Molecule	Unit	Value
Water (H_2O)	g/mol	18
Oxygen (O_2)	g/mol	16
Hydrogen (H_2)	g/mol	2

Table 5.6. Molecular mass of the elements involved in the electrolysis process

In this sense, knowing the molecular masses of each element we can observe that the required mass of water is 9 times greater than the mass of hydrogen produced. Then the final cost of water will be calculated as follows:

$$\text{Water consumed} = H_2 \text{ (kg) * 9}$$

$$\text{Water cost} = H_2\text{O price * water consumed}$$

5.1.2.4. Optimal electrolyzer

Once the important parameters for determining the optimal capacity of the electrolyzer are stated, the following step is to calculate the hydrogen marginal cost in order to select the capacity with the lowest one.

With the different possible capacities of electrolyzers, the total cost and the total hydrogen production were computed. Once this was set, the way to proceed is to determine the difference in total costs and hydrogen production between the studied capacity and the previous one. The idea of doing it like this is to be able to obtain the lowest variation in price, with the largest variation in hydrogen production within the different capacities. This will provide the lowest marginal cost, resulting in the optimal electrolyzer capacity.

$$min \frac{TC_i - TC_{i-1}}{H_{2i} - H_{2i-1}}$$

where *i* the capacity, in MW, of the hydrogen plant studied and CT the total cost (CAPEX + OPEX + water)

The resulting graph, where the marginal cost is represented according to the installed capacity of the electrolyzer, is the following one:

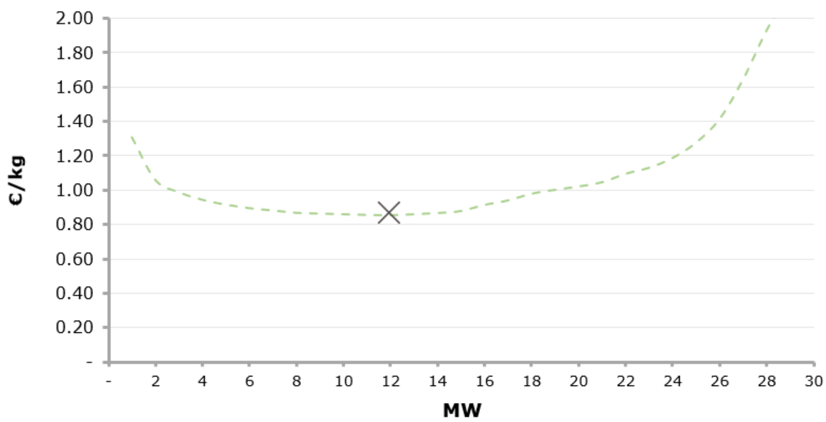


Figure 5.6. Electrolyzer's marginal costs according to the different hydrogen plant capacities.

The graph above represents the marginal costs according to the different hydrogen plant capacities. It can be observed that between 2 MW and 24 MW a "bath" shape is obtained and within these values, the optimal output power of the electrolyzer is found.

For the initial values of the possible output capacities of the hydrogen plant, the marginal costs associated are very high as hydrogen production is not yet sufficient to overcome the high capital and operating costs. On the other hand, if the final values are observed, these stand for just the opposite - low capital and operating costs but with a negligible variation in the production of hydrogen. The last values - 31 MW to 39 MW - were not represented as the results took exorbitant values.

The optimal solution for the hybrid configuration is an electrolyzer with a 12 MW of installed capacity, where the absolute minimum can be found. It should be noted that this value can vary depending on the reference year that is determined, however there is a range were the marginal costs are similar and so they could become a feasible solution (between 8 MW and 15 MW).

Underneath, in Table 5.7 the main characteristics of the optimal hydrogen plant are summarized.

Electrolyzer	**Units**	**Value**
Capacity	MW	12
Energy consumption	MWh	46,825
H_2 production	Tonnes	878
CAPEX	M€	11.32
OPEX	Thous. €/year	268
Marginal cost	H_2 €/kg	0.856

Table 5.7. Electrolyzer's optimal plant capacity characteristics.

The results obtained in the technical study will be subsequently used to analyze the economic impact of the plant as a whole, being able to determine the minimum price of green hydrogen.

5.2. Economic study

For analyzing the economic viability of the project, the electrolyzer and the solar plant must be taken into account.

The economic study can be approached from different perspectives, but the one used in the model is the one with which the Net Present Value (NPV) is obtained from the investment and operation of the solar generation plant and electrolyzer.

One of the aspects that differentiates this project with any other that is directly related to the electricity market, is that there is no hydrogen market and so no price or future price curve can be determined in order to develop the economic model. Thus, the way in which the economic model has been oriented is to determine the minimum selling price of green hydrogen at which the project would have a net present value of zero.

5.2.1. Economic parameters

A more detailed analysis needs to be developed for pricing hydrogen considering the costs incurred by the plant as a whole. In addition, it is necessary to consider general elements that are essential for determining the correct cash flows.

Among the main ones:

- The investment and operating costs of both the solar and hydrogen plant, as well as the cost of the water consumed to produce green hydrogen.
- The hydrogen production as a whole, considering the energy coming from the solar plant.

- Other general aspects that determine the profitability of the project: reference year, discount rate of the project, inflation rate, or even taxes, interests...

The main economic parameters that were introduced in the Model are shown in the Table 5.8.

Parameter	**Unit**	**Value**
Reference year	year	2022
Start-up time	years	2
WACC	%	8.0
Inflation rate	%	1.5
Taxes	%	25
Exchange rate	$/€	1.19

Table 5.8. Financial input parameters

These parameters can be varied according to the preferences of the project.

Based on the results of the technical study, the economic study of the installation was developed. Knowing that the optimal configuration is an electrolyzer with no batteries, the following table gathers the most relevant information needed to develop the cash flow analysis.

Year	**Acc. Deg. (%)**	**H2 production (ton)**	**Acc. inflation (%)**	**CAPEX (M€)**	**OPEX (thous. €)**	**Water (thous. €)**
2022	-	-	-	46.14	-	-
2023	-	438.98	1.5%	-	298.97	7.38
2024	1.0%	868.83	3.0%	-	606.90	14.82
2025	2.1%	859.70	4.6%	-	616.00	14.89
2026	3.1%	850.56	6.1%	-	625.24	14.95
2027	4.2%	841.42	7.7%	-	634.62	15.01
2028	5.2%	832.29	9.3%	-	644.14	15.07
20329	6.2%	823.15	11.0%	-	653.80	15.13
2030	7.3%	814.02	12.6%	-	663.61	15.19
2031	8.3%	804.88	14.3%	-	673.56	15.24
2032	9.4%	795.74	16.1%	-	683.67	15.29
2033	10.4%	786.61	17.8%	-	693.92	15.34
2034	11.4%	777.47	19.6%	-	704.33	15.39
2035	12.5%	768.33	21.4%	-	714.90	15.44
2036	13.5%	759.20	23.2%	-	725.62	15.49
2037	14.6%	750.06	25.0%	-	736.51	15.53
2038	15.6%	740.92	26.9%	-	747.55	15.79
2039	16.6%	731.79	28.8%	-	758.77	15.61
2040	17.7%	722.65	30.7%	-	770.15	15.65
2041	18.7%	713.52	32.7%	-	781.70	15.68
20442	19.8%	704.38	34.7%	-	793.43	15.71

Table 5.9. Hydrogen plant information along its operating life.

From the information presented in the table above, it will be calculated the optimal price for hydrogen. There were considered many other aspects such as: depreciation, amortization, taxes, etc. As mentioned previously, batteries are not considered, so the CAPEX and OPEX reflected in Table 5.9 is the sum of both the PV solar plant and electrolyzer.

The average degradation rate for 1000 hours of functioning of the plant is 0.11% however, this value can increase up to 0.2% if a PEM electrolyzer is considered. In the case study that is being analyzed, the technology is PEM, so a degradation factor of 0.2%/1000h was used.

Observing the numbers obtained, it can be seen that the 20% of degradation has not been exceeded, so there will be no need to invest in stack replacements. Nevertheless, in the **??** the lifetime of the assets are included and so, a more realistic result is obtained. A *NEL M4000 PEM* model with a useful life of 20 year needs 2 periods of maintenance and stack replacement. This will incur in higher costs, and therefore a higher price for hydrogen.

The economic study with an 8% WACC results in a final price of hydrogen of 6.65 €/kg. This was obtained making the NPV equal to zero.

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} = 0 \tag{5.4}$$

Where:

· R_t = net cash inflow-outflows during a single period t
· i = discount rate, WACC [%]
· t = number of periods

The following table summarizes the most important parameters from the optimal hydrogen system.

Parameter	**Units**	**Value**
Solar PV plant	MWp	49.80
Solar PV plant	MWac	39.2
Electrolyzer	MW	12.00
Energy consumed	MWh/year	46,825
H_2 production	tonnes/year	878
H_2O consumption	m^3/year	7,901.72
Total CAPEX	M€	46.14
Total OPEX	Thous. €/year	589.10
LCOH	H_2 €/kg	**7.00**

Table 5.10. Optimal result for the hybrid configuration.

6 Conclusions & future developments

This last chapter seeks to present the different conclusions reached within the study.

The production of green hydrogen from electrolysis will become one of the most important pillars in the decarbonization of the economy. Its versatility for a variety of end-uses such as production of electricity, transport, heating fuel, and many other industrial applications makes it a key asset in the energy transition.

The thesis shows the order of magnitude of capex and opex for electrolyzers and batteries, allowing anyone using the document to have very up-to-date market references and thus be able to evaluate an investment project.

The work is completed with an Excel model with which, firstly, size an electrolyzer from the energy coming from a solar PV generation plant, which consequently develops an economic optimum, arbitrating between kg of hydrogen produced and the corresponding total cost. Secondly, once the optimal capacity of the electrolyzer has been determined, it is possible to model the minimum hydrogen price necessary to recover the investment over the lifetime of the electrolyzer. These models are of complete use when valuing green hydrogen investments, sizing future projects, etc.

The results show in a practical way the main data extracted from the review of the state of the art. On an industrial scale, there is a large gap of approximately €5/kg between the cost of obtaining gray hydrogen and that of obtaining green hydrogen. Therefore, in order to achieve full industrial development of the technology, support mechanisms are needed, either via subsidies or any other form of injection of money. Only a balance of costs will encourage a complete technological shift from grey to green hydrogen in the different industrial applications that hydrogen is currently used for: fertilizers, mobility, etc.

6.1. Base case conclusions

1. **The optimal design for the electrolyzer adjacent to a PV generation plant nowadays is not competitive enough.**

   Having in mind the actual cost of hydrogen for industrial application - 2-3€/kg - the final price for green hydrogen (Table 5.10) that the Model returns is not competitive at all. If green hydrogen is going to become key in the energy transition, state aids must be granted to these projects, if not there will be no interest in investing in green hydrogen.

   It is worth mentioning that the model considers the cost of the already built PV solar plant and the expected investment for the electrolyzer, so the final price for hydrogen with which both investments will be recovered is quite high.

2. **The installation of batteries is strongly dependent on the year in which they are installed.**

   The installation of a battery system adjacent to the solar plant does not seem feasible from a technical and economic point of view.

   There is an expected drop in battery costs for the near future, so the design of a renewable power plant with batteries will be feasible and optimum.

3. **The lack of a competitive and regulated market from which to extract a hydrogen price makes it difficult to analyze the feasibility of this type of project.**

   The creation of a model to determine the normalized cost of hydrogen is necessary to determine its economic viability. The final price of hydrogen will need to be set at normalized cost and not by the marginal one, being this the way that mature, competitive markets such as the electricity one functions.

6.2. Green hydrogen and society

The study carried out helped evaluate the current status of green hydrogen in society. There are some aspects that are worth mentioning:

1. **The interconnection between the electricity and gas systems will be enhance thanks to hydrogen, increasing the usefulness of the already existing infrastructures.**

   One of Spain's main energy asset is the extensive gas network that it has, with a considerable storage capacity. Its functionality has increased as it allows the transport and storage of renewable gases (hydrogen, biomethane or even synthetic methane) contributing positively to the energy transition and offering the possibility of bringing decarbonization to all sectors of consumption.

   The principle advantage is the high storage capacity that it offers, although some hydrogen can be admitted with percentages and dilution rules depending on the regulation on each country. The use of storage provides a viable solution to one of the most critical points when considering the introduction of RES, the lack of capacity to store large amounts of energy - several MWh - due to the low energy density of batteries and their costs nowadays.

   An optimization of resources of the whole energy system is required and the coordination of both systems, electricity and gas, is essential. The development of new technologies around hydrogen can contribute to make investments profitable, both in terms of new renewable energy plants and electrolyzers.

2. **Hydrogen will become the enabler of Power-to-Gas allowing the storage of large amounts of energy.**

   This second point goes strongly related to the previous one. Renewable gases, hydrogen and synthetic methane are the only alternative for storing large amounts of energy in the form of chemical energy.

   Unlike the other storage technologies, this is the only option for storing large amounts of energy for long periods of time. Right now the costs are not competitive, but it is expected that by 2030 the costs will come down and the processes for storing renewable energy in renewable gases will become a reality, and by 2050 renewable gases could even become a substitute for fossil gases.

3. **Hydrogen is becoming the game-changer in the new European Green Deal, shifting towards Europe's 2050 energy targets.**

   Hydrogen plays an important role in the European Union's Green Deal. One of the objectives is to develop an exclusively internal industry to achieve electrolyzer plants of at least 100MW and improving the efficiencies they currently have, while reducing CAPEX, for the immediate future.

   These objectives, are mainly focused on developing and demonstrating the scalability of an electrolyzer that allows connecting renewable energies and industrial applications, without the sector losing competitiveness.

   There is still a long way to go, specially when referring to the investment costs that will make possible the energy transition towards decarbonization. With the objectives set by the EU Green Deal, the path towards efficiency and competitiveness set for 2050 is clearer, regardless of the many challenges still to be solved.

4. **An adequate hydrogen regulation must be established.**

   The new reality of green hydrogen is here to stay. Due to the new uses and application that this renewable gas has, is necessary to establish an adequate regulation based on technical standards, managed from a legislative point of view. Hydrogen and its new uses need a specific regulation and no longer be considered within an industrial gas regulation.

6.3. Future developments

1. **Encourage knowledge and technological development on the production, storage and use of hydrogen.**

   It will be necessary to encourage a demand growth in those sectors where the use of hydrogen is a step towards decarbonization in order to generate a new hydrogen market.

   Allowing the scaling up of the technology by implementing pilot plants is crucial in order to allow an appropriate learning curve as well as obtaining social acceptance of the technologies and uses of hydrogen.

   On the other hand, this will result in a cost reduction, necessary to obtain a competitive price in green hydrogen.

2. **Adaptation of gas structures for energy storage and transport.**

   As previously mentioned, hydrogen deployment can benefit from the use of gas infrastructures, thus allowing significant savings in the investment of building new gas pipelines exclusively for hydrogen.

   Therefore, these already existing gas infrastructures need to be recognised and legislate in order to be able to be used for the development of hydrogen in its many applications.

3. **Future green hydrogen demand will drive the development of a new market, with new restrictions, displacing conventional fuels.**

   The technical and economic study has been approached from the point of view of maximizing resources at the lowest possible investment. However, the demand for hydrogen has not been taken into account at any time and this will influence the maximum daily, or monthly, limit that the plant produces.

   The installation of hydrogen storage tanks is relevant to determine the maximum daily hydrogen production. These entail additional costs that have not been considered, which would increase the final cost of green hydrogen.

   The displacement of conventional fuels will influence positively in the final price for green hydrogen. Currently, this effect is being seen with the penetration of electric vehicles, changing the scope of the consumption of fuels for vehicles. The same effect will be seen in the near future with hydrogen, specially in heavy transport and industrial processes.

4. **Oxygen capture and storage technologies.**

   Although hydrogen production plants are oriented to the production of this compound, the main waste product is oxygen. However, the latter has not been considered under any criteria, and so its capture and storage could be put to other uses.

A

Sustainable Development Goals

The Sustainable Development Goals (SDGs), conceived on September 25, 2015, set out the challenges humanity must face to combat poverty, inequality, climate, environmental degradation, prosperity, peace and justice [UN21]. These goals are set out in the 2030 Agenda for Sustainable Development of the United Nations (UN).

Green Hydrogen is one the most promising vectors for industry and heavy transport decarbonisation and an innovative solution to collaborate with SDGS and to promote clean and affordable renewable energy.

***Goal 7**: Affordable and clean energy*

Figure A.1. Goal 7. Affordable and clean energy SDG.

Objective: Ensure access to affordable, reliable, sustainable and modern energy.

Increasing the share of renewable energy in the global mix helps have a cleaner environment. When consuming Green Hydrogen we contribute to installing affordable renewable clean energy

***Goal 9**: Industry, innovation and infrastructure*

Figure A.2. Goal 9. Industry, innovation and infrastructure SDG.

Objective: Build resilient infrastructure, promote sustainable industrialization and foster innovation.

It is in utilities' interest to find new solutions that enable sustainable consumption and production patterns. Hydrogen is one of this innovative solutions. ENGIE with its net zero carbon in 2045 goal, is acting to accelerate the transition to a carbon-neutral economy by reducing energy consumption through more environmentally-friendly solutions.

***Goal 13**: Climate action*

Figure A.3. Goal 13. Climate action SDG.

Objective: Take urgent action to combat climate change and its impacts.

Sourcing power from 100% renewable energy, utilities commit to reducing the emissions of CO2 and contribute to fight against climate change. ENGIE's objectives towards a net zero carbon aligns perfectly with the Climate Action SDG.

***Goal 17**: Partnership for the goals*

Figure A.4. Goal 17. Partnership for the goals SDG.

Objective: Revitalize the global partnership for sustainable development.

SDGs can only be realized with strong global partnerships built upon principles and values, with a shared vision and shared goals placing people and the planet at the center. This purpose unites the company, its employees, its customers, and its shareholders and reconciles economic performance with a positive impact on people and the planet. ENGIE's actions are evaluated in their entirety and over time.

B

Solar generation

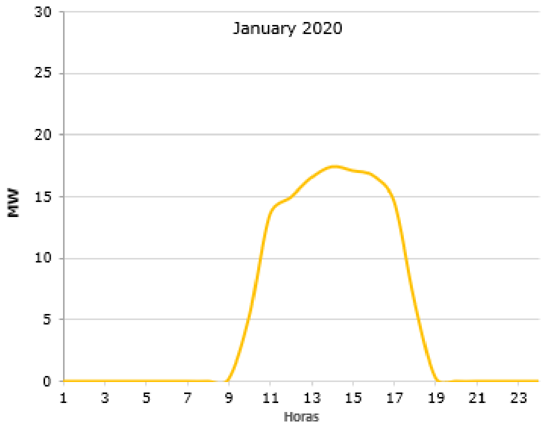
B.1. Solar generation table

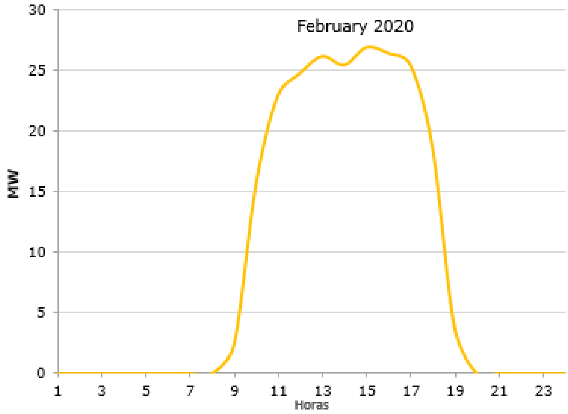
The following table shows the average solar generation from the Séneca PV solar plant throughout 2020. From these values, the graphs on Section B.2 are obtained.

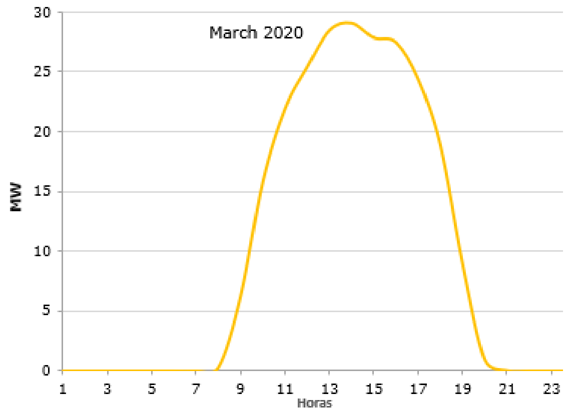
Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
0:00	-	-	-	-	-	-	-	-	-	-	-	-
1:00	-	-	-	-	-	-	-	-	-	-	-	-
2:00	-	-	-	-	-	-	-	-	-	-	-	-
3:00	-	-	-	-	-	-	-	-	-	-	-	-
4:00	-	-	-	-	-	-	-	-	-	-	-	-
5:00	-	-	-	-	-	-	-	-	-	-	-	-
6:00	-	-	-	-	-	-	-	-	-	-	-	-
7:00	-	-	0.3	-	0.8	0.2	-	-	-	0.3	-	-
8:00	0.2	2.4	6.22	4.4	12.9	3.3	1.2	0.2	4.4	6.22	2.4	0.2
9:00	5.2	15.6	15.9	13.3	21.8	16.9	12.4	7.4	13.3	15.9	15.6	4.4
10:00	13.5	22.9	21.9	17.7	26.7	27.0	25.2	23.2	17.7	21.9	22.9	8.9
11:00	14.9	24.8	25.4	21.7	30.3	32.6	30.3	30.0	21.7	25.4	24.8	12.2
12:00	16.5	26.2	28.5	25.4	32.5	34.1	33.2	32.4	25.4	28.5	26.2	13.3
13:00	17.4	25.5	29.1	25.3	34.1	34.9	34.1	32.6	25.3	29.1	25.5	15.0
14:00	17.1	26.9	27.9	26.9	33.4	35.5	34.3	32.3	26.9	27.9	26.9	15.3
15:00	16.6	26.4	27.5	24.8	31.9	35.3	34.4	31.9	24.8	27.5	26.4	14.5
16:00	14.6	25.4	24.4	21.8	31.2	35.5	33.8	31.3	21.8	24.4	25.4	11.2
17:00	6.5	18.6	18.8	19.7	30.6	34.6	33.4	31.7	19.7	18.8	18.6	3.0
18:00	0.3	3.7	9.0	18.1	24.9	33.1	32.6	31.3	18.1	9.0	3.7	-
19:00	-	0.1	0.9	13.4	19.6	32.9	30.2	29.1	13.4	0.9	0.1	-
20:00	-	-	0.1	2.3	6.6	27.1	26.3	21.9	2.3	0.1	-	-
21:00	-	-	-	-	0.1	13.2	11.7	5.8	-	-	-	-
22:00	-	-	-	-	-	1.1	0.8	0.1	-	-	-	-
23:00	-	-	-	-	-	-	-	-	-	-	-	-

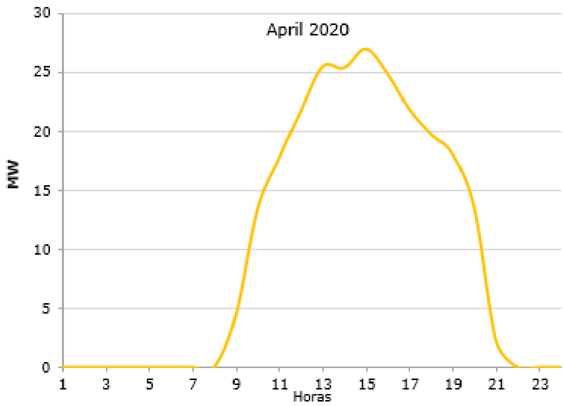
Table B.1. Monthly average solar generation, in MW.

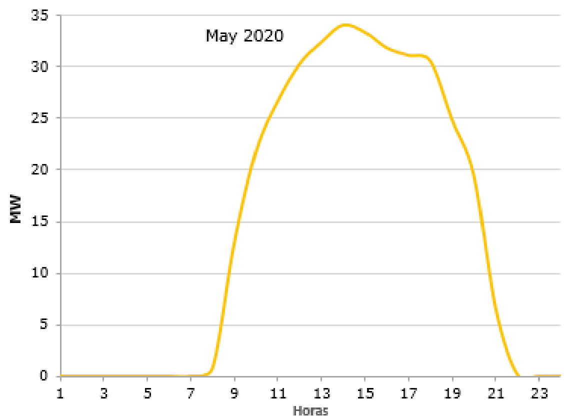
B.2. Solar generation graphs

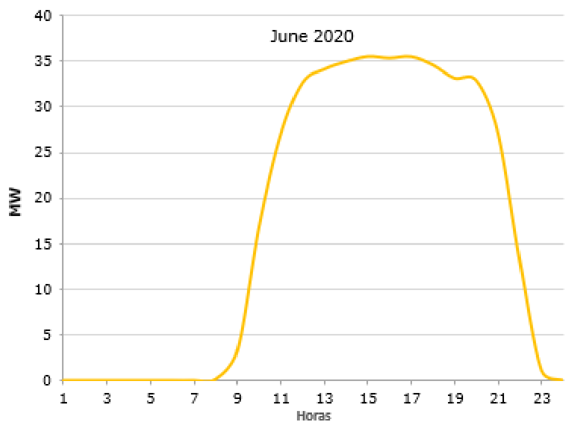


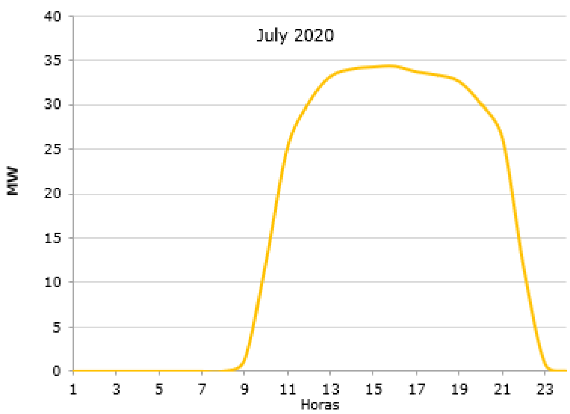


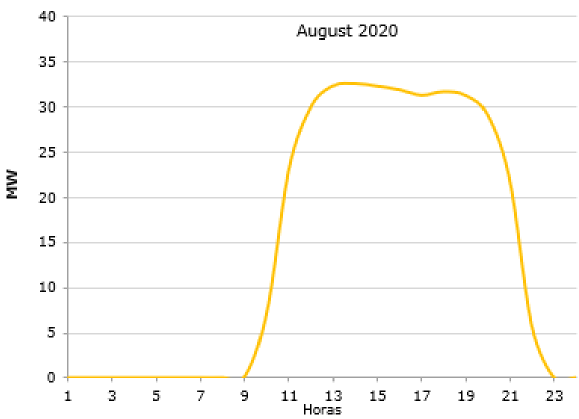












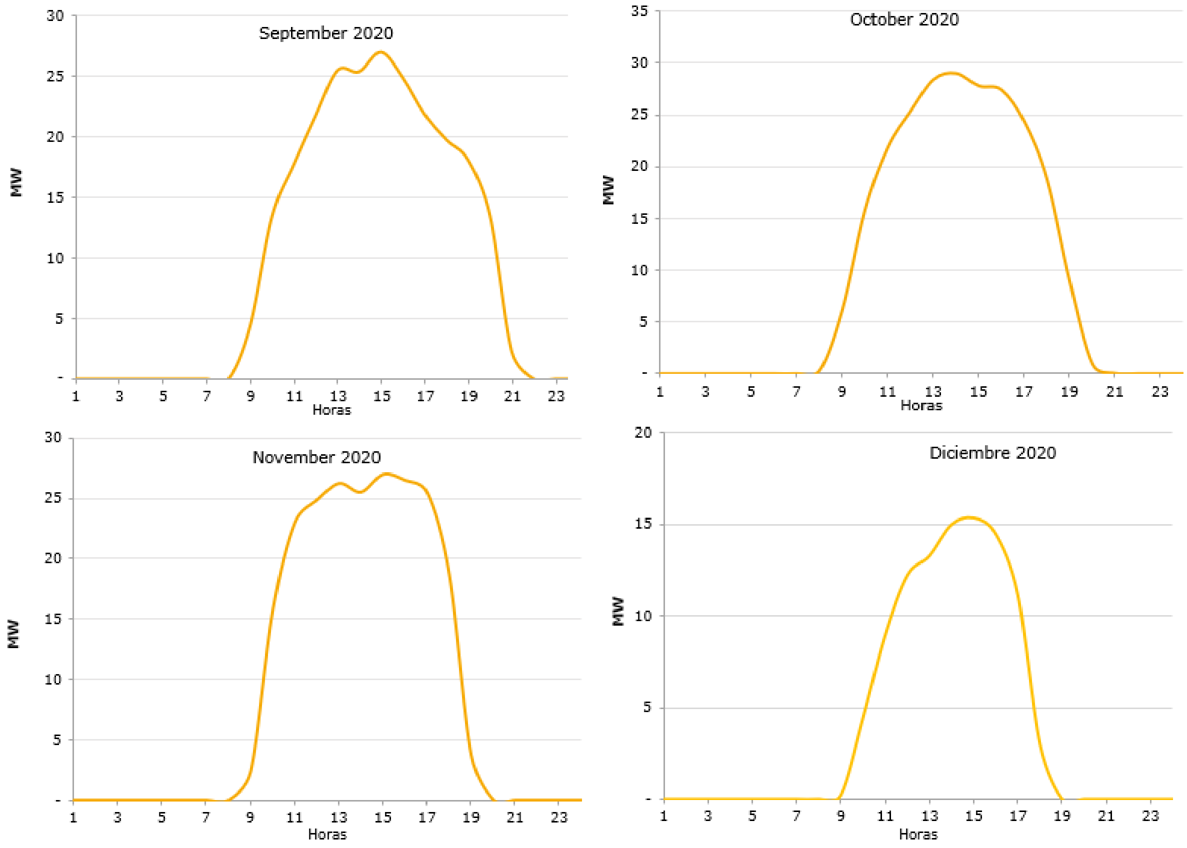


Figure B.1. Daily solar generation curve in Córdoba.

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