Trabajo Fin de Grado

Grado en Ingeniería de la Energía

# Analysis of the European Strategy for Hydrogen

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El tribunal nombrado para juzgar el Proyecto arriba indicado, compuesto por los siguientes miembros:

Presidente:

Vocales:

Secretario:

Acuerdan otorgarle la calificación de:

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El Secretario del Tribunal

*To my family, friends and teachers.*

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A mi familia y amigos, por su apoyo y ayuda. A mis profesores, por transmitirme sus conocimientos durante estos años de carrera, y especialmente a mi tutor Alfredo por ayudarme y guiarme con este proyecto y descubrirme el mundo del hidrógeno.

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*Begoña Vivanco Martín*

*Grado en Ingeniería de la Energía*

*Sevilla, 2022*

# Abstract

This Final Degree Thesis focuses on analysing the aspirations of the European Union within the hydrogen sector. This aim is achieved through the examination of the European Parliament's Hydrogen Strategy, allowing for a study of actions and projects in all hydrogen fields.

The analysis is preceded by an exposition of the energy sector current situation and a description of the technologies associated with hydrogen, as well as an explanation of the most relevant plans and organisations that shape the rest of laws and initiatives (Paris Agreement, EU Green Deal…). It is followed by an overview of the international and Spanish hydrogen developments and the conclusions achieved.

Any document that serves as a guide or strategy for any sector does inherently cover a wide range of topics so as to encompass the entirety of the sector, and this is the case for the strategy analysed. The European Parliament's Hydrogen Strategy includes hydrogen demand, infrastructure, research and innovation, production, policies and more. This wide range of topics in the document studied implies a wide range of topics to delve into in this thesis, resulting in more than 150 information sources consulted to elaborate the thesis.

The Hydrogen Strategy is crucial to understand the role of hydrogen in the EU and predict its future development. However, even though it was released about a year ago, it would already benefit from an update given that in a short period of time the energy context has changed (energy prices inflation, Russian conflict). In this situation of lack of security of supply and instability, the need for an energy carrier like hydrogen is more evident than ever.

Moreover, hydrogen can be the key to the green transition and decarbonisation in the EU, which is why it is so important to keep on developing its technologies and to pursue this strategy.

# Resumen


Este trabajo de fin de grado persigue analizar las ambiciones de la Unión Europea dentro del sector del hidrógeno. Este objetivo se alcanza a través del análisis de la Estrategia Europea para el Hidrógeno presentada por el Parlamento Europeo, que además permite que el estudio abarque todos los campos del sector del hidrógeno.

El análisis es precedido por una contextualización del sector energético actual y por una descripción de las tecnologías del hidrógeno (para producción, transporte, almacenamiento, usos…), y también por una explicación de los planes y organizaciones más relevantes y que da forma al resto de leyes e iniciativas (Acuerdo de París, EU Green Deal…). Al análisis le sigue un resumen del desarrollo en materia de hidrógeno a nivel internacional y nacional (español), y finalmente las conclusiones obtenidas.

Cualquier documento que cumpla el papel de guía o estrategia para un determinado sector abarca inherentemente un amplio abanico de temas para reflejar el sector al completo, y este es el caso de la estrategia que se analiza. La Estrategia Europea para el Hidrógeno incluye temas como la demanda de hidrógeno, infraestructura, investigación e innovación, producción, políticas, etc. Este amplio rango de temas del documento estudiado implica un amplio rango de temas que explorar en este trabajo de fin de grado, lo cual ha resultado en la consulta de más de 150 fuentes de información para la elaboración del trabajo.

La Estrategia para el Hidrógeno es crucial para comprender el papel del hidrógeno en la UE y predecir su desarrollo en el futuro. Sin embargo, aunque fue publicada hace alrededor de un año, ya necesitaría una actualización para poder incluir los cambios del contexto energético que han tenido lugar en este corto periodo de tiempo (inflación en los precios de la energía, conflicto con Rusia…). Dada esta situación de falta de seguridad de suministro e inestabilidad, la necesidad de contar con un vector energético como el hidrógeno es más evidente que nunca.

Además, el hidrógeno puede ser clave en la transición verde y descarbonización de la UE, por lo que es muy importante continuar desarrollando las tecnologías del hidrógeno y cumplir esta estrategia.

# Table of contents

# TABLE OF FIGURES

# ABBREVIATIONS

| | |
|---|---|
| CCS/U | Carbon Capture Storage and Utilisation |
| CHP | Combined Heat and Power |
| $CO_2$ | Carbon Dioxide |
| DOE | Department Of Energy (US Department of Energy) |
| EEA | European Economic Area |
| EU | European Union |
| EUR | Euro |
| FC | Fuel Cell |
| FCEV | Fuel Cell Electric Vehicle |
| GHG | Greenhouse Gas |
| GNI | Gross National Income |
| GO | Guarantee of Origin |
| HRS | Hydrogen Refuelling Station |
| $H_2$ | Hydrogen |
| IEA | International Energy Agency |
| LWH | Lower Heating Value |
| LNG | Liquid / Liquefied Natural Gas |
| LPG | Liquefied Petroleum Gas |
| MJ | Megajoule |
| $NH_3$ | Ammonia |
| PEM | Polymer Electrolyte Membrane |
| PV | Photovoltaic |
| RES | Renewable Energy Source |
| SME | Small and Medium-sized Enterprise |
| SOFC | Solid Oxide Fuel Cell |
| TJ | Terajoule |
| UK | United Kingdom |
| UN | United Nations |
| US | United States |
| USD | United States Dollar |

# 1 INTRODUCTION AND OBJECTIVES

The main objective of this Final Degree Thesis is the analysis of the European Union's view and strategy for hydrogen, which is crucial to attain an understanding of the hydrogen sector and comprehend its evolution within the green transition. The reason for this is that the EU is a very important actor in the sector so the measures it takes and the projects it develops have a major influence on the hydrogen market's advancement.

This objective is achieved by consulting more than 150 information sources, all listed in the References section.

Additionally, there is a brief explanation of the state of the art of the hydrogen technologies that cover the entire value chain (production, storage, transportation and use), concise, so as to give the reader the information required to grasp the analysis of the European hydrogen strategy. There is also an international and national (Spanish) take on hydrogen projects and strategies.

Nevertheless, as being said, the principal goal is to study the approach of the European Union to the hydrogen sector, which is accomplished using the European Parliament's Hydrogen Strategy [1] as the channel, and checking how its goals are being developed currently.

This thesis is developed within an energy context that strongly influences its content. While the main subject of this review is hydrogen, including its applications and the strategies elaborated, it is essential to consider the circumstances in order to understand hydrogen's role.

Probably the first concept to arise when thinking about energy context is climate change and the fight against it through decarbonisation and initiatives like the Paris Agreement. This agreement joined nations worldwide in 2015 to undertake the task of combating climate change, aiming to maintain the rise of global temperature this century below 2°C above pre-industrial levels, and even limit it to 1.5°C. Moreover, there are additional objectives within this agreement such as encouraging the participants to maintain their GHGs sinks (forests, for instance) or enhancing climate change education and training, public participation, awareness and access to information.

One way to assess the energy context is through energy related information, and particularly the data presented by the International Energy Agency, although it has to be stated that the data prolongs until 2019, so it does not reflect the current post-pandemic situation. It is also important to note that the IEA data regarding the European Union includes the United Kingdom (EU-28) since the figures provide information up to 2019, before the UK withdrew from the EU.

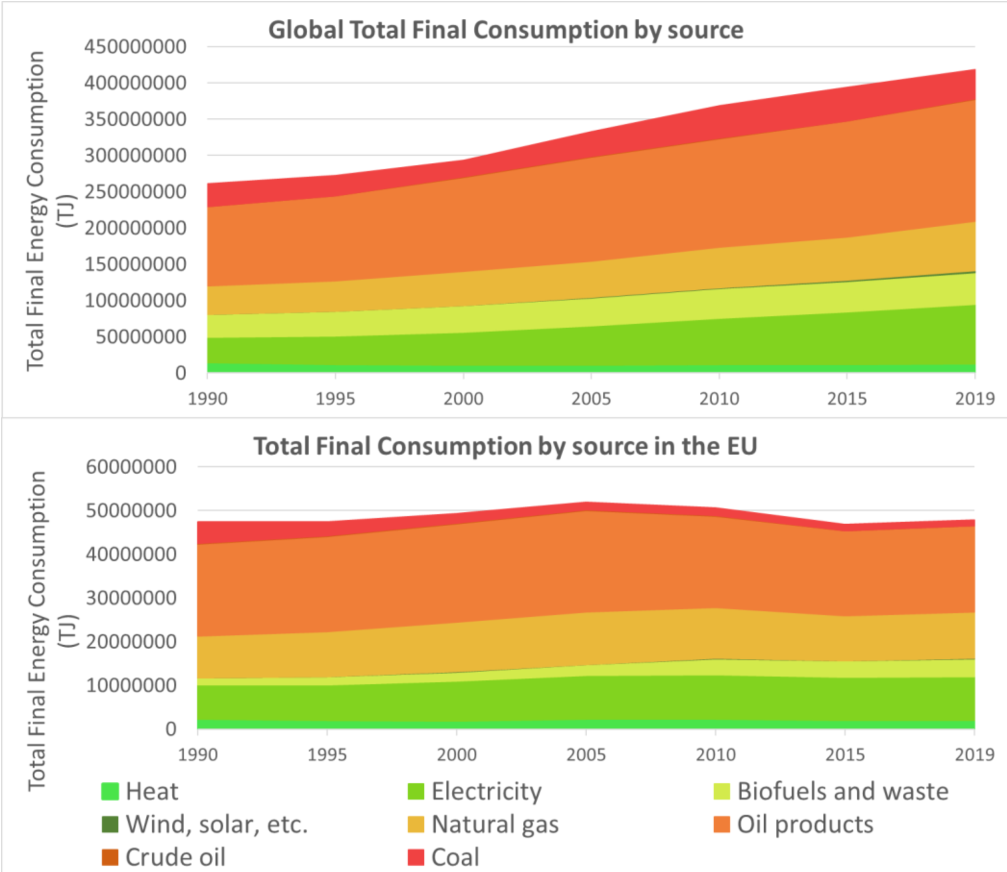



Figure 1. Comparison of the total final consumption by source worldwide and in the EU [3] and [4]

In Figure 1 it is seen that the energy consumption worldwide follows an increasing trend, covering renewable sources but also those that are fossil-based, while the EU has been able to stabilise and even begin a decreasing trend in consumption in the last years.

Actually, the final energy consumption in the EU dropped around an 8% from 2019 to 2020 reflecting the COVID-19 effects on consumption habits and industrial and public activity, such as the decrease in transport and industry consumptions due to lockdowns and restrictions, but this is clearly an out of the ordinary situation that does not really reflect the trend.

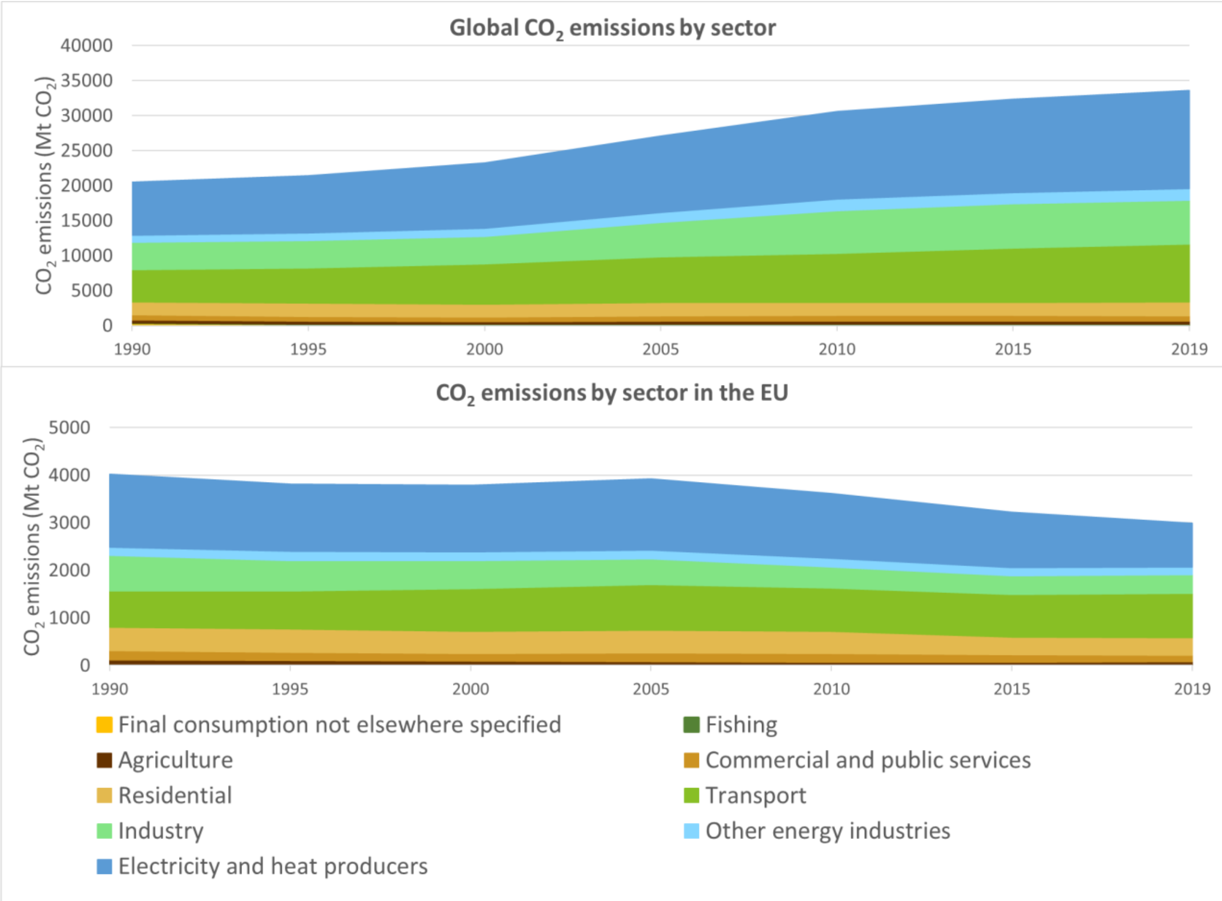



Figure 2. Comparison of $CO_2$ emissions by sector globally and in the EU [6] and [7]

In Figure 2 the comparison is similar to the previous one: the global $CO_2$ emissions are increasing but the trend in the EU is decreasing. In the past few years the EU has managed to remarkably reduce its $CO_2$ emissions in the electricity and heat production and industry sectors, and in most sectors in a more or less significant manner.

However, the one sector that goes against the trend is transport, which is not surprising given that it is one of the hard-to-abate sectors. This will be tackled later in the thesis since hydrogen technologies will be an important part of the decarbonisation of the sector.

One reflection that can be obtained is that energy demand and therefore consumption is increasing, and will continue to do so in a context in which population (even though growth rate is around 1%) is set to increase by 2 billion people by 2050, reaching almost 10 billion inhabitants. There will be an even larger demand for resources and energy is no exception.

It is also interesting to see the difference between the EU and the global trends. The European Union's position can be associated with the fact that it already is a developed economy that can focus on environmental matters more than developing economies or economies in transition.

The EU is therefore in a green transition, focusing on reducing energy demand, increasing energy efficiency and decarbonisation. This transition, however, needs to be safe and accessible for the population, but the market is susceptible to political and economic instability and phenomena such as the COVID-19 pandemic.

Actually, the global and especially the EU energy markets are currently facing the impact of the Ukraine's invasion executed by Russia in the beginning of the year. This is evidently a huge humanitarian crisis, and can be looked at from many angles, but given the scope of this thesis it is appropriate to focus on its impact on the energy markets.

Russia is one of the leading producers of both crude oil and natural gas, and is indeed the world's top natural gas exporter, with the EU being highly dependent of this trade. In 2020 the EU imported 29% of its extra-EU crude oil from Russia, 43% of natural gas and 54% of solid fossil fuel (coal) from Russia.

The COVID-19 pandemic had already contributed to the increase of energy prices, with natural gas prices reaching 180 €/MWh in December 2021, and this conflict has made things worse.

The sanctions imposed on Russia and the supply interruptions have led to a severe increase in prices and lack of security of supply. The European Commission is already taking action, having proposed a plan to overcome the dependency from Russia's fossil fuels before 2030, tackling the high natural gas prices and its effect on electricity prices and gas storage.

One final takeaway leading into this Final Degree Thesis itself could be that the green transition and the quest for climate neutrality are the only way to at least mitigate the effects of climate change and global warming. Furthermore, it can also be an opportunity for the development and deployment of new low-carbon or decarbonised energy solutions that can be competitive while better for the environment, and it is important to recognise how this technologies and ambitions can constitute the energy context of the future and how hydrogen has a crucial role to play.

# 2 ABOUT HYDROGEN

An essential step to take before studying the European's Union position regarding hydrogen and the initiatives that have emerged in the sector is to analyse hydrogen's basis and state of the art. Therefore, this section offers a clear and concise view of hydrogen technologies in the fields of production, transport, storage, end uses, etc.

Hydrogen, as a chemical element, is the most abundant in the universe. For hydrogen applications the hydrogen required is as a diatomic gas, $H_2$ which, despite the abundance of the element, cannot be found as such in nature, but with other substances (water, hydrocarbons…). As a consequence, $H_2$ has to be produced with the technologies explained in the hydrogen production section.

Low molecular weight and low density are also characteristics of hydrogen, the latter being a challenge in terms of storage. One very relevant property of $H_2$ is its high energy density, its LHV being 120 MJ/kg $H_2$.

As it will be remarked throughout the thesis, hydrogen and particularly green hydrogen is a key potential alternative for decarbonisation and the phasing out of fossil fuels, and also for energy system integration. It also presents itself as a buffer for renewable energy production thanks to its storage aspect, and this aspect can also contribute to security of supply and independency. It also represents an option to reduce $CO_2$ emissions in sectors difficult to decarbonise.

Its contribution to the sustainability of the EU's energy system is not the only perspective to be taken into account, since procuring a competitive hydrogen economy represents an economical opportunity. According to the European Parliament, the $H_2$ economy could entail the creation of up to a million direct jobs by 2030, 5.4 million by 2050.

Finally, it is important to recall that there are significant energy losses in all hydrogen sectors (production, transport, storage and end uses), and that is an obstacle to overcome.

## 2.1. Hydrogen production

### 2.1.1 Electrolysis

This is one of the most developed processes for hydrogen production and, even though its use is currently not widespread, it is expected to grow since it is the principal option to obtain renewable hydrogen.

The electrolysis reaction consists of obtaining hydrogen by using electricity to split water, with also oxygen as a by-product. This endothermic reaction is the one shown in Figure 3 along with its enthalpy of reaction. The energy given to the reaction could also be heat, being this the process of thermolysis, although it requires very high temperatures. Electrolysers are constituted by an anode and a cathode, which are separated by an electrolyte.

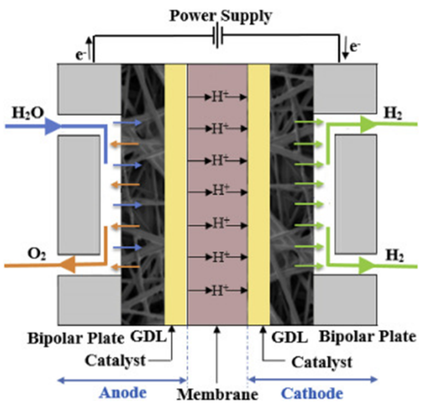
$$H_2O \longrightarrow H_2 + \frac{1}{2} O_2 \qquad \Delta H^0 = 286 \text{ kJ/mol}$$

Figure 3. Electrolysis reaction and enthalpy of reaction

There are different types of electrolysers, with different electrolytes, functions… The most used and developed are the Polymer Electrolyte Membrane (PEM), alkaline and solid oxide electrolysers, but there are more, such as the Anion Exchange Membrane electrolyser and the Proton Conducting Ceramic electrolyser.

## POLYMER ELECTROLYTE MEMBRANE ELECTROLYSER (PEM)

This type of electrolyser, depicted in Figure 4, is identified by its lack of a liquid electrolyte, since it actually has a solid polymer membrane. As seen in Figure 4, water in the anode reacts and forms oxygen and protons, as well as electrons that flow through the external circuit. Protons pass through the membrane and reach the cathode, where they join the electrons and form hydrogen.

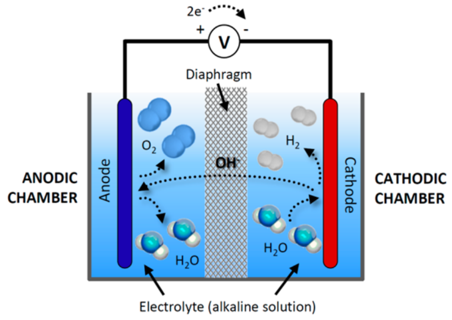



| | |
|---|---|
| Anode reaction | $H_2O\ (l) \rightarrow \frac{1}{2} O_2\ (g) + 2\,H^+(aq)\ + 2\,e^-$ |
| Cathode reaction | $2\,H^+(aq) + 2\,e^- \rightarrow H_2(g)$ |
| Global reaction | $H_2O\ (l) \rightarrow \frac{1}{2} O_2\ (g) +\ H_2(g)$ |

Figure 4. Representation and reactions of a PEM electrolyser [21]

## ALKALINE ELECTROLYSERS

This electrolyser, depicted in Figure 5, uses a liquid alkaline solution (sodium or potassium hydroxide) as electrolyte. Water splits in the cathode to form $H_2$, and the $OH^-$ that is formed as a result passes through a diaphragm to get to the anode where it ends up becoming oxygen.

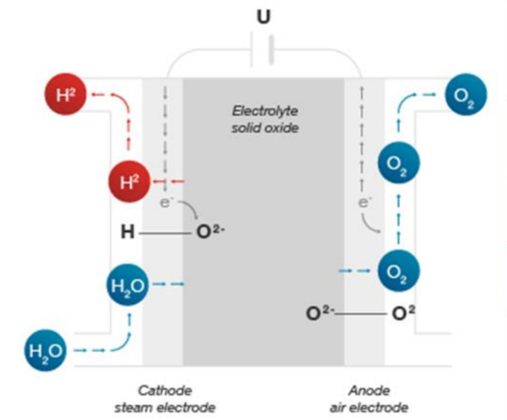



| | |
|---|---|
| Anode reaction | $2\,OH^- (aq) \rightarrow \frac{1}{2} O_2 (g) + H_2O(l) + 2\,e^-$ |
| Cathode reaction | $H_2O\,(l) + 2\,e^- \rightarrow H_2(g) + 2\,OH^- (aq)$ |
| Global reaction | $H_2O\,(l) \rightarrow \frac{1}{2} O_2 (g) + H_2(g)$ |

Figure 5. Representation and reactions of an alkaline electrolyser [22]

**SOLID OXIDE ELECTROLYSERS**

Finally, this electrolyser, that can be seen in Figure 6, has a solid ceramic material as its electrolyte. At the cathode, water and electrons react to form $H_2$ and $O^{2-}$. The negatively charged oxygen ions pass through the ceramic material to get to the anode, where it reacts to produce oxygen and electrons.




| | |
|---|---|
| Anode reaction | $O^{2-} (g) \rightarrow \frac{1}{2} O_2 (g) + 2\,e^-$ |
| Cathode reaction | $H_2O\,(g) + 2\,e^- \rightarrow H_2(g) + O^{2-} (g)$ |
| Global reaction | $H_2O\,(g) \rightarrow \frac{1}{2} O_2 (g) + H_2(g)$ |

Figure 6. Representation and reactions of a solid oxide electrolyser [20]

The last one is actually under development and its main characteristic is that, while the PEM electrolyser works at around 70-90°C and the alkaline at around 90°C, this electrolyser has an operating temperature in the 700-800°C range. The use of high temperature steam and possible use of waste heat make this electrolyser have the potential to be more efficient than the previous two, that have efficiencies of 70% to 80%.

As said before, electrolysis represents the most feasible option to produce renewable hydrogen commercially, and that is what makes it so significant.

Water is used as feedstock, and it is usually freshwater, but there are projects that combine the electrolysis with desalination. This concept and its advantages are analysed later in the thesis.

The electricity fed to the electrolyser is what can make the distinction between renewable and non-renewable hydrogen. It can be produced by several sources, including: solar (PV and concentrated) energy, wind energy, nuclear or even grid electricity that therefore may contain fossil fuels-based electricity. When the electricity is produced with renewable energy the hydrogen produced by electrolysis is considered renewable or green hydrogen.

### 2.1.2 Reforming

The process of reforming to obtain hydrogen can be put into practice using many fuels, such as: natural gas, coal, biomass, ethanol, LPG, etc. While all of these hydrocarbons are options, natural gas is by far the most used; one of the reasons is that it has lower $CO_2$ emissions associated than coal.

The basic schematic representation of the reforming process is depicted in Figure 7, although it may be altered depending on the final use of the $H_2$ produced.

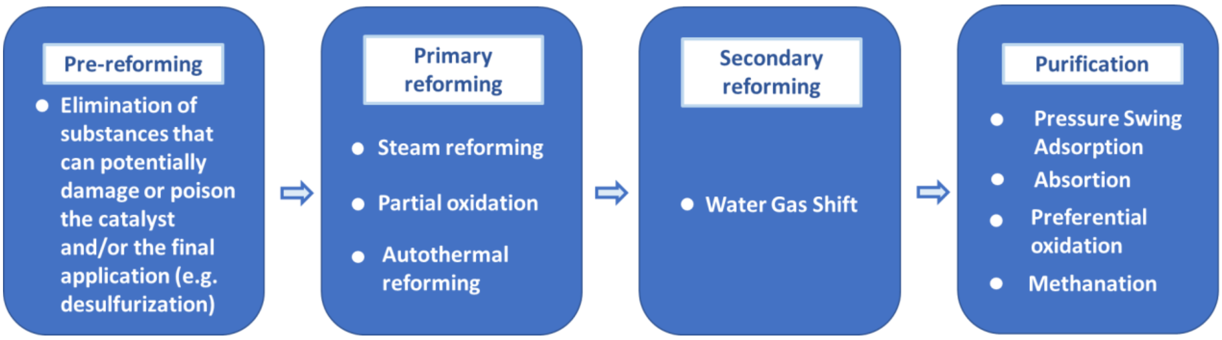



Figure 7. Schematic representation of the reforming process

A brief explanation of this process is:

- **Pre-reforming:** before the $H_2$ production, the entering flows are pre-treated so that they will not damage or poison the catalyst nor do they endanger the final application of the hydrogen; for instance, this entails a desulfurization.
- **Primary reforming:** Hydrogen is produced in a chemical reactor. The methods used are steam reforming, partial oxidation and autothermal reforming, and their reactions are shown in Figure 8. Steam reforming is the most used, particularly with natural gas, and may entail the use of catalysts. Partial oxidation is a semi-combustion, the by-product is not $CO_2$ but CO. Finally, the autothermal reforming is a combination of the previous two, and it self-regulates so that the energy demanded by the steam reforming (endothermic) is generated by the partial oxidation (exothermic).

| | |
|---|---|
| **Steam reforming** | $C_nH_m + H_2O \rightarrow nCO + \left[n + \frac{m}{2}\right] H_2 + H_2O$ |
| **Partial oxidation** | $C_nH_m + \frac{n}{2} O_2 \rightarrow nCO + \frac{m}{2} H_2$ |
| **Autothermal reforming** | $C_nH_m + H_2O + + \frac{n}{2} O_2 \rightarrow nCO + \left[\frac{m}{2} + 1\right] H_2$ |

Figure 8. Primary reforming methods and reactions

- **Secondary reforming:** the process used is the water gas shift. Basically, the flow from the primary reforming has CO and also $H_2O$ since it is added in excess. This flow enters a reactor and the resulting products are $H_2$ and $CO_2$; this way, the reforming is more efficient and more hydrogen is obtained.
- **Purification:** consists of purifying the flow coming from the water gas shift. It is executed taking into account the final application and what purity it requires, although it will not be a 100% pure hydrogen.

The hydrogen resulting from this process is not renewable, it has $CO_2$ emissions as a result. However, one way to mitigate it is using carbon capture and storage (and utilisation), abbreviated as CCS/U.

### 2.1.3 Other production technologies

There are many more hydrogen production technologies, all with different levels of development, emissions associated and feasibility. Some of them are:

- Coal and biomass gasification.
- (Solar) thermochemical water splitting.
- Photocatalysis.
- Photoelectrochemical Water Splitting.
- Microbial biomass conversion.
- Natural gas and biomass pyrolysis.

### 2.1.4 Hydrogen production characteristics

Despite all the techniques and research and innovation, hydrogen still has a considerable potential for growth.

In terms of production the figures are not great for renewable hydrogen, as $H_2$ represented around 2% of the European Union's energy mix by 2021 and 95% of that hydrogen was produced through fossil fuels.

One important aspect of hydrogen production is its cost. Some estimated figures given by the European Parliament are that renewable and low-carbon hydrogen are in the range of 2.5-5.5 €/kg $H_2$ and fossil fuel based $H_2$ costs about 1.5 €/kg $H_2$ to produce.

This is one obvious disadvantage of renewable hydrogen that will be mentioned throughout the document.

## 2.2. Hydrogen storage

Hydrogen storage is one very important characteristic of this sector. It is crucial for providing flexibility to the energy system on short and long-term. It can absorb or buffer the discontinuous generation of renewable sources, also respond to the grid demands, and provide security of supply (through seasonal storage, for instance) and reduce the dependence from imports. In general, it can help bridge fluctuations.

It is also important to reiterate that the low density of hydrogen is an issue for storage systems since it implies lower energy per unit of volume.

There are many technologies to store hydrogen, some are physical-based and some are material-based, all in different development states.

Overall, a good storage solution should have as much energy density as possible while being an established technology. It should also have reduced energy consumption and not require too much auxiliary systems. Finally, the storage system should be able to operate under different conditions and not take too long to restore.

### 2.2.1 Compressed gas

This is one of the most established $H_2$ storage technologies and consists of physically storing compressed gaseous $H_2$ into vessels and tanks when used for small-scale purposes, both stationary and mobile. The other use is in large-scale storage, in caverns or aquifers.

This technology suffers the low density problem, as well as the problem of low efficiency, since a 13% of hydrogen's LHV is actually consumed as electricity for the compression. One solution is to make a multi-stage compression with intermediate cooling.

There are different types of tanks, that can store hydrogen at different temperatures. For mobile applications there are 4 main types of vessels with different composition, storage densities, sensitivity to embrittlement, mechanical resistances, and costs. In mobile applications, particularly for fuel cell vehicles, hydrogen needs to be in the 350-700 bar range.

Regarding large-scale hydrogen storage, underground facilities are the option to discuss. There are different types of cavities, one is the porous media storage.

Porous rock storage sites can be sandstone formations, limestone cavities, and also saline aquifers or depleted oil fields. However, they can endure reactivity problems, such as hydrogen reacting with mineral constituents, and are therefore not the best options.

On the other hand, salt caverns do not present reactivity issues and have low $H_2$ permeability and are the most promising option. In the European Union there are currently around 50 salt caverns being used to store natural gas that could be $H_2$ storage sites.

### 2.2.2 Liquefied $H_2$

It consists of liquefying hydrogen and its potential use is for applications requiring high energy density such as space applications.

One issue that prevents the competitiveness of this technology is the high electricity consumption, that entails around 33% of hydrogen's LHV, a percentage that should be around 20% in order to be competitive.

### 2.2.3 Liquid organic hydrogen carriers

Liquid organic hydrogen carriers are organic molecules that store hydrogen by incorporating it in itself through a reaction, which is reversible to then release that hydrogen.

### 2.2.4 Ammonia

Hydrogen storage as ammonia is based on the Haber-Bosch process (ammonia synthesis). Ammonia can be produced with hydrogen and then be stored or transported as $NH_3$ to later obtain the hydrogen from the beginning. It is definitely convenient, since ammonia is one of the most produced chemicals worldwide, having a large infrastructure.

### 2.2.5 Metal hydrides

This technology is based on the interaction of hydrogen with different metals and alloys under certain temperatures and pressures, to form metal hydrides.

### 2.2.6 Other storage technologies

Some examples of different $H_2$ storage technologies under development are the following:

- Cryogenic liquid $H_2$
- Methanol
- Zeolites
- Carbon nanotubes

## 2.3. Hydrogen transportation

Transportation of hydrogen is one of the pivotal aspects of the hydrogen sector. $H_2$ is not always produced where it is consumed, but until recently that has been the case at industrial or chemical parks where $H_2$ was produced and consumed nearby, hindering the development of large-scale $H_2$ transport.

Nevertheless, the expected expansion and widespread deployment of hydrogen technologies make is making transport a crucial aspect to develop.

Besides the options that are presented subsequently, it is on topic to remark that gas infrastructure has the potential to be retrofitted, repurposed and used for hydrogen applications, as will be explained later in the thesis. One concept that is also explained is the difference between centralised and distributed hydrogen production, and how they affect transportation.

There are different means of transportation, and those can deliver hydrogen in different states. These states are also called packaging modes, and hydrogen is packed for its transportation and unpacked in the consumption site. Some of the packaging modes are the storage technology used for the packing, therefore there are compressed $H_2$, liquefied $H_2$, ammonia and liquid organic hydrogen carriers for instance.

Depending on the mode, packing can involve compression and liquefaction plants or chemical reactors, and unpacking can require compressors, pumps, ammonia cracking plants or dehydrogenation reactors.

The transportation technology used in every situation ultimately depends on lots of factors; some of the options are the following, also shown in Figure 9.


Figure 9. Some of the options for $H_2$ transportation. Pipelines [33] (upper left), the Suiso Frontier ship [32] (upper right), a tube trailer [27] (bottom left) and a liquid tanker [29] (bottom right)

### 2.3.1 Road transportation

For road transportation, hydrogen can be stored as a compressed gas and transported in trucks called tube trailers that carry long cylindric vessels; depending on the vessels used, the pressure can range from around 200 to 500 bar, and these trucks can carry a few hundred kilos.

Another option is to carry liquefied hydrogen, especially if there are no pipelines available and there is a high volume to be transported. The trucks transporting liquefied $H_2$ are called liquid tankers, and are cryogenic and insulated. It is not a simple task, since hydrogen is cooled to -253°C.

### 2.3.2 Pipelines

Hydrogen is transported through pipelines as a compressed gas. The potential of natural gas pipelines to be retrofitted and repurposed to transport $H_2$ makes this a very appealing option because of the reduction of costs.

This transportation possibility is appropriate for long distances and high volumes of hydrogen.

Some issues regarding the pipeline transmission alternative are the potential embrittlement that $H_2$ can cause to the metal pipelines, as well as the leaks and hydrogen permeation and the high costs, although the latter are problems concerning all technologies.

One interesting project on this topic is the European Hydrogen Backbone initiative [31], in which 31 energy infrastructure operators join efforts to develop an integrated pipeline (new and retrofitted) network to connect hydrogen applications around Europe to strengthen the $H_2$ market and economy.

### 2.3.3 Maritime transportation

This option enables the transport of high volumes of hydrogen over long distances. The hydrogen is also liquefied, cooled to -253°C. This is a complex and expensive option, and currently there is only one operating project.

That project is the Suiso Frontier, a ship that transports liquefied hydrogen from Victoria, Australia to Kobe, Japan. This ship is the first of its kind and has been built by Kawasaki Heavy Industries. It has a 1250 $m^3$ storage tank with vacuum insulation.

## 2.4. Hydrogen end uses

Hydrogen has already been presented as an energy carrier and its ability to absorb renewable energy production fluctuations and balance the energy system through storage has been remarked. In this section the objective is to explain what the actual end uses or applications of $H_2$ are.

It is relevant to be aware of what the current hydrogen consumption scene is like, and this is actually shown in Figure 10. The global $H_2$ consumption is mainly used in industry: 43% used to produce $NH_3$, 52% for refining and desulphurisation processes and 5% for the synthesis of methanol and other uses.

After analysing the hydrogen strategy presented by the European Union, one conclusion might be that this pie chart is bound to change and include all of the end uses that are going to be explained.

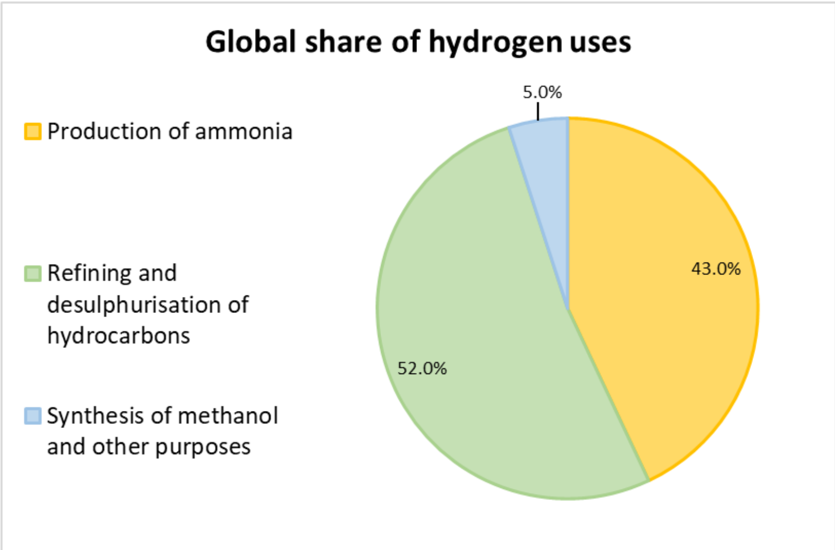



Figure 10. Share of hydrogen uses worldwide [1]

Before studying each of the end uses, it is fitting to explain a technology used in many of the applications: the fuel cell.

A fuel cell is a device that can convert the chemical energy of fuel into electricity through an electrochemical reaction. The fuel can be hydrogen, that is why FCs are in several end uses of $H_2$. This is a modular technology; fuel cells can be connected in series to each other to form stacks.

There are various types of fuel cells according to the electrolyte they use. Some of them also differ in the reaction that occurs, the fuel and catalyst they use and the operating temperature amongst other factors.

A comparison of some of the most used and developed fuel cells can be seen in Figure 11; they are the polymer electrolyte membrane fuel cell (PEM FC), the alkaline fuel cell (AFC), the phosphoric acid fuel cell (PAFC), the molten carbonate fuel cell (MCFC) and the solid oxide fuel cell (SOFC).

| | PEM FC | AFC | PAFC | MCFC | SOFC |
|---|---|---|---|---|---|
| Electrolyte (common) | Perfluorosulfonic acid membrane | Alkaline polymer membrane | Phosphoric acid | Molten lithium, sodium and/or potassium carbonates | Yttria stabilised zirconia |
| Operating temperature | 70 – 80°C | 70 – 100°C | 150 – 200°C | 600 – 650°C | 500 – 1000°C |
| Uses | Transportation, distributed generation, portable and backup power | Transportation, space, military, backup power | Distributed generation | Distributed generation | Distributed generation, auxiliary power |
| Observations | Expensive catalysts, sensitivity to fuel impurities | Sensitivity to $CO_2$ in fuel, lower cost of components | Suitable for CHP, expensive catalysts | High efficiency, suitable for CHP, fuel flexibility, components suffer because of high temperatures | High efficiency, suitable for CHP, fuel flexibility, components suffer because of high temperatures |

Figure 11. Types of fuel cells and their characteristics [35]

To understand the functioning of this device and what the different parts are, it is interesting to analyse the PEM fuel cell since it is used for transportation applications; moreover, a schematic representation of a PEM fuel cell is shown in Figure 12.

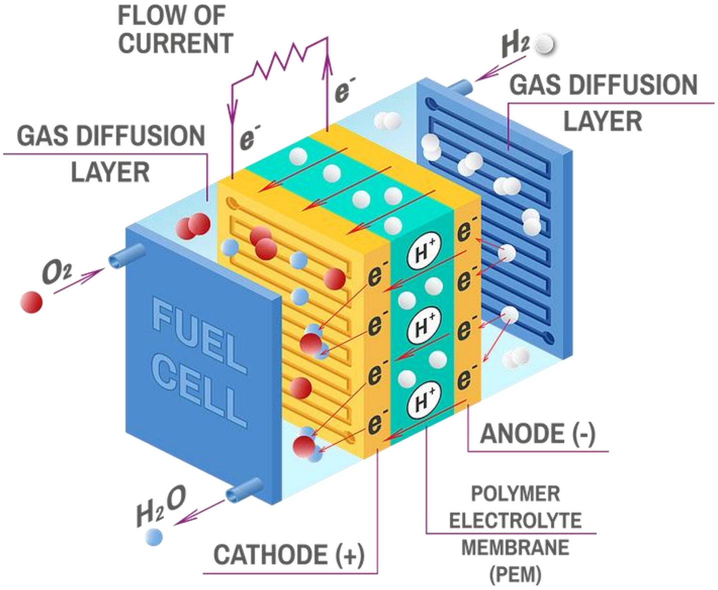



Figure 12. Schematic representation of a PEM fuel cell [34]

The fuel cell consists of two electrodes, anode and cathode, separated by an electrolyte. Next to each electrode there are also gas diffusion layers that enable the transport of reactants and the removal of product water. On each side there is a bipolar plate that gives mechanical resistance and enables the assembly of the fuel cell into a stack, and also has channels through which the fuel and air pass.

The fuel, in this case hydrogen, passes from the inlet to the anode and the air (or $O_2$, the oxidant) reaches the cathode. Hydrogen then separates into protons and electrons, and those electrons flow through an external electric circuit. The protons pass through the membrane and reach the cathode. The reactions are shown in Figure 13, and its parallelism with the reactions of a PEM electrolyser can be seen.

| | |
|---|---|
| Cathode reaction | $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ |
| Anode reaction | $H_2 \rightarrow 2H^+ + 2e^-$ |

Figure 13. Reactions in a PEM fuel cell

A more thorough explanation of the fuel cell functioning and the different types could be made, but this brief analysis is enough to understand the role of the fuel cell in the following hydrogen applications.

### 2.4.1 $H_2$ industrial uses

The industrial use of hydrogen is its most established purpose.

One application of $H_2$ is in the sector of oil refining, which accounted for a consumption of almost 40 Mt of hydrogen in 2020. This $H_2$ has been mostly non-renewable, but there are more and more plants producing hydrogen with steam reforming and then using CCS/U, therefore using low-carbon hydrogen. Additionally, there are refineries in Europe already using or expecting to use electrolysis to produce their hydrogen.

Hydrogen is also used for the production of ammonia through the Haber-Bosch process, which is then used mainly to produce fertilisers. Another industrial application is methanol production using hydrogen.

Finally, the other principal use of hydrogen in industry is the production of steel, which is detailed in the section of this thesis that analyses the European Parliament's hydrogen strategy.

### 2.4.2 $H_2$ in the transport sector

According to the IEA, transport alone represented about 30% of the European Union's total GHG emissions in 2019, although this share has probably changed since COVID-19. It is therefore an important section to decarbonise.

Direct electrification and batteries are not an option for some cases such as heavy-duty vehicles, ships and aeroplanes; hydrogen is the alternative to decarbonise those cases.

#### 2.4.2.1 Fuel Cell Electric Vehicles

Fuel cell electric vehicles (FCEVs) use hydrogen as fuel, storing it in a tank on the car. This hydrogen is converted in electricity to power the electric motor of the vehicle thanks to the fuel cell in it.

Therefore, these cars emit water and excess air, no harmful tailpipe emissions. Furthermore, if the $H_2$ is renewable then this makes for a major light-duty vehicle decarbonisation solution.

Besides this advantage there are other benefits such as the short refuelling time (less than 4 minutes) and their contribution to strengthening the hydrogen market.

They are also more efficient than conventional vehicles, quieter and have a driving range of about 400 -500 km.

Some of the main concerns regarding this technology and hindering its development are the high costs of both hydrogen as a fuel and the vehicle itself and the scarce deployment of the infrastructure required (hydrogen refuelling stations).

Some of the two most popular commercial options of FCEVs are Hyundai NEXO and Toyota Mirai, pictured in Figure 14, and cost about 70000 € each.

Figure 14. FCEVs, Hyundai NEXO [42] (left) and Toyota Mirai [43] (right)

#### 2.4.2.2 Hydrogen for heavy-duty road transport

Hydrogen powered fuel cells are also the pathway for some heavy-duty transport sectors that are difficult to decarbonise.

Also, when compared with light-duty vehicles, heavy-duty vehicles powered with fuel cells need longer lifetimes and higher cell voltage.

One example are trucks, a sector where being a fuel cell vehicle is beneficial thanks to the long driving range and the short refuelling time. There are already fuel cell trucks in Europe, one of the models being the Hyundai XCIENT, pictured in Figure 15, that has a 190 kW fuel cells system, 400 km driving range, refuelling time of 15 minutes, and 7x32 kg $H_2$ tanks.


Figure 15. Hyundai XCIENT fuel cell truck [46]

Another type of vehicle that uses the fuel cell technology is the bus. Fuel cell buses are actually quite popular in hydrogen projects. Besides the previously mentioned benefits (emissions reduction, driving range, short refuelling time) they have had good reception within the citizens of the areas they have been implemented in.

According to the European Commission, there are almost 400 fuel cell buses registered in Europe, and this number is expected to grow significantly. In Figure 16 all the European locations where fuel cell buses are already circulating or planned to do so.

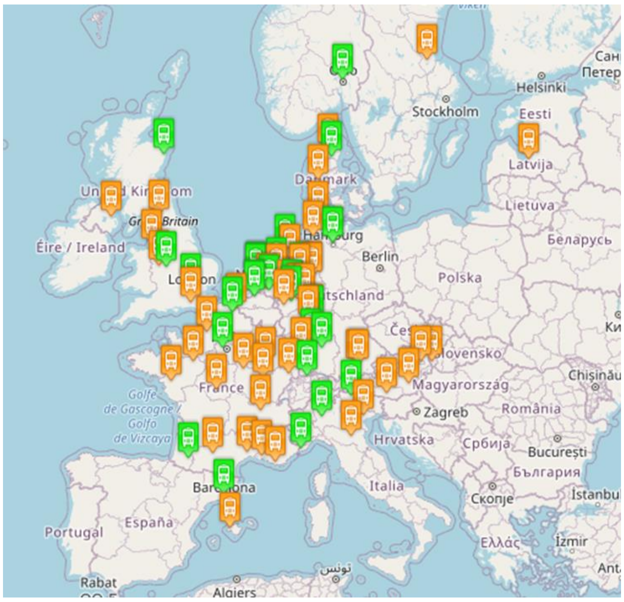



Figure 16. European locations where fuel cell buses are operating (green) or planned to be implemented (orange) [47]

Finally, there are prototypes for fuel cell machinery such as excavators, dump trucks or mixer trucks, but probably the one that comes to mind is forklifts, which are being developed by companies such as Toyota.

#### 2.4.2.3 Hydrogen for maritime transport

The shipping industry is also pursuing decarbonisation, and in Europe that is being developed through projects like the MARANDA project and the FLAGSHIPS project.

The first one consisted in the development and validation of a PEM fuel cell-based hybrid powertrain system

The second is aiming to develop hydrogen fuel cell vessels commercially by 2030, the Zulu and the FSP Waal vessels. They will use PEM fuel cells and have hydrogen storage onboard.

Both are also attempting to validate hydrogen applications in the maritime sector.

#### 2.4.2.4 Hydrogen for aviation

The aviation sector is another one that can make use of hydrogen as a means to decarbonise. Planes use kerosene and therefore emit $CO_2$, but this would not be the case when using hydrogen. Furthermore, if the hydrogen is renewable, obtained from electrolysers powered with renewable energy, then aviation can be a part of the green transition.

Small, short-range flight planes are more likely to use propellers turned by electricity provided by fuel cells, and those fuel cells would be fed hydrogen. For bigger planes the solution would be to burn $H_2$ to power jet engines. Hydrogen solutions and the storage they require are usually bulkier than the conventional approaches, so planes would be slightly different, with a longer length.

According to the report on hydrogen-powered aviation commissioned by FCH 2 JU and Clean Sky 2, short-range, $H_2$-powered flights could be commercially available by 2035 in the EU, with an extra cost of about 18 € per person. Medium-range flights (7000 km) could be in the same position by 2040.

There are some issues to be tackled to enable the deployment of hydrogen aviation, such as the development of $H_2$ storage solutions so that enough hydrogen can be carried on the planes, the development of refuelling for the aviation applications at the airports and the configuration of the actual hydrogen systems within the plane. The regulation and standards considering these technologies also have to be developed.

Spain is one of the countries pushing the boundaries in this sector, having flown a hydrogen-powered aircraft as far back as 2008. Currently the country is involved in the HEAVEN project funded by the EU. The aim is to develop a fuel cell based powertrain and cryogenic hydrogen storage for a small aircraft (4 passengers).

The aircraft company Airbus is also considering hydrogen as the way to decarbonise aviation. They contemplate both hydrogen propulsion with fuel cells and hydrogen in gas turbines, or hydrogen used to create synthetic fuels. Furthermore, they are developing the ZEROe concepts, three aircrafts that use hydrogen.

#### 2.4.2.5 Hydrogen refuelling stations

Hydrogen refuelling technologies are crucial to the development of all $H_2$ transport solutions.

For road transport, hydrogen refuelling stations (HRS) like the two shown in Figure 17 are installed to fill vehicles with hydrogen.


Figure 17. Actual picture [58] and schematic representation of a HRS [59]

These stations have:

- Optional hydrogen production system; this is only in the case that $H_2$ is produced on-site.
- Hydrogen storage facilities; $H_2$ can be produced on-site, brought by truck (liquefied or compressed), or come by pipelines, but in all cases there are tanks to store it.
- Compressors to take hydrogen to the maximum required pressure.
- High pressure buffer storage; many stations have a cascade system.
- Refrigeration system; hydrogen needs to be cooled down during its expansion before being dispatched.
- Dispensers to deliver the fuel to the vehicles.

The dispatch pressure is 350 bar for heavy-duty vehicles and 700 or 350 bar for light-duty vehicles. Some HRS have $H_2$ availability at both pressures and some only one pressure level. This can be seen in the interactive HRS Availability Map by the Fuel Cells and Hydrogen Observatory, which classifies the 180 HRS according to the pressure they provide.

### 2.4.3 Power generation

Power generation is yet another way to use hydrogen. Fuel cells can be implemented in power generation with steam and/or gas turbines. This can increase the efficiency of the system and reduce its $CO_2$ emissions. The fuel cell appropriate for this application is the solid oxide fuel cell (SOFC), since it operates at very high temperatures.

For instance, Mitsubishi proposes a SOFC (100 MW, fed with natural gas) + gas turbine + steam turbine combined-cycle system to replace large-scale thermal power plants, and would have a transmission end-power generation efficiency of more than 70%, and a $CO_2$ emissions reduction of 20%.

Also, stationary fuel cells can be used as power generators, connected to the grid or being auxiliar power systems. There are various projects for this application, and they use solid oxide, PEM or alkaline fuel cells.

### 2.4.4 Combined heat and power

Combined heat and power, CHP, refers to the simultaneous production of electricity and useful heat, both from the same source or process. The systems with CHP have an increased efficiency.

Actually, there is even trigeneration to also obtain cooling.

Regarding the topic of this thesis, it is remarkable that CHP can be fuel cell based, particularly using PEM FC and SOFC. It can be used both in an industrial and in a residential context as micro-cogeneration.

In Europe, for instance, the project PACE (pathway to a competitive European fuel cell micro-CHP market) works to deploy fuel cell micro-cogeneration units for houses and small businesses. Some of the benefits it notes is the $CO_2$ emissions reduction and the fact that it is a smart grid solution.

### 2.4.5 $H_2$ injected into the natural gas grid

Injecting hydrogen into the natural gas infrastructure (pipelines, storage systems) is a solution to facilitate the decarbonisation of the natural gas grid. Not only does hydrogen have a high LHV, but also can be a renewable energy carrier blended with natural gas in the grid, reducing the $CO_2$ emissions.

One of its main benefits is that it takes advantage of infrastructure already built and paves the way for the green transition.

While most of the infrastructure is established, there are still some requirements such as renewable energy generators and electrolysers to produce renewable hydrogen, as well as the retrofitting of equipment to adapt to hydrogen.

However, there are some issues linked to this option such as:

- As mentioned previously, hydrogen can cause embrittlement of metal pipes and therefore pipes have to be altered, for instance they might have to get an inner layer of chemicals to protect the steel.
- The injection of hydrogen alters the maintenance measures, and more are necessary.
- The blending threshold varies amongst countries and applications, hindering common regulatory frameworks, as seen in Figure 18. An example of "certain conditions" is the 8% as opposed to the 2%

standard in Germany, which can be reached if there are no compressed natural gas filling stations associated with that network.

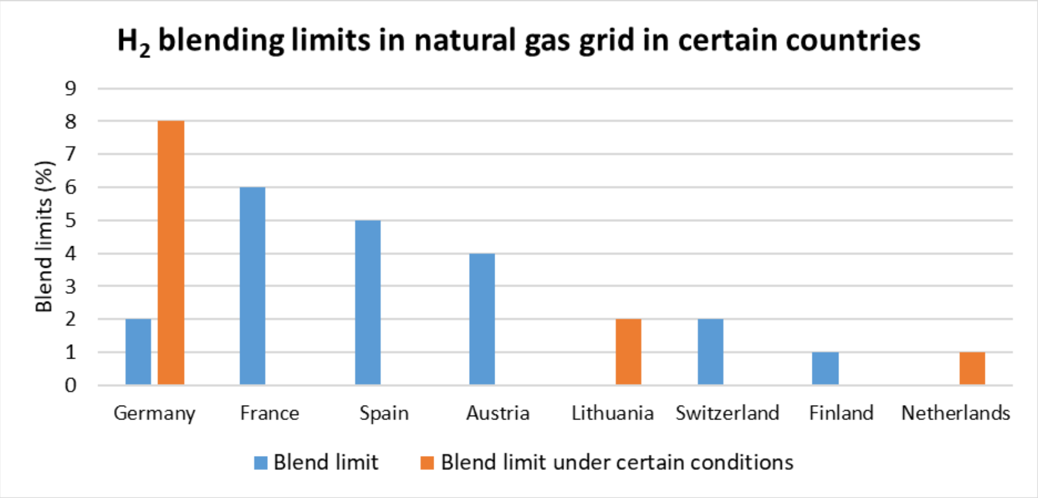



Figure 18. Hydrogen blending limits in the natural gas grid in certain countries, in %v [64]

Moreover, the Technical Association of the European Natural Gas Industry (MARCOGAZ) deemed that up to a 20%$_v$ of $H_2$ is possible, and that blending up to 10%$_v$ $H_2$ does not require huge alterations.

## 2.5. Hydrogen safety

Safety regarding hydrogen is very important, as it is for every fuel.

Hydrogen has been used for a long time, especially in the industrial sector, enabling for experience in terms of safety.

Many $H_2$ characteristics are positive: it is not explosive, poisonous, toxic, environmentally damaging, etc. However, there are some controversial issues that require extra caution.

First, $H_2$ has a wide range of concentrations in air in which it is flammable, and low ignition energy, lower than other fuels. It is important to remark that hydrogen diffuses quickly so its concentration in air in case of a leak would be low, and in low concentrations its ignition energy is similar to other fuels, although it is no reason to underestimate this fact.

Hydrogen also has to avoid the combination of the 3 combustion factors (fuel, oxidant and ignition source), as every other fuel.

The $H_2$ molecule is the smallest and lightest molecule, much lighter than air; therefore, in case of a leak hydrogen diffuses rapidly, and is less likely to burn. Detecting leaks is also very important since hydrogen's flames when burning are almost invisible.

One aspect that has been talked about previously is the fact that hydrogen, when expanding, heats up; this is significant for HRS, where $H_2$ is refrigerated before dispatch to protect the vehicles' tanks from the high temperatures.

Finally, and also previously mentioned, metal elements in $H_2$ systems can suffer embrittlement when in contact with this molecule, so safety measures need to be taken.

# 3 EUROPEAN ORGANISATIONS, INITIATIVES AND PLANS REGARDING RENEWABLE ENERGY AND HYDROGEN

Throughout this thesis many organisations, plans, strategies and more have and will come up, and some of those are gathered in this section.

Nevertheless, it is appropriate to first explain some of the initiatives and plans that are crucial to the hydrogen development topic and mentioned throughout the Hydrogen Strategy. Those are:

- **PARIS AGREEMENT**

  This agreement has been already mentioned in the Introduction section, which is not rare given that it is one of the most popular environmental initiatives worldwide. As said before, through this initiative different nations aim to maintain the rise of global temperature this century below 2°C above pre-industrial levels, or even limit it to 1.5°C.

  Some of the crucial aspects of this pact to fight climate change, besides the temperature goals and in addition to those mentioned in the introduction, are the achievement of global peaking of GHG emissions, the establishment of "nationally determined contributions" by each country, as well as National Adaptation Plans, and even coping with the unavoidable negative consequences of climate change.

- **EU GREEN DEAL**

  This European environmental strategy is the main approach of the European Union to tackle climate change and its effects. The actions within the Green Deal cover fields such as energy, industry, climate, environment, transport, etc.

  The European Union Member States have committed, amongst other things, to reduce GHG emissions by 2030 by 55% compared to the GHG emissions in 1990. In addition to the emissions reduction, the Green Deal aims to transform and bring innovation to the European economy through the creation of jobs or the decrease of energy dependency from other countries.

  Within the Green Deal, many laws and strategies have been adopted, such as the European Climate Law, the EU Industrial Strategy, the EU Strategy for Energy System Integration and the European Strategy for Hydrogen, and the REPowerEU plan.

- **REPOWEREU**

  The REPowerEU Plan has been recently issued by the European Commission as a consequence of the effects of the Russian invasion of Ukraine on the energy market, focusing mainly on achieving energy independency, so as to not be subjected to Russian fossil fuels.

Therefore, the plan includes measures that will accelerate the green transition, centred on the production of renewable energy in the EU (reduces both emissions and dependency), the saving of energy (through efficiency measures, for instance), and the diversification of the EU's energy supply.

- **UN SUSTAINABLE DEVELOPMENT GOALS**

  The United Nations developed the 17 sustainable development goals as part of its 2030 Agenda for Sustainable Development; all the UN Member States committed to these goals in 2015, and every year the UN reports the progress achieved. While all of these goals are equally important and crucial to sustainable growth, the ones concerning the topics of this thesis are: "Goal 7: Affordable and clean energy", "Goal 9: Industry, innovation and infrastructure", "Goal 13: Climate action".

  These goals have targets and indicators associated with them.

  The first one focuses on enabling access to sustainable and affordable energy for everyone and, for example, one target is to increase the share of renewable sources in the energy mix by 2030, and the indicator associated is that share.

  The second goal mentioned aims to promote sustainability for industrialisation and innovation, as well as the creation of infrastructure. An example of target is the aim to improve research and promote growth in the number of researchers, that is why one of its indicators is the number of researchers per million inhabitants.

  Finally, the goal 13 takes on climate change and the fight against it, one of its targets being that Member States include measures to fight climate change in their national plans, and total GHG emissions per year being an indicator.

  Nevertheless, it is important to reiterate that all 17 goals are significant, and some cover broader aspects that have an effect on the energy sector and therefore the role of hydrogen.

That being explained, it is appropriate to take a look at some of the organisations and plans that appear during the entirety of this thesis: those that are mentioned in the European Parliament's Hydrogen Strategy, and also those that come up in the elaboration of its analysis; therefore, by no means is this an exhaustive list of the bodies and strategies associated with the hydrogen sector, but a gathering of some that have come up during the study.

The list can be seen in Figure 19, although there are more organisations, strategies, etc. appearing throughout the document. Out of the 36 listed, 28 are European, which can mean that they are either founded, funded or appointed by the European Commission or by European companies. The other 8 are international and include the EU. Again, it is not representative of the entire sector, but it is predictable that in an analysis of the EU hydrogen strategy the majority of bodies and plans referred to are European.

It is also remarkable to note that most of the hydrogen associations and plans have been created in these past years, and even some of those concerning renewable energy and sustainability. This shows how hydrogen is actually having what is hopefully its definitive breakthrough and how its role in decarbonisation is backed up by organisations, plans, projects, etc.

| | Decarbonisation, renewable energy, sustainability | Hydrogen |
|---|---|---|
| Organisations<br>Partnerships<br>Coalitions… | • Clean Aviation Joint Undertaking<br>• European Union Agency for the Cooperation of Energy Regulation (ACER)<br>• European Partnership for transforming Europe's rail system<br>• EU Clean Steel Partnership (CSP)<br>• European Association for Storage of Energy<br>• European Partnership – Towards zero-emission road transport (2ZERO)<br>• European Partnership for Clean Energy Transition<br>• Processes4Planet<br>• International Energy Agency (IEA)<br>• International Renewable Energy Agency (IRENA)<br>• Carbon Neutrality Coalition<br>• Clean Air Task Force | • Fuel Cells and Hydrogen Joint Undertaking<br>• Clean Hydrogen Partnership<br>• Hydrogen Europe<br>• European Clean Hydrogen Alliance<br>• Renewable Hydrogen Coalition<br>• H2 Island Hub<br>• International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)<br>• European Green Hydrogen Acceleration Centre<br>• HySafe |
| Plans<br>Strategies… | • Carbon Contracts for Difference<br>• The action plan for critical raw materials<br>• EU Strategy for Energy System Integration<br>• Sustainable and Smart Mobility Strategy | • European Parliament's "A European Strategy for Hydrogen"<br>• European Commission's "A Hydrogen Strategy for a climate-neutral Europe"<br>• European Hydrogen Backbone Initiative<br>• Clean Energy Ministerial Hydrogen Initiative |
| Platforms<br>projects… | • The Important Projects of Common European Interest (IPCEIs)<br>• EUREKA<br>• Clean Energy for EU Islands | • Mission Innovation Hydrogen Valley Platform<br>• Hydrogen Public Funding Compass<br>• CertifHy™<br>• HyResponder |

Figure 19. Organisations, initiatives, plans, platforms, etc., regarding renewable energy and sustainability as well as hydrogen

# 4 A EUROPEAN STRATEGY FOR HYDROGEN

This chapter can be considered the core of the thesis, since it consists in the review of the document generated by the European Parliament "A European Strategy for Hydrogen" expressing its goals and wills on this topic.

The European Parliament resolution of 19 May 2021 on a European Strategy for Hydrogen [1] is comprised of three sections:

- Documents, reports, communications, Directives and just about everything falling under the spectrum of information the European Parliament has regarded in order to create this text.
- Goals and starting point for the hydrogen strategy. This section's content is already developed in the previous chapters of the thesis.
- The statements made by the European Parliament.

Moreover, the statements are also subdivided, facilitating the review that is the aim of this thesis. These subdivisions, which are subsequently developed, are the following:

- Overall.
- Hydrogen classification and standards.
- Ramping up hydrogen production.
- Citizen engagement.
- Hydrogen infrastructure.
- Hydrogen demand.
- Research, development, innovation and financing.
- International cooperation on hydrogen.
- The role of hydrogen in an integrated energy system.

Nevertheless, before commencing the thorough analysis of these sections, it is appropriate to go into detail about the bodies associated with this document.

In the first place there is the European Parliament, the organisation behind the document being studied. This legislative body is one of the three established in the European Union and, along with the Council of the European Union, has the role of the legislator / has the task to adopt EU legislation determine on budget matters. This Strasbourg-based organisation is comprised of 705 Members of the European Parliament (MEPs) that are voted into power and are organised in political groups and is presided by Roberta Metsola.

Finally, it is pertinent to note that the European Parliament supervises the work of different EU bodies, including the European Commission.

Secondly, the Member States can be found mentioned all throughout the document, undoubtedly referring to the Member States of the European Union listed in Figure 20.


Figure 20. Member States of the European Union [72]

Lastly, across this European Strategy for Hydrogen the European Commission is repeatedly alluded to, being urged, called on, encouraged, asked, or requested to accomplish or execute something, amongst others, by the Parliament.

The European Commission is the branch of the European Union that enforces the law, the executive body. It consists of an organisation headed by a President and 27 members of the Commission or "Commissioners" or "the College of Commissioners" headquartered in Brussels and currently presided by Ursula von der Leyen.

The Commission is divided into Directorates-General according to the various policy areas (budget, climate action, defence industry and space, energy, etc), as well as and service departments and executive agencies to handle specific issues or programmes.

Regarding the Commission's work several roles and functions can be found, some of them being: to develop and implement the European Union policies, to participate in the elaboration of the EU's overall strategy, to propose and ensure the correct implementation of EU laws, to plan the European development policy and deliver aid worldwide and to propose and implement the European Union budget and manage its funding amongst other functions.

## 4.1 Statements

These statements are expressed by the European Parliament; therefore, this is the body that stresses, welcomes, underlines, etc., all throughout the document, expressing its views on a hydrogen strategy. For the review per se, different excerpts from the document are quoted literally, which are recognised by the use of italics, and analysed by topic.

### 4.1.1 Overall

In this first section there are 6 statements regarding different generic aspects of hydrogen relevant to the strategy.

Some of those are that:

*The EU hydrogen strategy* [needs to] *cover the whole value chain* [and also has to] *be compatible with* [the agreements, plans, and goals already existing, particularly:] *the Paris Agreement, the EU's climate and energy targets for 2030 and 2050, the circular economy, the action plan for critical raw materials and the UN Sustainable Development Goals*.

The EU Parliament:

*Welcomes the hydrogen strategy for a climate-neutral Europe proposed by the Commission including the future revision of the Renewable Energy Directive, as well as […] the Member State strategies and investment plans for hydrogen*. [It] *also urges the Commission to align its approach on hydrogen with the new EU industrial strategy and make it a part of a coherent industrial policy*.

The Commission's hydrogen strategy was actually released together with the European Clean Hydrogen Alliance as part of the New EU Industrial Strategy and therefore is in line with it.

The New EU Industrial Strategy was presented by the Commission in March 2020. This policy aimed to support the twin transitions (digital and green), support SMEs or maintain Europe's competitiveness amongst other objectives.

However, as the Commission remarks, shortly after the COVID-19 pandemic was officially declared, and the lessons learned from that experience led the Commission to update the industrial strategy in May 2021, keeping the same priorities but also adding some new points:

- Reinforce the resilience of the single market.
- Support EU's open strategic autonomy by addressing strategic dependencies.
- Accelerate the twin transitions.

Another aspect discussed in this section is:

*The importance of the principle of technology neutrality*, [specifically:] *the EU Parliament underlines the importance of a resilient and climate-neutral energy system based on the principles of energy efficiency, cost efficiency, affordability, and security of supply*. [It also] *notes that direct electrification from renewable sources is more cost-, resource-, and energy-efficient than hydrogen […] but factors such as security of supply, technical feasibility and energy system considerations should be taken into account when determining how a sector should decarbonise.*

One more point discussed in this section is

*The need to maintain and further develop EU technological leadership in clean hydrogen through a competitive and sustainable hydrogen economy with an integrated hydrogen market.*

Indeed, the role of the European Union in relation to renewable hydrogen is that of technological leadership and maintaining that is fundamental to the hydrogen market.

Following this thinking, the Renewable Hydrogen Coalition exists to represent investors, entrepreneurs, companies, industrial off-takers and more in the field of hydrogen with the view of positioning Europe as the leader in renewable hydrogen technologies.

Moreover, the Commission declared in a press release in May 2022 that the Commissioner for Internal Market and 20 industry CEOs signed a Joint Declaration within the European Electrolyser Summit committing to a tenfold increase in electrolyser capacity, as detailed in the section "Ramping up hydrogen production".

In this Joint Declaration it is stated that to reach the targets proposed the EU needs to ramp up its manufacturing capacities for renewable and low-carbon hydrogen production, principally electrolysers.

Currently the manufacturing capacity of electrolysers in Europe is about 1.75 GW of hydrogen output per year and this number is expected to grow exponentially following the Fitfor55 and RePowerEU targets.

This sector covers a larger spectrum of technologies: electrolysers manufacturers, suppliers of electrolyser components and materials, infrastructure, etc. Therefore, the European Clean Hydrogen Alliance will establish an Electrolyser Partnership to connect them.

The companies that signed the Joint Declaration are those shown in Figure 21, some are multinationals and some are Europe-based such as the Italian De Nora or the French Elogen. These enterprises have committed to work on integrating the hydrogen value chain, to deal with the raw materials dependency, to implement recycling systems and to invest in research, development and innovation in their fields. They have also committed to be aligned with the EU climate goals and plans, making the reception of state aid or funding easier and faster.


Figure 21. Companies which signed the Joint Declaration [76]

This part mentions the Hydrogen Valleys too, since the EU Parliament:

*Recognises the efforts undertaken by hydrogen valleys […] throughout the EU […], underlines their important role initiating the production and application of renewable hydrogen* and *urges the Commission to build on these initiatives, support their development and help those involved to pool their know-how and investments.*

It is then appropriate to explain what a Hydrogen Valley is.

Hydrogen Valleys are defined as regional ecosystems that cover the value chain, linking hydrogen production, storage, transportation, and various end uses such as mobility, energy, or industrial feedstocks. They are also known as Hydrogen Hubs and are usually recipients of multi-million EUR investments. Many projects have emerged worldwide and are intended to impulse economic development in the geographic regions they are located in, as seen in Figure 22.

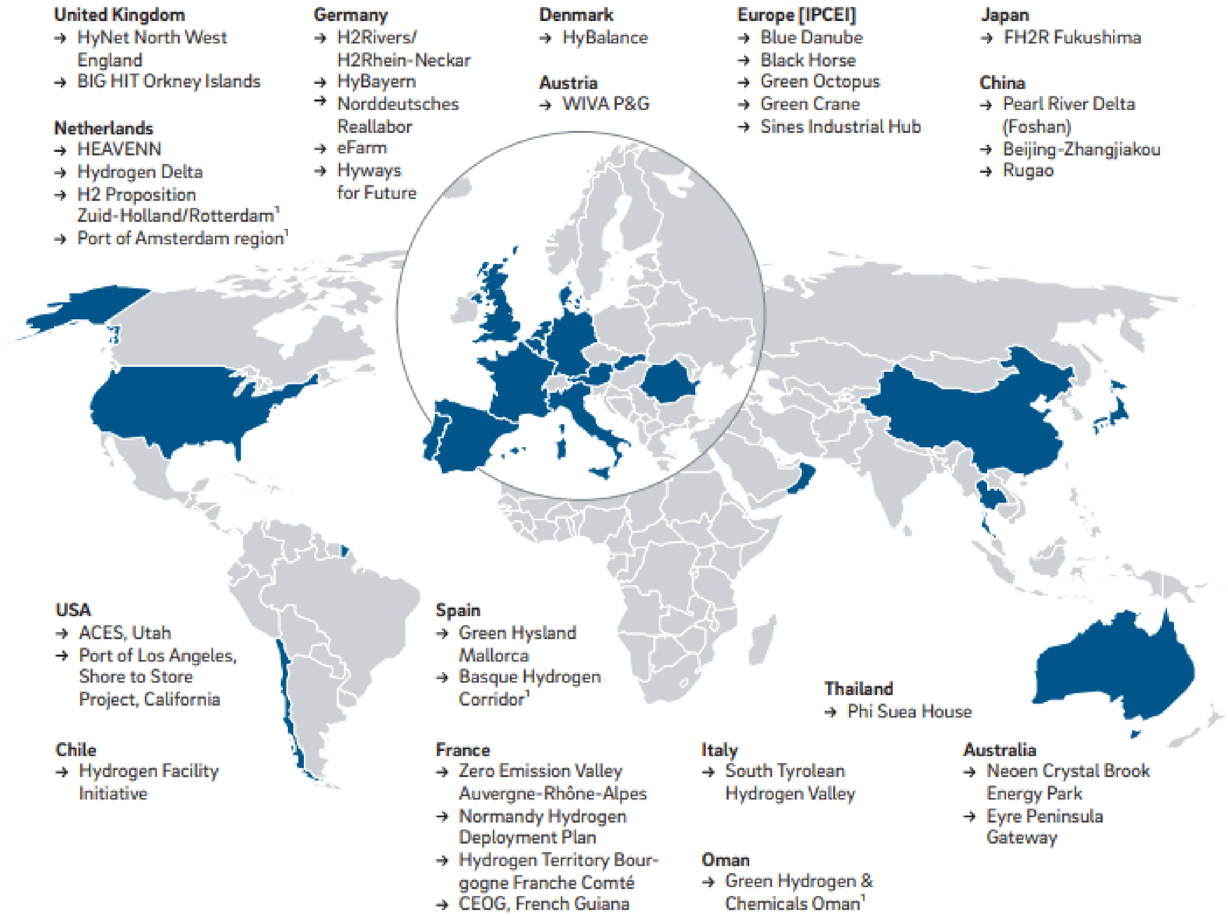



Figure 22. Hydrogen Valleys worldwide [78]

To determine the characteristics of the Valleys it is fitting to refer to the report issued in the Mission Innovation Hydrogen Valley Platform in March 2021, Hydrogen Valleys, Insight into the emerging hydrogen economies around the world [77].

According to the report, Hydrogen Valleys have some common traits despite the different types of projects and the various circumstances that determine them. These characteristics are:

- They are large in scale.
- They have a clearly defined geographic scope.
- They cover the value chain broadly.
- They supply to various end sectors.

Being large is something that could be deduced since it has been mentioned before that these projects involve multi-million EUR investments. Furthermore, they encompass smaller projects within themselves, constituting the main Hydrogen Valleys.

They cover a delimited geography, and that is a characteristic present whether the scope is local or international.

The considerable value chain coverage is, again, part of the Hydrogen Valleys definition, and so is the wide range of end uses and sectors in which hydrogen is utilised.

One main attraction of the Hydrogen Valleys is the fact that they are integrated systems since they cover the value chain, they combine supply and demand. This means they are crucial in the development of the hydrogen industry and economy.

Moreover, while climate change is still the principal motivation behind projects, there are other significant purposes, including economic interest, energy security or industrial strategy.

However, and this is a topic that is going to appear eventually in this Final Degree Thesis, regulation and policy entail barriers in the hydrogen sector. Some of the hurdles Hydrogen Valleys can sustain are: difficulty with the authorizing of permits for infrastructure or end-use applications, overly strict safety regulation or no regulation at all, taxes on electricity from RES, etc.

Another analysis of interest elaborated in this report is the differentiation between three different archetypes of Hydrogen Valleys in regard to their value chain setups, as seen in Figure 23.

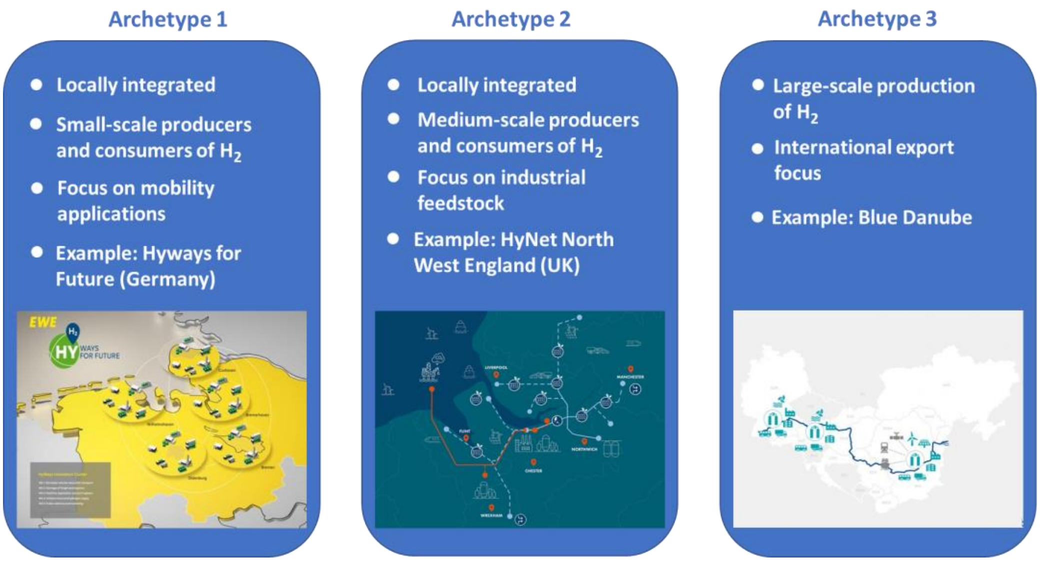



Figure 23. Hydrogen Valleys archetypes [77], [79], [80] and [81]

In addition, in this section the Parliament expresses the critical role of renewable hydrogen, stating that:

*Hydrogen produced from renewable sources is key to the EU's energy transition as only renewable hydrogen can sustainably contribute to achieving climate neutrality in the long term*, [but also] *notes with concern that renewable hydrogen is not yet competitive.*

The Commission and the Member States are then urged to tackle this lack of competitiveness.

Finally, the Parliament:

*Highlights that hydrogen-derived products such as synthetic fuels produced with renewable energy constitute a carbon-neutral alternative to fossil fuels and can […] contribute […] to the decarbonisation of a wide variety of sectors.*

### 4.1.2 Hydrogen classification and standards

In this section many topics are discussed. First the matter at hand is the classification of hydrogen.

According to the EU Parliament:

*A common legal classification of the different types of hydrogen is of utmost importance*, [and] *the classification proposed by the Commission* [is welcomed] *as a first step*. [This classification will require] *comprehensive, precise, science-based and uniform EU-wide terminology* [that will enable the adoption of] *national legal definitions*; [therefore, the Commission is urged to] *conclude its work on establishing such terminology*.

[Furthermore, the classification] *should be determined according to an independent, science-based assessment, stepping away from the commonly used colour-based approach*; [moreover, some desired characteristics for the classification are:]

- *It should be based on the life cycle GHG emissions throughout hydrogen's entire production and transport process*
- *It should take into account transparent and robust sustainability criteria in line with the principles of the circular economy*
- *It should be based on averages and standard values per category, such as the objectives of sustainable use and the protection of resources, the handling of waste and the increased use of raw and secondary materials, pollution prevention and control, and finally, the protection and restoration of biodiversity and ecosystems.*

Regarding these statements, the first question that arises is: Which is the classification proposed by the Commission?

The Commission's proposed classification is elaborated according to the carbon content of hydrogen, which varies based on the technology and energy source associated with the hydrogen production. The different types are listed in Figure 24.

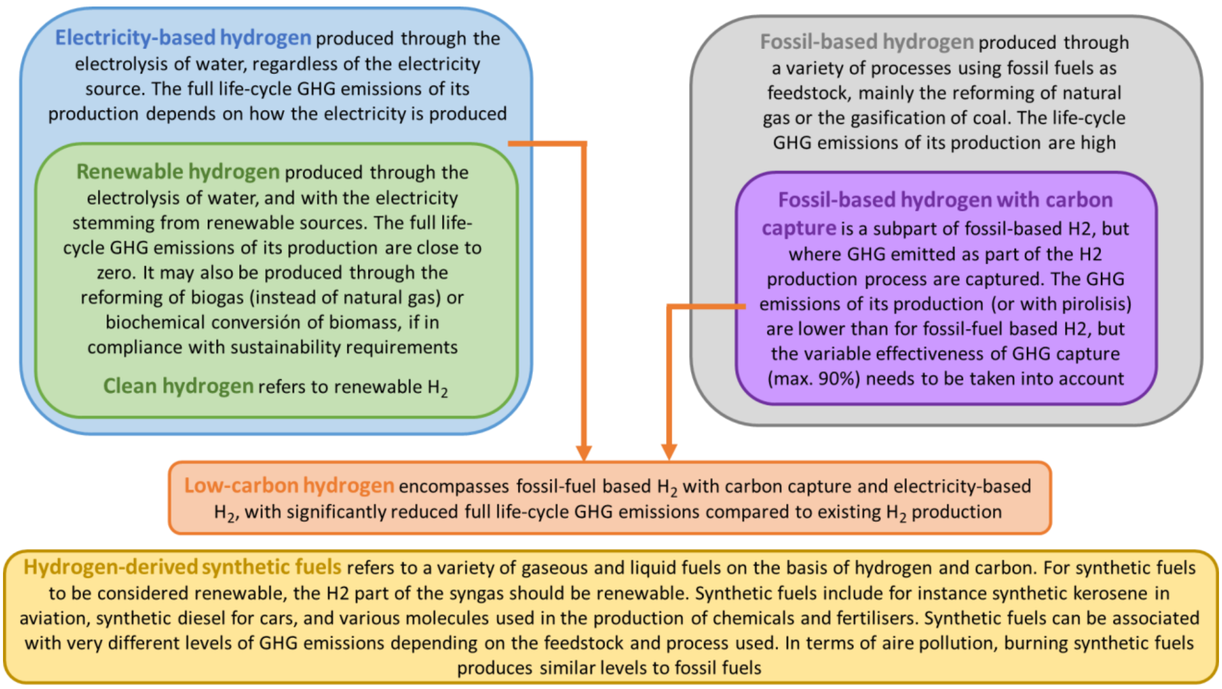



Figure 24. Hydrogen classification proposed by the European Commission [162]

However, the EU Parliament:

*Notes […] that avoiding using two names for the same category of hydrogen, namely 'renewable' and 'clean', as proposed by the Commission, would provide further clarification, and […] that the term 'renewable hydrogen' is the most objective and science-based option.*

As explained in the Strategy, this categorisation can be a precedent or a model for the future classification, particularly in opposition to the colour-based.

The colour-based classification is the most frequently used. However, not only does it not comply with the characteristics required by the Parliament, but it also bears the burden of a lack of homogeneity besides the main three colours.

The principal hydrogen types within this classification are:

- **GREEN HYDROGEN**: produced through the electrolysis of water; the electricity that powers the electrolyser comes from renewable sources (wind, solar…), therefore green hydrogen has no GHG emissions associated. It can also include hydrogen produced from waste biomass.
- **BLUE HYDROGEN**: it is produced by steam reforming together with carbon capture and storage (CCS).
- **GREY HYDROGEN**: it is produced from fossil fuels, mostly by steam methane reforming but without carbon capture and storage. Some sources include black and brown hydrogen in this category.
- **BROWN AND BLACK HYDROGEN**: these types of hydrogen are produced through gasification of brown coal (brown hydrogen) and black coal (black hydrogen), although some sources consider that hydrogen produced through the gasification of any fossil fuel is black or brown hydrogen. Since there is no carbon capture associated, this is the most environmentally damaging type of hydrogen.

- **TURQUOISE HYDROGEN**: this is the hydrogen produced through methane pyrolysis, resulting in hydrogen and solid carbon. There are no GHG emissions associated with the production itself. However, depending on the source making the classification, there are emissions associated with the mining and transport of the natural gas, emissions associated with how the thermal process is powered, and emissions associated with the use of the solid carbon generated as a by-product (whether it is used or stored).
- **PINK / PURPLE HYDROGEN**: hydrogen produced through electrolysis powered by nuclear energy. Sometimes this type is also called red or even yellow, depending on the source making the classification.
- **YELLOW HYDROGEN**: this colour for hydrogen demonstrates the lack of homogeneity previously acknowledged, since it is used to describe hydrogen produced by electrolysis using electricity from the grid, hydrogen produced by electrolysis using solar power, hydrogen produced through direct water splitting or as mentioned before, it can sometimes be alluding to what is known as purple hydrogen.
- **WHITE HYDROGEN**: this type of hydrogen is found in underground deposits, generated by natural geochemical processes inside the Earth's crust. While this is the main definition, some sources also describe white hydrogen as the result of the direct splitting of water molecules thanks to concentrated solar energy.

It is relevant to note that in December 2021 the European Commission released its legislative Package on Hydrogen and Decarbonised Markets, which consisted in three legislative proposals. Particularly, in the Proposed Gas and Hydrogen Directive, legal definitions for renewable hydrogen and low-carbon hydrogen were stated, which will hopefully clarify the role of hydrogen regarding the regulatory framework and prompt the development of the hydrogen market, infrastructure…

- **Renewable hydrogen** (as defined in the Proposal Directive to Amend RED II): renewable fuels of non-biological origin and biomass fuels that meet a 70% GHG emission reduction compared to fossil fuels setting specific sub-targets for the consumption of renewable hydrogen (50% of total $H_2$ consumption for energy and feedstock purposes in industry by 2030 and 2.6% of the energy supplied to the transport sector).
- **Low-carbon hydrogen**: hydrogen the energy content of which is derived from non-renewable sources, which meets a GHG emission reduction threshold of 70%.

Furthermore, it is pertinent to cite the EU Parliament, that states that:

*The classification of different types of hydrogen would inter alia serve the purpose of providing consumers with information and it is not meant to stall the expansion of hydrogen in general.*

[Another matter at hand in this section is] *the urgent need for EU and international standards and certification*. [The EU Parliament] *stresses that the standardisation system needs to be based on a holistic approach and must be applicable to imported hydrogen; calls on the Commission to introduce a regulatory framework with robust and transparent sustainability criteria for the certification and tracking of hydrogen in the EU, taking into account its greenhouse gas footprint throughout the value chain, including transport, in order to also trigger investment in sufficient supplementary renewable electricity generation; also calls on the Commission to provide […] a regulatory framework for hydrogen that ensures standardisation, certification, guarantees of origin, labelling and tradability across Member States.*

In this regard, it is relevant to mention the project CertifHy, that has enabled the elaboration of certification schemes in Europe (expected to go international) as well as the creation of a stakeholder platform.

Its aim is to promote the production, procurement, and use of "non-renewable", "renewable", and "low-carbon" hydrogen for all uses, supporting the growth of the $H_2$ market.

CertifHy™ has developed Guarantee of Origin certificates, a system of electronic certificates that authenticates, for a certain situation, the quantity of hydrogen produced, and the registered device used as well as the process utilised. These GO certificates are kept in the CertifHy™ Registry database. One of their features is the detachment from the location since a certain amount of $H_2$ can acquire the properties of the $H_2$ associated with the GO certificate.

The GO certificates are generated for each hydrogen quantity produced and registered, and this $H_2$ is tracked during its life cycle, meaning there is no double use within the registry.

The CertifHy™ GOs consist of the elements in Figure 25, pictured below:

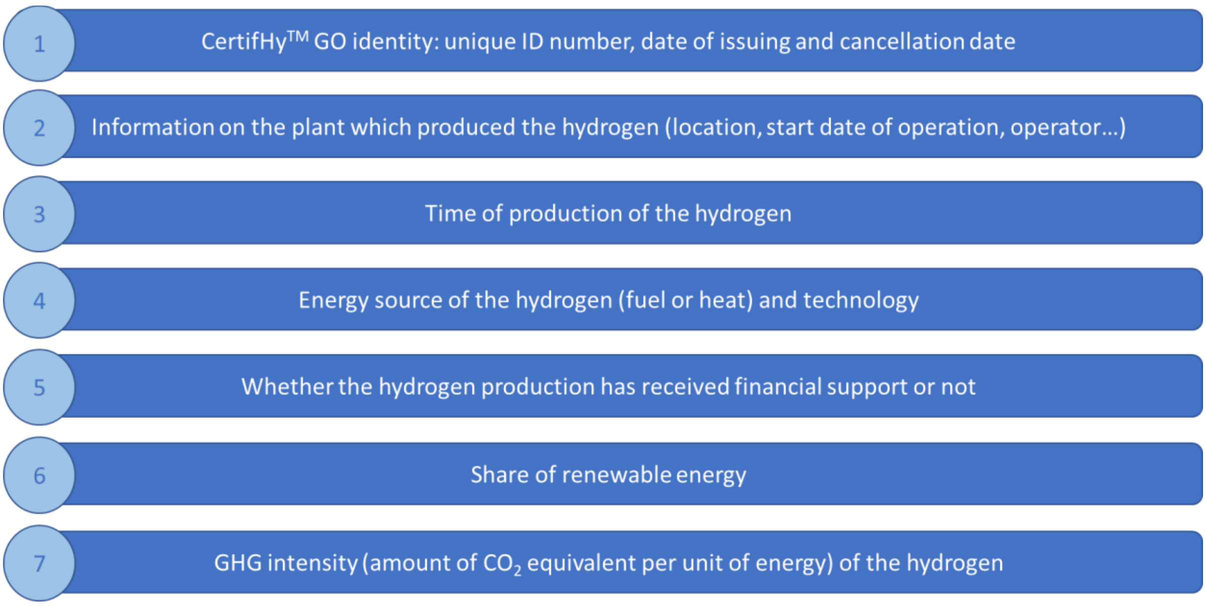



Figure 25. Content of the CertifHy™ GOs [84]

These certificates can also have labels, particularly the "CertifHy™ Green hydrogen" and the "Low-carbon hydrogen" labels.

Many advantages are linked to having a reliable certification system as expressed in the CertifHy website. Some of them are:

- It incentivises the creation of a new business model through product differentiation
- There is an increase in liquidity and transparency thanks to a globalised European market
- It is a standardised solution recognised between the market players and makes it easy to trade
- It provides trust to end consumers
- It allows consumers to transfer value towards the production method they want to support
- The use of renewable or low carbon $H_2$ can be independent from the location
- It increases the role of hydrogen in the energy transition

- It measures the impact of $CO_2$ emissions
- Enables consumers disclosure

About the certification itself, it is important to know about the GHG calculation and allocation.

CertifHy™ performs a case study for each production technique (electrolysis, SMR+CCU, chloralkali, etc.) and develops a dedicated GHG allocation method which is then used as a part of the CertifHy™ scheme.

The concept of GHG intensity used is based on $CO_2$ emissions of the whole production trajectory ("well-to-gate") to produce hydrogen with a certain quality and pressure, including the emissions of transportation to the production site.

This project is a consortium led by Hinicio, composed of the associations shown in Figure 26, requested by the European Commission, and financed by the Clean Hydrogen Partnership.


Figure 26. Organisations associated with CertifHy™ [84]

Finally, this section tackles the concept of safety regarding hydrogen. The EU Parliament:

*Highlights that safety protocols in demand sectors need to be updated continuously with regard to hydrogen use […]* [and] *asks […] that best-practice examples and a hydrogen safety culture be promoted throughout the EU.*

### 4.1.3 Ramping up hydrogen production

This section assesses several topics within the ramping up of hydrogen production.

Firstly, and quite persistently, the EU Parliament asks for a regulatory framework for hydrogen and comments on the need to reduce the costs of hydrogen, particularly the EU Parliament:

*Highlights that in order to ensure the internal hydrogen market functions well […] a […] regulatory framework for a hydrogen market should be […] proposed by the Commission* and *calls on the Commission and the Member States to reduce regulatory and economic hurdles in order to foster a quick market uptake of hydrogen.*

[This framework] *should be aligned with other relevant legislation […]. The Commission* [must] *look […] into the review of the Renewable Energy Directive, the Energy Taxation Directive and the ETS Directive in order to ensure a level playing field and a future-proof regulatory framework.*

[Moreover, the EU Parliament] *believes that the EU gas market design and the Clean Energy Package could serve as a basis and example for the regulation of the hydrogen market*.

*An adequate regulatory framework* [is a requisite, together with] *the necessary investments* [and competitive renewable energy, to make] *renewable hydrogen* competitive *before 2030*.

While very articulate, a few questions arise when reading this such as: what are the regulatory and economic barriers to the hydrogen market? What characteristics should the regulatory framework have? How can the EU gas market design and the Clean Energy Package establish a basis for the hydrogen market?

The hurdles, for instance, are:

- Taxes and levies on renewable energy; the Member States should reduce them in order to eliminate double charging of taxes and fees on electricity generated form hydrogen facilities.
- Missing regulation, poor regulatory environment, legal uncertainty, inconsistency across countries.
- Issues regarding permits (for construction, deployment, operating…) due to the lack of $H_2$ experience of the permitting authorities and the missing procedures for this sector; also unclear requirements.
- High investments needed and high costs.

Therefore, the regulatory framework for the hydrogen market should be able to overcome these barriers while also being

*Coherent, integrated and comprehensive, respecting the principles of proportionality, subsidiarity and better regulation,* [and allowing for the scaling up of the $H_2$ market].

Finally, it is time to answer the remaining question: what are the EU gas market design and the Clean Energy Package and how can they serve the $H_2$ market?

The Clean Energy Package is a 2019 energy policy framework aiming to help to decarbonise the European Union's energy system in compliance with the Green Deal objectives. This package is comprised of 8 laws regarding subjects such as energy efficiency, energy performance in buildings or electricity directive.

The EU gas market design, as well as the electricity market, has the goal of procuring an unbiased and non-discriminatory market environment to develop liquid wholesale markets. The experience from this market results in the identification of certain needs for the $H_2$ market, particularly regulatory principles like Third-Party Access, no discrimination, unbundling from vertically integrated activities and transparency.

Moreover, the hydrogen regulatory framework can be based on the Internal Energy Market for gas and electricity while also considering the particularities of the $H_2$ market.

It is important to note that the hydrogen infrastructure is bound to evolve as a monopoly and the regulatory framework should reflect that. The hydrogen market should be developed together with the required infrastructure, and a dynamic regulation could incentivise investments for this, while also being flexible to adapt to the different developments of the Member States in terms of hydrogen market.

Afterwards, the EU Parliament:

> *Encourages the Commission and the Member States to devise specific solutions in order to ramp up hydrogen production in less connected or isolated regions such as islands, while ensuring the development of related infrastructure, including by repurposing it.*
>
> [Moreover, it] *stresses the potential to convert some existing industrial sites into renewable hydrogen production facilities, planning such conversions of industrial sites with the workers and their trade unions.*

The EU has already taken an interest in islands, as proven by Clean energy for EU islands, a secretariat driven by the European Commission that serves as a platform for the clean energy transition of the EU islands. It provides assistance and information on policy, regulation, etc., including a national scope for the countries with inhabited islands, regarding topics such as those shown in Figure 28. This is necessary given the inherent challenges islands face indicated in Figure 27.

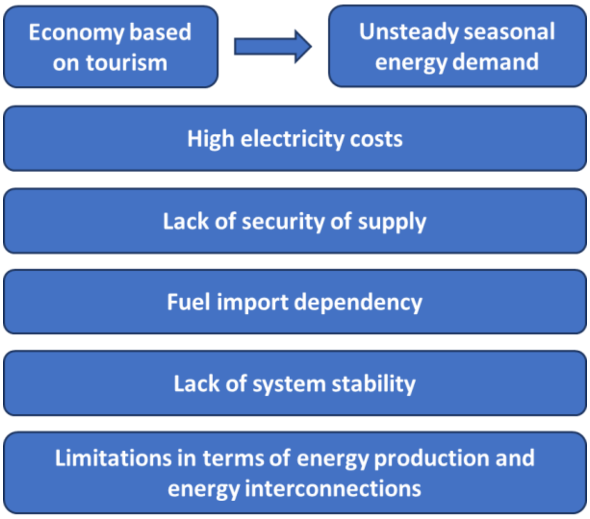



Figure 27. Challenges inherent to islands

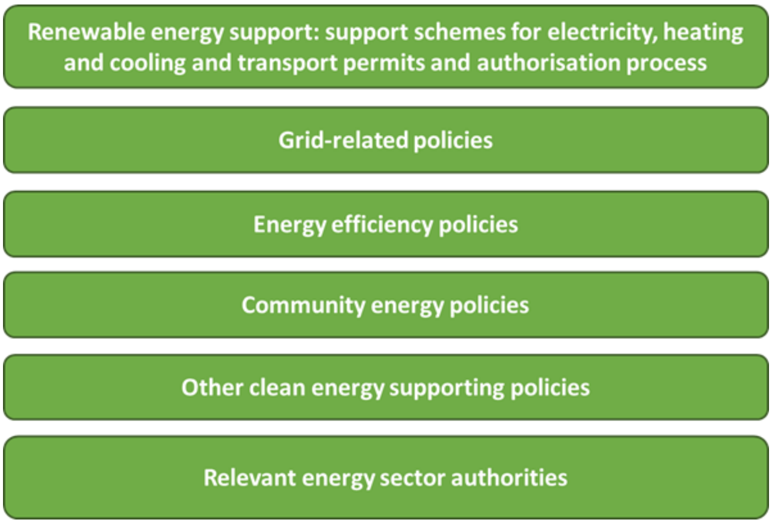



Figure 28. Topics Clean energy for EU islands gives information about [88]

A remarkably interesting project in this matter is Green Hysland, being developed in Mallorca (Spain) and aiming to be a blueprint for other islands; in this document Green Hysland is analysed in the "Changing the Scope" section, but within this topic is fitting to mention that one of its goals is to boost hydrogen deployment in other European islands through the coalition "H2 Island Hub"; the projects and initiatives joining the coalition are shown in Figure 29.


Figure 29. Members of H2 Island Hub [89]

Another example is the Orkney Islands project in Scotland, where there is usually an excess of renewable energy production that would be wasted if not for hydrogen. The system, as seen in Figure 30, consists of electrolysers fed with the renewable energy produced there that produce the $H_2$ that is stored or transported by ferry and used for fuel cells to supply heat and power for buildings, the marina and for three ferries.

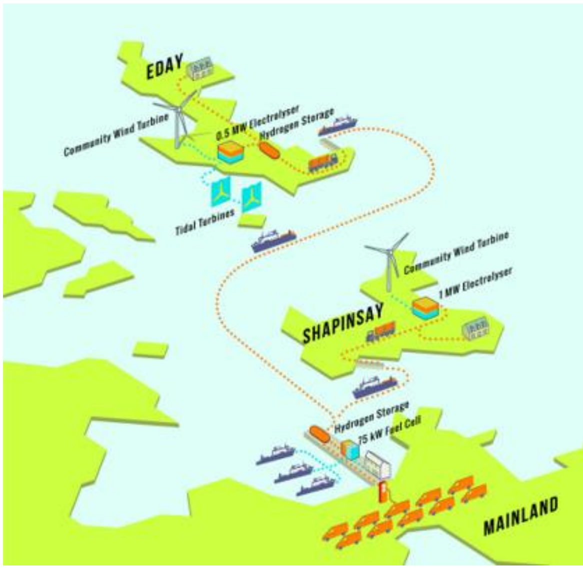



Figure 30. Representation of the Orkney Islands setting [90]

Changing the subject, another message is that the EU Parliament:

*Welcomes the ambitious goals of increasing the capacity of electrolysers and renewable hydrogen production* [and] *calls on* [this organisation] *to develop a roadmap for the deployment and upscaling of electrolysers and to forge partnerships at the EU level to ensure their cost-effectiveness.*

In the Commission's 2020 hydrogen strategy it is stated that the renewable hydrogen electrolyser capacity in the EU wanted by 2024 is 6 GW (1 million tonnes of renewable hydrogen associated). Therefore, it is in that document that the Commission discusses the scaling up of production.

However, a month after the Parliament's $H_2$ strategy was released, in June 2021, Delta-EE, a global hydrogen intelligence service, announced that the electrolysis capacity reached by 2050 would be 2.7 GW, therefore missing the 2024 target.

Nevertheless, this company later issued a whitepaper in March 2022 expecting a fulfilment of the 2024 target. Moreover, as previously explained, there has been a Joint Declaration signed within the European Electrolyser Summit in May 2022. In this Joint Declaration the participants commit to a tenfold increase in electrolyser capacity; also, it is acknowledged that to produce 10m tons of renewable $H_2$ around 90-100 GW of electrolyser capacity would be needed. That implies a considerable increase, although in the short term the electrolyser manufacturers in Europe expect a manufacturing capacity of 17.5 GW.

This escalation happens in the context of the RePowerEU Communication, previously reviewed.

The EU Parliament also expresses its views on fossil-based hydrogen and low-carbon hydrogen.

> [Particularly], *recognises that there will be different forms of hydrogen on the market, such as renewable and low-carbon hydrogen, and underlines the need for investment to scale up renewable production […] while recognising low-carbon hydrogen as a bridging technology in the short and medium term.*
>
> [The Parliament also] *calls on the Commission to assess approximately how much low-carbon hydrogen will be needed for decarbonisation purposes until renewable hydrogen can play this role alone.*
>
> [That being said, the Parliament] *stresses the importance of phasing out fossil-based hydrogen as soon as possible* [and] *urges the Commission and the Member States to […] start planning that transition […] so that the production of fossil-based hydrogen starts decreasing swiftly, predictably and irreversibly.*
>
> [It also] *highlights that effective support measures should be directed at the decarbonisation of existing fossil-based hydrogen production* [and] *urges that measures aimed at the development of the European hydrogen economy should not lead to the closure of the fossil-based hydrogen production sites, but to their modernisation and further development.*

Completely eliminating fossil-based hydrogen is not an easy task given that currently it represents 95% of the hydrogen produced in Europe. On the other hand, low-carbon hydrogen represents the 0.7% but is considered to be a bridging technology that will contribute to the transition to a fully renewable hydrogen use. While the Commission is yet to give an exact assessment on low-carbon $H_2$, it has granted it its role in the Hydrogen and Decarbonised Gas Package, issued in December 2021, although including it in a broader category, low-carbon fuels.

In addition, in this section the EU Parliament:

> *Underlines the role that environmentally safe carbon capture storage and utilisation (CCS/U) can play in reaching the European Green Deal objectives and supports an integrated policy context to stimulate the uptake of environmentally safe CCS/U applications […] in order to make heavy industry climate-neutral where no direct emission reduction options are available, noting the need for research and development in CCS/U technologies.*

Besides, it is important to be aware of the role of renewable energy in the hydrogen strategy and that is why the European Parliament:

> *Underlines that a hydrogen economy requires significant additional amounts of affordable renewable energy*

*and the corresponding infrastructure for […]* [its] *production […] and its transport to hydrogen production sites and […] to the end users*; [also] *calls on the Commission and the Member States to start the roll-out of sufficient supplementary renewable energy capacity to supply the electrification process and the production of renewable hydrogen.*

[It also] *considers that the deployment of appropriate renewable energy capacity in proportion to the need for renewable hydrogen can help to avoid conflict between the capacity required for electrification, electrolysers and other purposes and the need to meet the EU's climate goals; welcomes, in that regard, the Commission's plans to increase EU renewable energy target for 2030 and its proposed strategy on offshore renewable energy.*

[Moreover, it stresses that] *renewable hydrogen can be produced from several renewable energy sources such as wind, solar and hydropower*, [and that…brownfields have potential…] *to provide space for renewable energy production*; [also, it] *invites the Commission […] to assess how offshore renewable energy sources could pave the way for the wide development and uptake of renewable hydrogen.*

The premise of this subdivision is straightforward: an increase in renewable hydrogen production implies an increase in renewable energy capacity.

Some questions that might come to mind are: how much renewable energy capacity is enough to cover both the electrification process and the renewable hydrogen production? And what is the EU renewable energy target for 2030?

Within the Climate Target Plan the goals of reaching the target of 40% GHG emissions reduction by 2030 (compared to 1990) is increased.

The Commission's objective is to achieve a 55% GHG emissions reduction by 2030 (also compared to 1990), and that means that the share of renewable electricity produced in the EU is bound to reach at least 65%, and the gross final consumption share of renewable electricity would reach almost 40%. This renewable electricity will help decarbonise many sectors through direct electrification and also through renewable hydrogen.

Next, the Parliament comments on the strategy on offshore renewable energy and the assessment of its role in relation to renewable hydrogen.

This strategy is in line with the 55% GHG emissions reduction previously mentioned since offshore renewable energy will be part of the renewable energy installed to reach the targets.

Offshore renewable energy encompasses different technologies such as:

- Offshore wind technology, with bottom-fixed wind turbines
- Floating offshore wind technology
- Tidal energy technology
- Wave energy technology

And lesser developed:

- Algal biofuels technology
- Ocean thermal energy conversion technology
- Floating photovoltaic technology

As in November 2020, the date the "EU Strategy to harness the potential of offshore renewable energy for a climate neutral future" was issued, the installed offshore wind capacity was 12 GW.

By 2030 the goal is to have at least 60 GW and 1 GW installed of wind capacity and ocean energy capacity respectively. By 2050 those numbers could increase, achieving 300 GW and 40 GW (respectively) of installed capacity. Within this strategy it is estimated that almost EUR 800 billion will be required.

The increase in renewable energy available can contribute to indirect electrification through hydrogen and synthetic fuels. Furthermore, in the Commission's hydrogen strategy the goal is to have 40 GW of electrolysis installed capacity, thus there is a need for renewable energy production.

One possibility to deliver the energy produced offshore to the mainland is through hydrogen produced on site and transported through hydrogen pipelines or by ship.

This opportunity has not gone unnoticed by companies such as Siemens Gamesa and Siemens Energy, that are already developing an approach to integrate an electrolyser into an adapted offshore wind turbine to produce renewable hydrogen. The system, shown in Figure 31, consists of their most powerful wind turbine, an electrolyser fed with the electricity produced by the turbine and water obtained directly from the sea and treated in a desalination process, and a $H_2$ dryer to purify the hydrogen.

This decentralised model entails a CAPEX reduction, an increase of the system efficiency and an increase of the plant load factor in comparison to a centralised model (electrolyser close to consumer facilities, not integrated in the wind turbine).

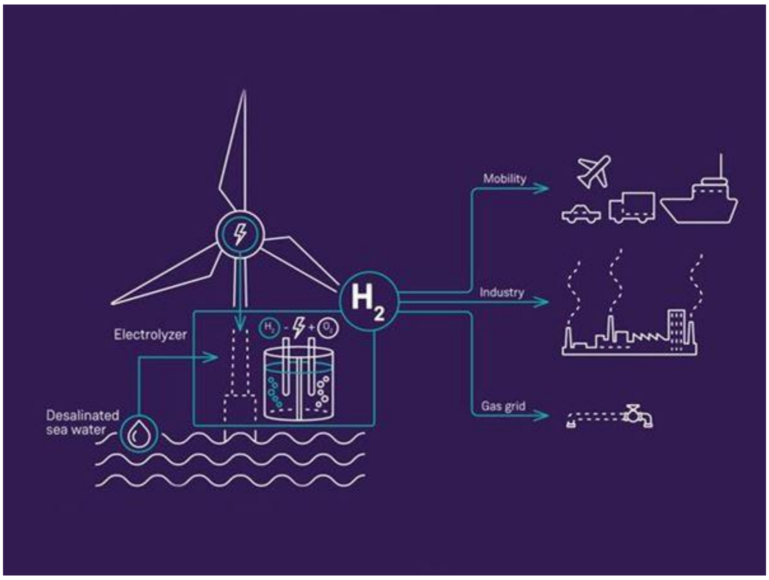



Figure 31. Decentralised offshore wind and hydrogen production system by Siemens Gamesa and Siemens Energy [98]

Another example of this sector's growth is the case of the North Sea and its vast potential in terms of renewable energy production, particularly offshore wind energy and hydrogen production. The research program North Sea Energy studies its potential to be an integrated system and is developing multiple research and pilot projects such as the PosHYdon project in the Netherlands, that combines offshore wind, offshore gas, and offshore hydrogen.

Changing to a different subject, in this section the Parliament also comments on the taxes and levies associated with the hydrogen sector in Europe, particularly:

*Calls for the revision of the Energy Taxation Directive; calls on Member States to consider reducing taxes and levies on renewable energy across the EU […] to eliminate double-charging of taxes and fees on electricity generated from hydrogen facilities […] and to strengthen financial incentives to produce renewable energy, while simultaneously further working towards the phase-out of fossil fuel subsidies, tax and levy exemptions.*

The European Parliament demands a revision of the Energy Taxation Directive, adopted in 2003, since this directive is not up to date with the hydrogen technologies and market, nor is it aligned with the EU climate and energy policies.

The proposal for a Revision of the Energy Taxation Directive was issued two months after the Parliament's hydrogen strategy, in July 2021.

The principal modifications were:

- A new tax rates structures is established using the energy content and environmental performance of the electricity fuels as the criteria, not the volume. The most environmentally damaging fuels sustain the highest minimum rates.
- The minimum rates are to be adapted annually to reflect the most recent prices.
- The taxable base is being extended; more products are included and some of the exemptions and rate reductions are removed.
- Kerosene and heavy oil used for air and maritime transport within the EU are no longer exempt from energy taxation.

These alterations will hopefully help get a better indication of the environmental impact of fuels and electricity, and allow for cleaner decisions.

Another aspect also contemplated in the revision is the double taxation of electricity, and this is particularly significant for electricity generated from hydrogen facilities, as remarked by the Parliament.

In the revision it is tackled, deeming that electricity storage or electricity transformation facilities could be regarded as redistributors when supplying electricity to avoid it.

The Parliament also considers the Member States' different situations regarding their hydrogen economies:

*The transition to a climate-neutral energy system should be planned carefully, taking into account […] starting points and infrastructure, which may differ across the Member States […]. The Member States should be flexible when designing […] State aid measures, for the development of their national hydrogen economies*; also *asks the Commission […] to provide more information on planned differentiation and the flexibility of support measures.*

Lastly in this section the topic of resources emerges. The Parliament:

*Underlines the significant amount of natural resources, such as water, needed for hydrogen production and the problems this may cause for water-scarce regions in the EU; stresses the importance of increasing resource efficiency, minimising the impact on regional water supplies, ensuring the careful management of resources and land use for the production of hydrogen and avoiding any contamination of water, air or soil, deforestation or loss of biodiversity, as a result of the hydrogen-related production chain.*

The resource depletion is a remarkably interesting topic that is relevant to every technology and sector and is a broad subject that can be covered on its own.

In this thesis, however, the focus is on hydrogen production and the resources and materials associated with it, particularly, as the Parliament mentions, water.

Water scarcity is increasingly becoming a concern for Europe and it is getting worse as a consequence of climate change. According to a report issued by the European Environment Agency (EEA) in October 2021 [105], currently during an average year about 20% of European territory is affected by water stress.

Water scarcity and droughts have a higher impact on southern Europe, as seen in Figure 32. This Figure, taken from the EEA report, shows the projected change in annual and summer precipitation in Europe in the 2071-2100 time span.

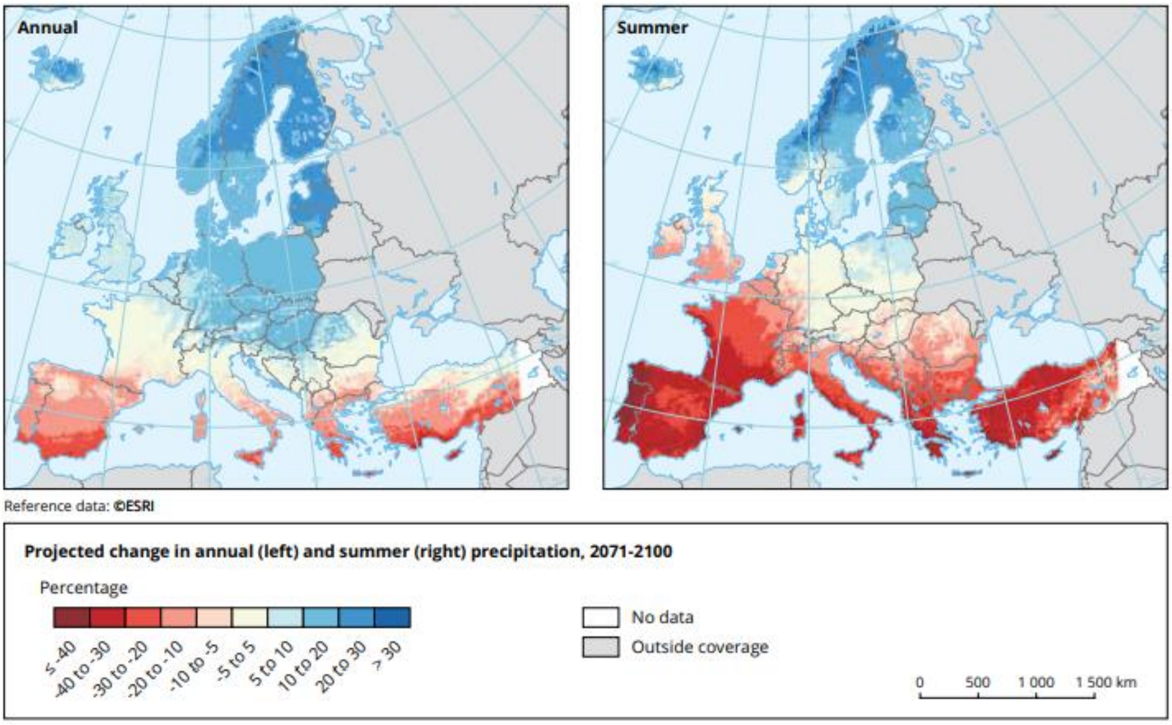



Figure 32. Projected change in precipitation in Europe [105]

Again, it is a vast subject and could be talked about exhaustively, but a brief conclusion could be that there is a need to enhance water management and make it more efficient, avoiding water scarcity and pollution, although it is explained in detail in the report previously mentioned. It is pertinent to note that there are associations, such as Water Europe, water directives and even drought management plans by some Member States.

Water consumption for hydrogen production differs depending on the technology and the energy source. Hydrogen produced through SMR requires water as feedstock; particularly, when using natural gas, 4.5 kg of water are needed per kg of $H_2$ just as feedstock, as calculated in Figure 33, although reaction efficiency, consumption for cooling and other uses make this number bigger.

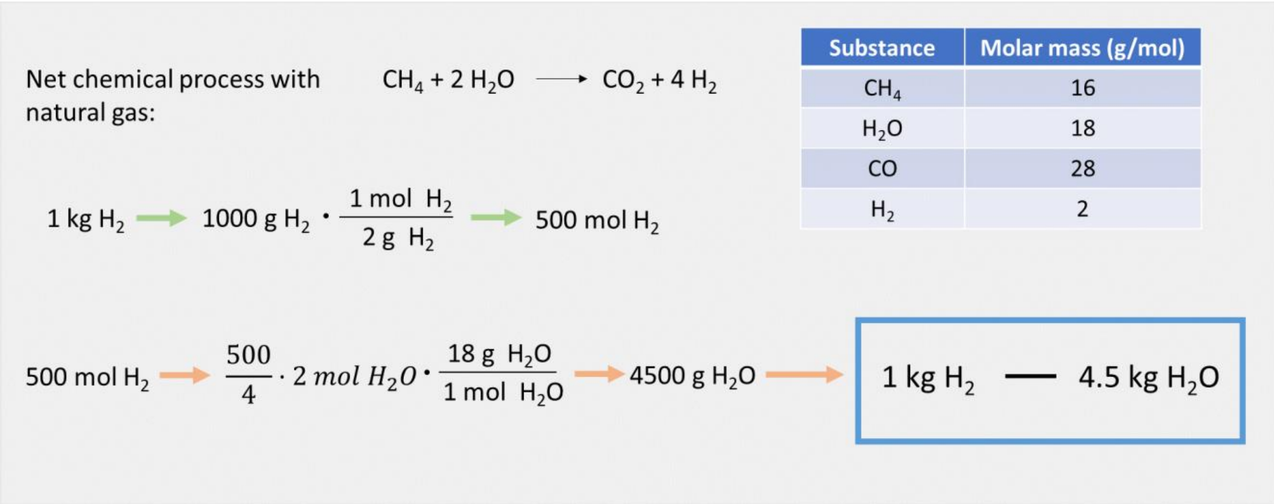



Figure 33. Stoichiometric water requirement for Steam Methane Reforming

Hydrogen produced through electrolysis requires 9 kg of water per kg of $H_2$ produced, shown in Figure 34, but again that is from the stoichiometric point of view, since reaction efficiency and other uses increase this ratio. Furthermore, the electricity fed to the electrolyser also has water consumption with it (cooling, mining, refining, etc., including renewable energy).

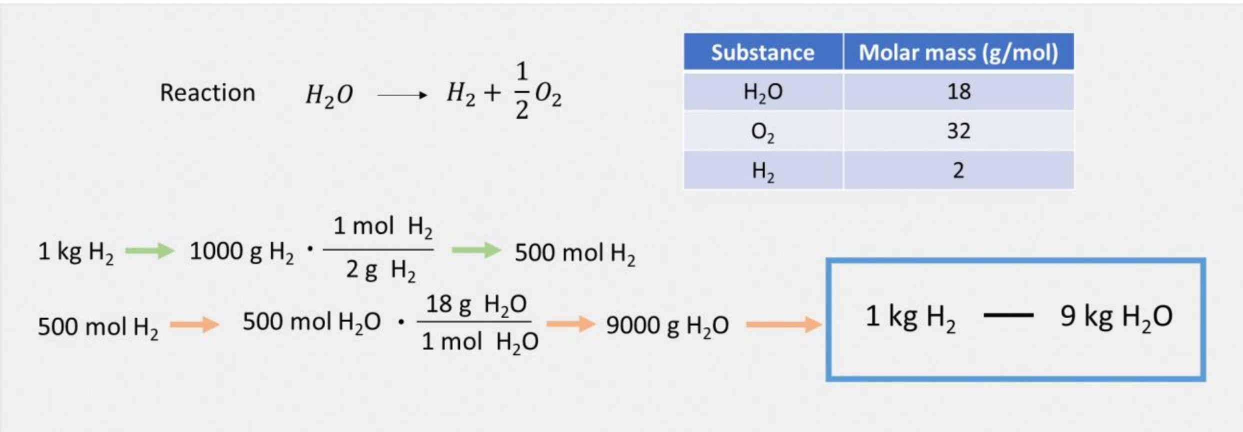



Figure 34. Stoichiometric water requirement for electrolysis

Water consumption also depends on the end use of $H_2$. If the hydrogen is consumed in a fuel cell for instance, then the by-product is water, although it is not clear whether this water is returned to the body of water it belonged to. However, if the $H_2$ is used in chemical synthesis the water is not entirely recovered.

As previously commented, the European Union's goal is to produce 10 million tons of renewable $H_2$ per year by 2030. In IRENA's 2020 report "Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5°C climate goal" it is estimated that the water consumption of the production of renewable hydrogen is around 18 to 24 kg per kg of $H_2$, and that is without taking into account the electricity source. Making a simplistic calculation using the ratio of 20 kg $H_2O$ / kg $H_2$, reaching the EU's goal of 10 million tons of renewable $H_2$ per year would require 200 million tons of water.

One interesting solution to this issue is the desalination of salt water, which accounts for 99% of the planet's water. The main desalination process nowadays is reverse osmosis and, while this tackles the resource aspect, the ratio "freshwater obtained / saltwater consumed" is up to 0.5, and adding desalination increases the complexity and energy required of a project.

### 4.1.4 Citizen engagement

Regarding citizen engagement, the EU Parliament underlines that:

[It] *will play an important role in the implementation of […]* [the] *energy transition* [and that it is important to ensure] *that all stakeholders share the costs and benefits in an integrated system.*

[It also states] *that renewable energy communities can be involved in the production of hydrogen and recalls the obligation to provide them with an enabling framework in accordance with Directive (EU) 2019/944 and requests that they benefit from the same advantages as other stakeholders.*

The significance of citizen engagement is also expressed in the Clean Hydrogen JU's Work Programme 2022, particularly in the call for proposals "Public understanding of hydrogen and fuel cell technologies". It is stated that public acceptance of the hydrogen technologies and applications is fundamental for the transition to a $H_2$ economy and this organisation asks for projects that analyse, assess and enhance the engagement of citizens.

Renewable energy communities are legal entities (associations, partnerships…) that allow citizens to participate and invest in energy assets and access the energy markets with similar conditions to other market actors. This communities, in line with the directive previously mentioned, can participate actively in the market by generating, consuming, sharing, selling or storing electricity, and the citizens benefit from lower energy prices.

They are also a way to earn public acceptance of renewable energy projects.

Regarding the guidance and assistance to these organisations, the European Commission with funding from the Parliament has created the Energy Communities Repository, which was launched in April 2022.

Also, in the revision of the Renewable Energy Directive the renewable energy communities and citizens within them are encouraged to develop, involving them in the clean energy transition.

[Afterwards, the Parliament] *stresses that in order to have a properly functioning EU hydrogen market, people with specialised skills are needed, especially with regard to safety and underlines the necessity of a […] training system; calls on the Commission to adopt an action plan aimed at guiding Member States to develop […] training programmes for workers, engineers, technicians and the general public, and to create multi-disciplinary teaching programmes for economists, scientists and students […]* [also] *calls for the launch of an EU initiative focused on employment, training and development for women.*

[It also] *stresses the importance of preserving and tapping into the potential of workers with technical skills employed in existing industries, and recalls the right of workers to be trained and upskilled during working hours with their wages guaranteed.*

In the pasts, projects regarding the safety training topic were developed. In the European context for instance HyResponse was conceived from 2013 to 2016. This project's aim was to create a Hydrogen Safety Training Platform and to instruct European First Responders to assess situations, make decisions and be prepared for the emergency response level in the event that an accident happened on site. The guidance was focused on hydrogen safety regarding all aspects: production, distribution, storage, fuel cell cars, buses and forklifts, refuelling stations, fuel cells for combined heat and power, etc.

Following the steps of HyResponse and within the context of FCH JU (Clean Hydrogen Partnership), HyResponder was created with the objective of developing a "train the trainer" programme regarding hydrogen safety, also for responders in the EU. Beyond the European Union there are more organisations committed to this subject such as HySafe, the International Association for Hydrogen Safety.

Moreover, the EU (FCH 2 JU) also started the European Hydrogen Safety Panel and now it will help ensure hydrogen safety in projects and programmes and promote a hydrogen safety culture.

Last in this section the EU Parliament:

*Calls on the Commission to produce data on the possible impacts, opportunities and challenges […] in relation to the scaling-up of hydrogen […]* [and] *suggests the launch of an EU skills partnership on hydrogen under the Pact for Skills.*

The Pact for Skills was established in November 2020 and is a knowledge, resource and networking hub for companies, partnerships and other organisations to develop skills in Europe. Regarding the commitments under this Pact some European industrial partnerships are found, such as: Pact for skills in construction, Aerospace & defence skills partnership or the Skills partnership for offshore renewable energy. Therefore, it is appropriate for a Skill partnership on hydrogen to be launched.

### 4.1.5 Hydrogen infrastructure

In the hydrogen infrastructure section a few topics are discussed.

First the EU Parliament:

*Emphasises the urgent need to develop infrastructure for hydrogen production, storage and transport, to incentivise adequate capacity-building, and to develop demand and supply in parallel […]* [also] *notes the […] benefits of combining hydrogen production and infrastructure with other aspects of flexible, multi-energy systems such as waste heat recovery from electrolysis for district heating.*

The example given by the Parliament, waste heat recovery from electrolysis for district heating, is actually an idea already being explored. As it is further explained in the paper "Power to hydrogen & district heating" [118] a considerable amount of waste heat is produced in the electrolysis process, although the exact amount depends on the technology used; according to this paper, the concept of waste heat potential encompasses process excess heat, product gases and cooling of stack, convection and radiation losses and it can constitute up to 29% of the energy input, and this heat could be used for instance for preheating the return line of the district heating network. It contributes to the energy efficiency of the system and it is an application worth considering since the electrolysis capacity is bound to grow; again, it is further analysed (technologically, economically, etc.) in the paper mentioned.

Next the Parliament:

*Welcomes the Commission's proposal to amend the TEN-E Regulation* and *appreciates the inclusion of hydrogen as a dedicated energy infrastructure category.*

*Notes that […] the planning, regulation and development of infrastructure for the transmission of hydrogen over longer distances and storage, as well as adequate financial support for that infrastructure, should already be being undertaken […] welcomes […] the future inclusion of hydrogen infrastructure in EU plans, such as the Ten-Year Network Development Plans.*

The Trans-European Networks for Energy was first released in 2013 to stipulate the guidelines for cross-border energy infrastructure in Europe, establishing nine priority corridors (divided geographically) that connect regions, supporting the development of their oil, gas and electricity infrastructure and also three priority thematic areas: smart grids deployment, electricity highways and cross-border carbon dioxide network. The Commission, as the Parliament indicates, proposed a revision in December 2020. The aim of this revision was to adapt the regulation to the Green Deal objectives by supporting infrastructure for clean energy technologies including hydrogen and doing the opposite for fossil fuels.

This revised Regulation is contributing to the elaboration of the regulatory framework and planning of the hydrogen infrastructure, also tackling transport and electrolysis, which will simplify bureaucratic operations and therefore stimulate investments.

This section also mentions the Ten-Year Network Development Plan (TYNDP), which is a programme developed by the European Network of Transmission System Operators for Electricity (ENTSO-E) every two years to regulate the European electricity transmission network and it is relevant to the development of infrastructure.

[The Parliament also] *notes that […] hydrogen assets may be newly constructed or converted from natural gas, or a combination of the two.* [It] *encourages the Commission and Member States to make a science-based assessment of the possibility of repurposing existing gas pipelines for the transport of pure hydrogen and the underground storage of hydrogen* and it *notes that repurposing…gas infrastructure…could maximise cost efficiency, minimise land and resource use and investment costs and minimise the social impact*, [and could also] *be relevant for the use of hydrogen in the priority sectors of emission-intensive industries […] calls on the Commission to assess where hydrogen blending is currently used […] with a view to identifying infrastructure needs.*

It is often commented that the gas infrastructure can be converted to integrate transportation and storage of hydrogen with less difficulties and inconveniences than other options.

This topic is developed in the GIE Position Paper: Regulation of Hydrogen Infrastructure [123]. GIE is the acronym for Gas Infrastructure Europe, the association that represents the gas infrastructure operators, that manage gas transmission networks, storage systems and LNG terminals.

Within the context of the Green Deal and the 55% GHG emissions reduction target, and given the similarities between hydrogen and natural gas, GIE members are committed to tackle these goals through hydrogen.

The hydrogen market is bound to develop and the increase in demand implies an increase in transport, storage, import and export infrastructure to manage the large volumes of $H_2$. This infrastructure can be newly built in the cases that is economical, and it can also be a result of retrofitting and repurposing the existing gas infrastructure. The second option is linked to time and cost savings, reduction of land resource use and increase in social acceptance, taking advantage of the fact that gas infrastructure is fitting for this conversion.

The current European gas infrastructure is well developed and has a wide scope, allowing for the safe management of hydrogen and for the decarbonisation of the energy system when used for hydrogen transportation and storage. An economic assessment by the European Hydrogen Backbone Initiative shares the following figure: the existing gas infrastructure can be repurposed at 10%-35% of the costs of building the $H_2$ infrastructure from scratch.

Regarding underground storage, which is an option that enables seasonal storage and provides security of supply, the options considered are salt caverns, porous rock storage sites and aquifers, as explained in the storage section of this thesis. The first can be entirely filled with $H_2$ with no reactivity issues, but the last two require to be retrofitted to blend $H_2$ with natural gas.

Finally, in relation to the LNG terminals in this paper it is remarked their suitable role, since they can be retrofitted and repurposed and allow for the import and export of hydrogen, being able to receive different $H_2$-based energy carriers.

Afterwards the Parliament:

*Stresses the importance of […] integrated network planning with the guidance of public bodies like the European Union Agency for the Cooperation of Energy Regulators (ACER) and the participation of stakeholders and scientific bodies; suggests, in that regard, that cost-benefit calculations for the location of renewable hydrogen production, transport and storage infrastructure be made and that the need to build new ones be examined […] highlights the financial benefits of placing hydrogen production facilities close to renewable energy production sites or the same site as demand facilities.*

Indeed, ACER is one of the principal assisting organisations regarding the European energy market and network, aiding the regulatory authorities of the different Member States and coordinating them. This body also collaborates on the elaboration of network rules, monitors the energy market and reports on that topic, amongst other tasks.

Regarding renewable hydrogen-related infrastructure and location, some of the criteria for the production site location selection can be that shown in Figure 35. Hydrogen distribution infrastructure, which is not so widespread, has been explained in a previous section along with its challenges and types, and so has storage.

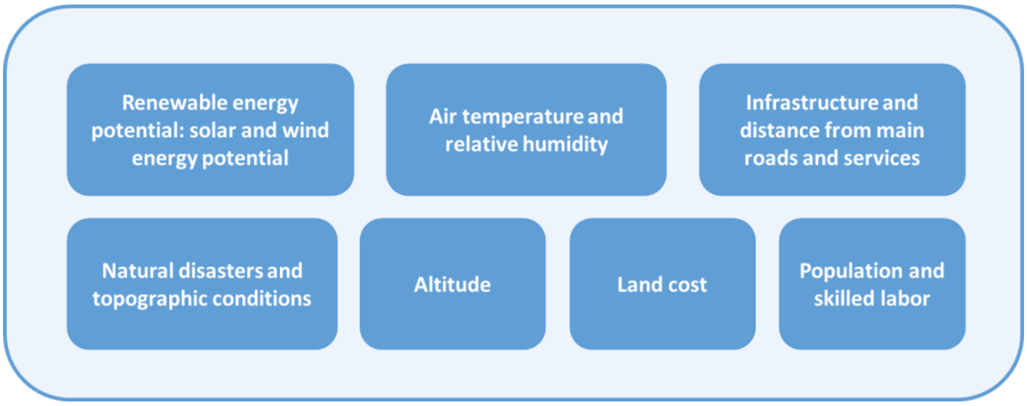



Figure 35. Criteria to select the $H_2$ production facility location

But even once the location is chosen, there are still barriers to overcome, particularly in this section the cost is discussed. It has already been said that electrolysis is not the cheapest option currently but it is being promoted to be the main one in Europe and there is a clear need for driving down the costs. Besides research and development regarding the technology, there is the possibility of choosing the location favourably, which might mean either placing the $H_2$ production site close or in the renewable energy production site, or placing it near/in the demand sites. This is a way to make the most of the resources already available and/or reduce the cost and complexity of the distribution system.

Making a distinction, these options can be named "centralised production" and "distributed production". Centralised hydrogen production – producing all the $H_2$ in one facility near or in the same site as the renewable energy production site – has lower production costs, not only because the electricity is produced in close proximity to the facility, but mainly because of the economy of scale. However, the demand or end uses sites might be far away from the facility, therefore increasing the transportation costs.

For distributed production – producing $H_2$ where the demand or end uses sites are – is the opposite and so are the conclusions: the distribution costs are lower but the production costs soar.

Both options are feasible, and some may be more adequate in a certain situation, for instance distributed or on-site production can be suitable for an industry with a high volume of hydrogen consumption.

After that, the European Parliament:

*Underlines the necessity of regulating hydrogen infrastructure and the need to uphold unbundling as a guiding principle for the design of hydrogen markets […]* [since it] *plays a key role in ensuring that innovative new products are put on the energy market in the most cost-efficient manner.*

The principle of unbundling in network systems consists in the separation of the activities that entail competition from those in which competition is not possible or permitted. In the energy context, an example of the first kind is production and purchase of energy, and an example of the second is energy distribution; actually, in Europe the gas and electricity networks are monopolies.

The reason behind this principle is that a company that operates in a competitive activity cannot participate in the monopolistic activity related, and it can be applied in various degrees.

In terms of energy (electricity, gas and eventually hydrogen), the network and distribution system are considered crucial, and access to it must be fair and non-discriminatory. If unbundling were not present, a company, for instance, in the distribution system can act according to its own interests regarding its activities in production or consumption, and can work against a competitor by denying access.

Finally in this section the EU Parliament:

*Stresses the strategically essential role of multimodal maritime and inland ports as innovation pools and hubs for the import, production, storage, supply and utilisation of hydrogen; underlines the need for space for and investment in port infrastructure.*

Ports are an essential part of hydrogen distribution and trade but are also significant participants in the adoption of hydrogen technologies, accelerating their own decarbonisation.

One example of the incorporation of hydrogen technologies is the H2Ports project, co-founded by the European Union through Fuel Cells and Hydrogen 2 Joint Undertaking, that has the goal of evaluating and demonstrating the use of Fuel Cells port equipment. It takes place in the Port of Valencia (Spain) and will validate the use of the three applications: a FC-based Reach Stacker, a FC-based Yard Tractor and a hydrogen mobile supply station in the daily, real port operations.

A second example is the Global Ports Hydrogen Coalition within the Clean Energy Ministerial Hydrogen Initiative (CEM H2I) coordinated by the IEA. The CEM H2I is an initiative by which various governments that aims to boost the deployment and commercialisation of hydrogen and fuel cell technologies, and the Global Ports Hydrogen Coalition contributes to that goal by enhancing collaboration in projects to scale up the use of hydrogen-based fuels in ports. Some of the projects associated with this coalition are those in Figure 36, including the previously mentioned H2Ports.

- Port of Marseille – **HyAMMED**
- Port of Marseille – **Jupiter 1000**
- Port of Marseille – **Energy recovery from cruise ships' wastewater**
- Port of Marseille – **Green mobile energy for reefer containers**
- Port of Valencia – **H2Ports / Fuel Cells and Hydrogen in Ports**
- Port of London Authority – **Hydrogen Highway Project**
- Port of Antwerp – **Renewing, greening and optimizing the port's fleet**
- Port of Amsterdam – **H2SHIPS project**
- Port of Amsterdam – **Multi Fuel Port: Spatial Safety**
- Niedersachsen Ports – **WASh2Emden project**
- Port of Gothenburg – **Tranzero Initiative**
- Port of Gothenburg – **Hydrogen production facility and filling station**
- Port of Vienna – **H2 meets H2O**
- Ports of Stockholm – **Carbon footprint, energy optimization and sustainability reporting**
- Port of Yokohama – **Hydrogen Supply Chain Joint Study**
- Port of Kobe – **Environmental Measures in Reclamation Projects**
- Port of Los Angeles – **Zero Emissions Pathway Technology Demonstrations**
- Port of Long Beach – **C-PORT Zero Emissions Demonstration Project**
- Port of Auckland – **GHG Emission Reduction Pathway**

Figure 36. Ports and their projects within the Global Ports Hydrogen Coalition [130]

### 4.1.6 Hydrogen demand

This next section delves into hydrogen demand.

First the EU Parliament:

*Acknowledges that the focus on hydrogen demand should be on sectors for which the use of hydrogen is close to being competitive or that currently cannot be decarbonised using other technological solutions […] the main markets […] are industry, air, maritime and heavy-duty transport; believes that, for these sectors, roadmaps for demand development, investment and research needs should be established.*

[Also] *agrees with the Commission that demand-focused policies and clear incentives for the […] use of hydrogen […] in order to trigger the demand for hydrogen – such as quotas for the use of renewable hydrogen in a limited number of specific sectors, European Investment Bank guarantees to reduce the initial risk of co-investments until they are cost-competitive, and financial tools, including Carbon Contracts for Difference (CCfD) for projects using renewable or low-carbon hydrogen – could be considered.*

As mentioned, renewable hydrogen has high costs that halt its competitiveness and progress and, although costs are expected to decrease, this development needs to be paired with financial support and incentives.

One of the options proposed is quotas for the use of renewable hydrogen in some sectors and applications outside of the EU Emissions Trading System.

In the paper "Analysing the impact of a renewable hydrogen quota on the electricity and natural gas markets" [132] the renewable hydrogen quota is a policy tool to impulse the use of renewable hydrogen and in this study it is imposed on the demand side. The conclusions of this study indicate that the implementation of this quota would lead to an increase in renewable energy capacity, an increase in electricity price and a decrease of the prices in the gas market.

The other example given is Carbon Contracts for Difference (CCfD), a funding mechanism through which governments can give investors a guarantee on a price that rewards $CO_2$ emission reductions, a price different to what is established in the EU Emissions Trading System. The goal is for this to be an incentive to accelerate investments in low-carbon or renewable energy projects. Nevertheless, it is important to note that they might produce distortions on the emissions market, since they can disrupt the free price formation.

Moreover, the Parliament adds that:

[There is a] *need to ensure that the compensation remains proportionate and to avoid the duplication of subsidies for both production and use, the creation of artificial needs and undue market distortions.*

Subsequently, the Parliament expresses its interest in the use of hydrogen in the industry:

*Urges the Commission to promote lead markets for renewable hydrogen technologies and their use for climate-neutral production – especially in the steel, cement and chemical industries – as part of the update and implementation of the New Industrial Strategy for Europe; calls on the Commission to assess the option of recognising steel produced with renewable hydrogen as a positive contribution to meeting fleet-wide $CO_2$ emission reduction targets; further urges the Commission to soon come forward with an EU strategy for clean steel.*

The EU industrial strategy has already been tackled, so in this section the main character is steel, particularly green or clean steel.

The first matter to elaborate on is the concept of clean steel itself. The steel industry can be decarbonised in various ways: using carbon capture and storage (CCS), using biomass as fuel and as a reducing agent instead of coke or by electrification. Within the last option, hydrogen-direct reduction is the principal path taken by steel companies in Europe.

A brief, basic explanation of this process could be that it consists of using hydrogen to replace fossil fuels in the steelmaking process. A schematic representation of the process can be seen in Figure 37. First there is the ironmaking process, during which the iron ore pellets are reduced in a shaft furnace and become direct reduced iron that is then compacted into hot-briquetted iron. The reducing agent in this case would be hydrogen. Then the hot-briquetted iron is taken to an electric arc furnace and transformed into liquid steel.

Depending on the source of the electricity and the hydrogen consumed, a certain level of decarbonisation can be reached. If the electricity comes from a renewable source and the hydrogen is produced by electrolysis fed by renewables, then $CO_2$ emissions reduction can be almost total.

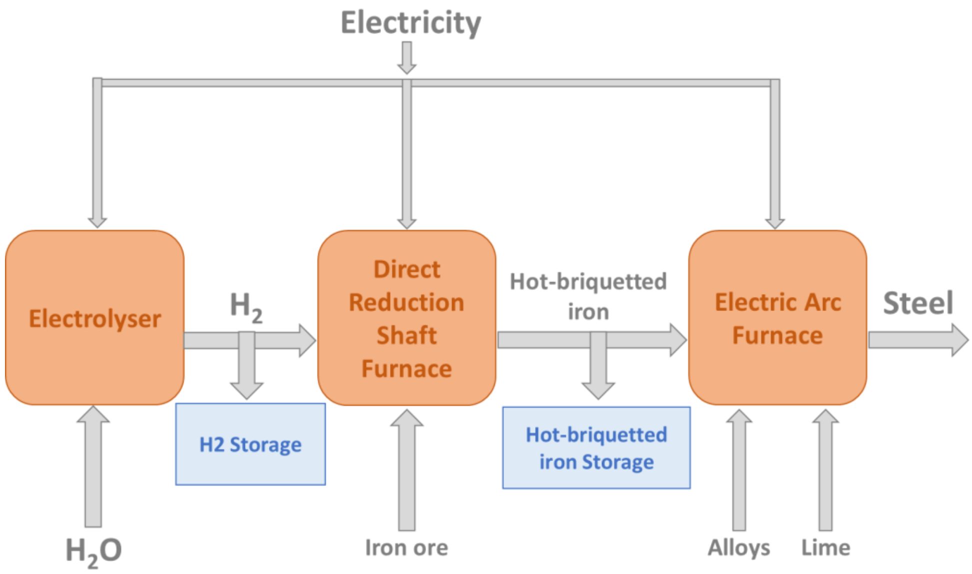



Figure 37. Schematic representation of the hydrogen-direct reduction steelmaking process [138]

For context, 5.7% of the total EU GHG emissions are a result of the EU steel industry, making this sector a considerable target for decarbonisation.

According to the European Steel Association (EUROFER), that has even proposed a Green Deal on Steel, the hydrogen strategy is welcomed in the sector, since the transition to a zero or low-carbon steelmaking process would require around 5.5 million tonnes of $H_2$. Having a clear hydrogen strategy and strengthening the hydrogen economy and market in Europe are key to maintaining Europe's technological leadership and also establishing the European industry as a reference in decarbonisation while still being competitive.

Clean steel, while more expensive to produce, will result in environmental benefits (especially $CO_2$ emissions reduction) and regional synergies, since the $H_2$ network or hub created for a steel plant can incorporate other consumers and bring on new jobs and projects.

One month after the release of the Parliament's hydrogen strategy that is being analysed, the EU Clean Steel Partnership was founded. Shortly after, its Strategic Research & Innovation Agenda (SRIA) was issued.

In this document it is stated that this Partnership aims to contribute to reaching the Green Deal and Paris Agreement targets by reducing steelmaking emissions and also contribute to a circular economy in the EU. The Partnership's general objective is also defined, which is to develop technologies to reduce the $CO_2$ emissions linked to steel production by around 80-95% of the emissions level in 1990; this objective is to be reached without compromising the sector's competitiveness. The complete approach can be read in the Agenda itself, including context, ambitions and expected impacts.

Lastly for the clean steel topics, these are a few examples of applications:

- In May 2022 the company ArcelorMittal undertook the hydrogen-direct reduction path to produce steel. They successfully replaced 6.8% of natural gas with green hydrogen for 24 hours in their Quebec steel plant. This sets the ground for tests with a higher percentage of $H_2$ and eventually the competitive production of clean and low-carbon steel.

- The German steel producer company Thyssenkrupp Steel and the also German company STEAG have agreed, through a Memorandum of Understanding concluded in March 2022, that the Thyssenkrupp Steel plant in Duisburg shall be supplied with hydrogen and oxygen from the STEAG's future electrolysis plant in Walsum. This $H_2$ will allow for $CO_2$ emission reduction in the steelmaking process.

Sweden's steel industry is a significant participant in the clean steel sector, with two strong initiatives: HYBRIT and H2 Green Steel.

- HYBRIT, which stands for Hydrogen Breakthrough Ironmaking Technology, pursues the goal of a decarbonised steel industry and a fossil-free value chain, and it is composed of the Swedish companies SSAB (steelmaking), LKAB (mining) and Vattenfall (energy). There is actually a pilot plant in Sweden that uses the process of reducing iron ore with renewable hydrogen which has obtained successful results, having produced fossil-free pellets. Moreover, SSAB is collaborating with Volvo within the HYBRIT initiative to produce cars with clean steel and in October 2021 the first vehicle made of fossil-free steel was revealed by the companies and is the first of more that will be launched in 2022. The vehicle, shown in Figure 38, is a load carrier to be used in mining and quarrying.
- H2 Green Steel is a company founded in 2020 with the aim of decarbonising the steel industry and ramping up the green steel production in Sweden. One of their main projects is the Boden electrolysis and steel plant for clean steel production by 2024. Another interesting project is one in collaboration with the Spanish company Iberdrola for 2.3 billion EUR to build a 1 GW green hydrogen plant that will then feed the $H_2$ to a direct reduction tower to produce green steel in Spain.


Figure 38. The Volvo load carrier, first vehicle made of fossil-free steel [142]

Finally in the hydrogen demand section, $H_2$ for transport is tackled. The EU Parliament:

*Recalls that the transport sector is responsible for a quarter of $CO_2$ emissions in the EU […]* and *underlines the potential of hydrogen to be one of the instruments used to reduce $CO_2$ emissions in transport modes, in particular where full electrification is more difficult or not yet possible.*

As commented by the Parliament, full electrification is one option to decarbonise the transport sector, but it is not possible for all types of transport. Aviation, maritime and heavy-duty transport are difficult or impossible to be electrified currently.

[Also] *underlines […] the importance of revising the TEN-T (trans-European transport network) Regulation and the Alternative Fuels Infrastructure Directive to ensure the availability of publicly accessible hydrogen refuelling stations […]* [and] *welcomes the Commission's intention to develop hydrogen refuelling infrastructure under the Sustainable and Smart Mobility Strategy.*

[Moreover, the Parliament] *underlines that hydrogen's characteristics make it a good candidate to replace fossil fuels […]* [and] *stresses that the use of hydrogen in its pure form or as a synthetic fuel or biokerosene is a key factor in the substitution of fossil kerosene for aviation […] stresses that stronger legislation is needed to incentivise the use of zero-emission fuels.*

[Finally], *calls on the Commission to increase research and investment within the framework of the Sustainable and Smart Mobility Strategy.*

The Trans-European Transport Network Regulation (TEN-T) is a policy that handles the development of transport networks, routes, terminals, etc. in Europe. It also defines requirements for the infrastructure in terms of quality, safety or environmental impact for instance and incentivises sustainability and innovation.

Its network development can be divided into "Core Network" and "Comprehensive Network"; the first one, to be finished by 2030, covers the key connections (identifying 9 Core Network Corridors), while the second, to be finished by 2050, contains the rest of regions and connections.

However, these guidelines were first issued in 2013 and do not reflect the current situation and targets and, as the Parliament remarks, did not include hydrogen infrastructure. The Commission itself has recognised the need for a revision of this policy to keep up with new technologies and sustainability objectives such as the European Green Deal goals. Subsequently, in April 2019 the review process commenced, and the revised guidelines were released in December 2021 by the Commission.

Some of the revised topics are: utilisation of innovative technology, the demand for certain cities to have urban mobility plans that are sustainable and for climate-proofing of projects amongst many more. It is pertinent to remark the requirement to develop refuelling and charging infrastructure for alternative fuels applications, as asked by the Parliament and in agreement with the Alternative Fuels Infrastructure Directive. There are new milestones as well, and a new phase, the "Extended Core Network, to be finished by 2040"; the new network layout can be seen in Figure 39 while being compared with its previous version.

Currently the European Council and Parliament are in the midst of agreeing on the final proposed regulation, having released a briefing in March 2022 in which it is indicated that there are still a few steps until it is adopted.

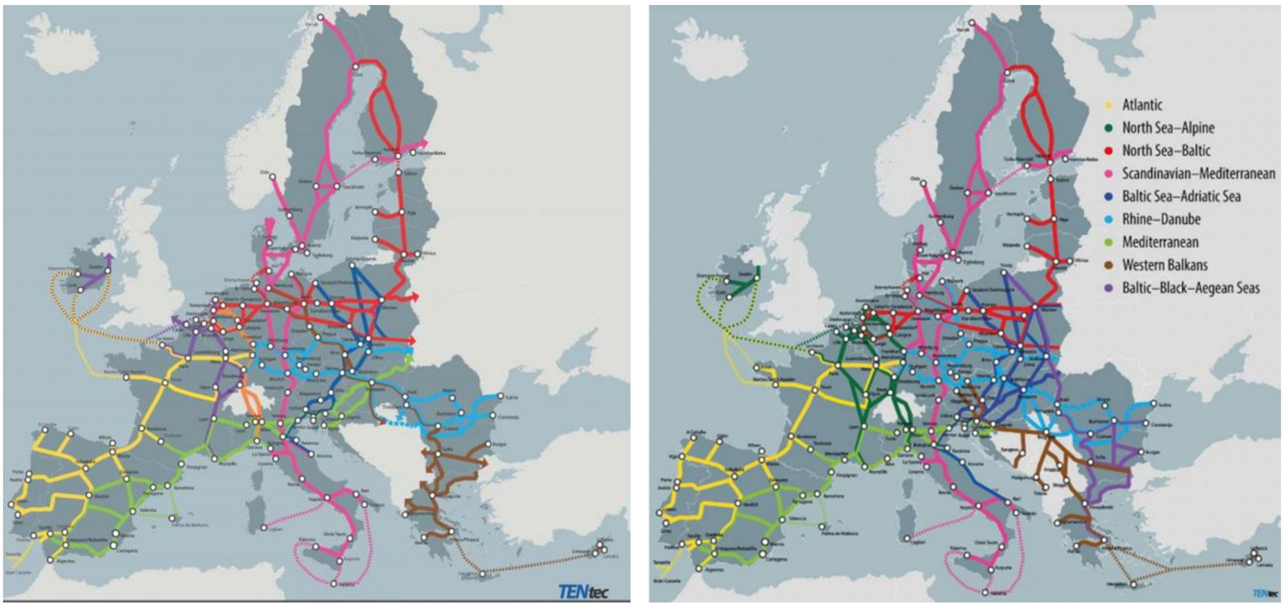



Figure 39. TEN-T network layout in the 2013 version [145] (left) and revised (2021) version [147] (right)

The Parliament also mentions the Alternative Fuels Infrastructure Directive, which dates back to 2014 and aimed to establish measures for the development of alternative fuels infrastructure, setting out requirements and technical specifications for said infrastructure. The alternative fuels concept includes hydrogen, but the directive did not obligate the Member States to include hydrogen refuelling stations in their national policy frameworks.

In the Commission's "Fit For 55" package presented in July 2021 there was a proposal to revise this directive and convert it to a regulation. This proposal, according to the March 2022 briefing on its evolution, is awaiting Committee vote. Some of the most relevant modifications regarding the hydrogen subject are the mandatory targets for hydrogen refuelling points and overall infrastructure.

The revision of the Alternative Fuels Infrastructure Directive was actually already alluded to in the Commission's Sustainable and Smart Mobility Strategy in 2020, which is also mentioned by the Parliament, as it will indeed be an instrument to reach the EU's sustainability targets and includes hydrogen infrastructure as well.

### 4.1.7 Research, development, innovation and financing

In this section, as indicated by its name, the Parliament lists its statements on research, development, innovation and financing in the context of the European hydrogen strategy.

First the EU Parliament addresses the role of research, development and innovation:

*Stresses the importance of research, development and innovation along the whole value chain and of carrying out demonstration projects […] including pilot projects […] in making renewable hydrogen competitive and affordable.*

*Calls on the Commission to stimulate research and innovation efforts relating to the implementation of large-scale high-impact projects.*

*Underlines that significant amounts of money need to be invested to develop and increase the production capacity of renewable hydrogen […] which would also require de-risking renewable hydrogen investments, for example through Contracts for Difference.*

*Calls on the Commission to develop a […] renewable energy and hydrogen investment strategy aligned with national research and innovation strategies.*

*Welcomes the European Clean Hydrogen Alliance* [and] *the important projects of common European interest (IPCEI)* amongst other *renewable hydrogen initiatives.* [Also] *encourages the Alliance to come up, in cooperation with […] FCH JU, with an investment agenda and a project pipeline.*

*Welcomes the renewal of the FCH JU under Horizon Europe; stresses the importance of its work and asks the Commission to use it as a competence centre for hydrogen and provide it with sufficient financial resources […]* [also] *calls on the Commission to make use of the experience gained through the FCH JU and to incentivise further research into fuel cell and hydrogen energy technologies.*

*Believes that EU research and development efforts should focus on a wide range of potential new renewable hydrogen sources and technologies, such as hydrogen from photosynthesis, algae or electrolysers with sea water.*

Concerning this subject, it is useful to refer to the Commission Staff Working Document Building a European Research Area for clean hydrogen – the role of EU research and innovation investments to deliver on the EU's Hydrogen Strategy, [152] issued in January 2022.

In this document the role of research, development, innovation and funding is analysed, remarking its importance in maintaining Europe's technological leadership in renewable hydrogen, and many Member States have embraced research and innovation in their own hydrogen strategies. The EU Research and Innovation Framework Programmes have enabled the investment of more than 1 billion euros through two FCH JU to develop hydrogen technologies and projects during the 2008-20211 period. However, there is still a need for investments in the research and innovation field, especially to give non-competitive but market-ready hydrogen technologies the means to be deployed, and also to give an impulse to the advantages associated, such as new jobs creation in the EU (up to 5.4 million positions by 2050) and the increase energy supply autonomy.

The development of a common Strategic Research and Innovation Agenda for renewable hydrogen is one goal of the European Research Area, although some of the necessary research and innovation activities can be already defined:

- Encompass large-scale demonstration projects.
- Cover new renewable hydrogen production technologies.
- Support every renewable energy technology and source, since the production of renewable hydrogen requires renewable energy in large quantities and low prices.
- Encourage investments to develop projects with large-scale integrated hydrogen value chains.
- Stimulate the development of safe hydrogen infrastructure.
- Devise solutions for hard to abate transport sectors (aviation, train, heavy-duty vehicles, maritime).

And regarding some cross-cutting issues:

- Encourage circularity of hydrogen equipment.
- Address the impact of hydrogen technology (environmentally, socially, economically).
- Reduce the consumption of critical raw materials.
- Enhance safety and public acceptance of the hydrogen technologies.

Another concept mentioned by the Parliament is Important Projects of Common European Interest (IPCEI), which is an instrument that will support hydrogen projects, particularly large-scale and cross-border projects that are beneficial for the European Union. In the Commission Staff Working Document previously mentioned it is stated that 22 countries that belong to the European Union, as well as Norway, agreed to the establishment of IPCEIs in the hydrogen sector, having signed a manifesto in 2020, but has not been adopted yet. It did, however, gain the interest of the industrial sector.

Also, a project pipeline is being developed in Europe by the Clean Hydrogen Alliance, particularly regarding bankable investment projects that cover the entire hydrogen value chain, and one significant outcome is the easier coordination of investments between public and private stakeholders.

The Parliament also comments on the importance of FCH JU, which has been mentioned throughout this Final Degree Thesis, therefore it is time to properly break down this partnership.

The partnership Fuel Cells and Hydrogen Joint Undertaking is both private and public, and its objective is to support research, development and demonstration of hydrogen and fuel cell technologies in Europe. This partnership was established in May 2008 joining the European Commission, Hydrogen Europe (representing industries) and Hydrogen Europe Research, working from 2014 under Horizon 2020.

However, the present tense might not be adequate to use; the partnership had a second phase “FCH 2 JU” and finally terminated its functions in November 2021. Nevertheless, it was quickly followed by Clean Hydrogen JU (also Clean Hydrogen Partnership), established the day after to be the successor of FCH JU.

FCH JU has indeed played a crucial role in the hydrogen sector’s development in Europe; it has enabled the collaboration of different stakeholders; it has participated in the deployment of 72 of the 159 hydrogen refuelling stations in Europe; it has also supported the hydrogen valleys and created the TRUST database, and much more.

In short, this partnership has and will continue to contribute to the development of hydrogen sector in Europe.

In this section the Parliament also:

> [Enumerates some EU] *financing instruments* [and] *programmes* [that] *have a key role* [in the] *development of a hydrogen economy across the EU*, [such as:] *the Recovery and Resilience Facility, Horizon Europe, the Connecting Europe Facility, InvestEU […], the European Regional Development Fund, the Cohesion Fund, the Just Transition Fund and the ETS Innovation Fund.*
>
> [Also] *stresses the need to make sure there are synergies between […] investment funds, programmes and financial instruments.*

Some of the funding instruments are relatively new, such as the Recovery and Resilience Facility, aiming to alleviate the impact of the coronavirus pandemic. Horizon Europe, for instance, focuses on research and innovation in different fields with a 95.5 billion euros as budget. Another example mentioned is the Cohesion Fund, which supports investment concerning Member States with a GNI per capita below 90% EU-27 average, regarding transport infrastructure and environment.

Regarding the synergies, the Commission does indeed support synergies between the European funding instruments, since they are key to uniting resources, can lead to operational agreements. The Clean Hydrogen Joint Undertaking, for instance, may be benefited from collaborating with other European partnerships such as:

- 2ZERO
- European Partnership on zero-emission waterborne transport
- European Partnership for transforming Europe's rail system
- European Partnership for Clean Aviation
- Processes4Planet
- European Partnership for Clean Steel
- European Partnership for Clean Energy Transition

The final topic discussed in this section is:

> *The inclusion of hydrogen deployment in the general objectives of the Partnership for Research and Innovation in the Mediterranean Area (PRIMA) […] in order to strengthen research and innovation capacities and to develop […] innovative solutions across the Mediterranean region.*

This partnership is actually focused on sustainable water management and agri-food systems in the Mediterranean region. It has been established since 2018 and ever since, it has developed tens of projects, but none of them emphasise hydrogen technologies.

While there are still no projects about hydrogen, the deployment of $H_2$ technologies can indirectly have an effect on the water management and agri-food sectors, such as the installation of desalination plants or the production of fertilisers with renewable hydrogen.

### 4.1.8 International cooperation on hydrogen

In this second-to-last section of the Parliament's Hydrogen Strategy, the subject discussed is Europe's international cooperation in the hydrogen sector.

*It is emphasised that the EU's leading role in the production of hydrogen technologies presents an opportunity* *to promote EU industrial leadership and innovation on a global level while reinforcing the EU's role as a global climate leader; underlines […] the goal of increasing domestic hydrogen production, while acknowledging that Member States may also […] explore the possibility of importing energy or hydrogen.*

*Moreover, the Parliament calls […] on the Commission and the Member States to engage in an open and constructive dialogue in order to establish […] cooperation and partnerships with neighbouring regions, such as North Africa, the Middle East and the Eastern Partnership countries […] underlines that this cooperation would be beneficial for creating clean and new technology markets […], enhancing the transition to renewable energy and achieving the UN Sustainable Development Goals*

[Furthermore, the Parliament] *emphasises international cooperation on hydrogen with non-EU countries, in particular with the UK, the European Economic Area, the Energy Community and the US […] in order to strengthen the internal market and energy security; stresses that cooperation should be avoided with non-EU countries that are subject to EU restrictive measures […] and with those that do not guarantee compliance with safety, environmental standards and transparency requirements.*

[Finally,] *considers that hydrogen should become an element of the EU's international cooperation, inter alia within the framework of the International Renewable Energy Agency's (IRENA's) work […] and the European Neighbourhood Policy.*

International cooperation is indeed of major significance to boost the green transition worldwide, and particularly to enhance the hydrogen economy in Europe not only in relation to $H_2$ production but for imports.

The Parliament remarks some of the benefits of creating international partnerships, which is fitting given that the Commission is concentrating on multi-lateral collaborations with industrial countries and emerging economies. The Commission is also supporting cooperation with countries in close proximity to the EU and also Africa, Latin America and potentially some Eastern countries.

One example of international cooperation in the hydrogen sector is the Mission Innovation Clean Hydrogen Mission, which was established in June 2021 and is directed by the Commission, the UK, the US, Chile and Australia. One main target is the development of at least a hundred large-scale, integrated clean Hydrogen Valleys.

Another example is the participation of the Commission (and FCH JU) in organisations such as the Clean Energy Ministerial Hydrogen Initiative, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) and EUREKA.

Finally, it can be remarked that the Commission also works with the IRENA, the World Energy Council or IEA, particularly the IEA Hydrogen Technology Collaboration Programme in energy related matters and specifically hydrogen.

The Parliament also shows interest in making Europe the model, the reference point in terms of hydrogen, stating that:

*The EU should promote its hydrogen standards and sustainability criteria internationally;* [the Parliament also] *calls […] for the development of international standards and the setting up of common definitions and methodologies for defining overall emissions from each unit of hydrogen produced, as well as international sustainability criteria as a prerequisite for […] imports.*

[Moreover,*] encourages the Commission to promote the role of the euro as the reference currency in the international trade of hydrogen.*

This position is reasonable, especially when aiming to become the global hydrogen leader. However, some sources such as the German Energy Agency (dena) and World Energy Council – Germany in their report Global Harmonisation of Hydrogen Certification [158] do not have such an optimistic impression. In this report the feasibility of implementing a uniform global certification system for renewable $H_2$ is analysed. Certain standards and criteria from different countries and organisations are studied and the conclusions express the complexity of reaching uniformity. Moreover, it is also noted that in that scenario of homogeneity of standards, the EU would have to give up some of its requirements regarding renewable hydrogen. This thought leads to the notion that within the current standardisation heterogeneity the strict (stricter, when compared with other countries) requisites may result in a loss of appeal for the EU hydrogen market, since companies would choose less rigid conditions in other markets.

### 4.1.9 The role of hydrogen in an integrated energy system

In this last section the subject is the discussion on how hydrogen fits in an integrated energy system.

First, the EU Parliament:

> *Underlines the need for an integrated energy system in order to achieve climate neutrality by 2050 […] and reach the goals of the Paris Agreement; welcomes in that regard the inclusion of hydrogen in the Commission's Strategy for Energy System Integration […] considers that more emphasis needs to be placed on innovative projects combining the production and recovery of electricity, hydrogen and heat.*

This EU Strategy for Energy System Integration was released by the Commission in July 2020 within the Green Deal and counts on the implementation of the Clean Energy Package that was analysed in a previous section.

An integrated energy system translates as the interconnection of different energy carriers and energy end uses with themselves and each other, as visually expressed by the Commission in the image shown as Figure 40. Therefore, electricity, heat and cold, and fuels can be linked to each other, industry, transport and buildings can also be linked to each other, and they can all join and be an integrated system. This can ease decarbonisation and optimise the energy system.

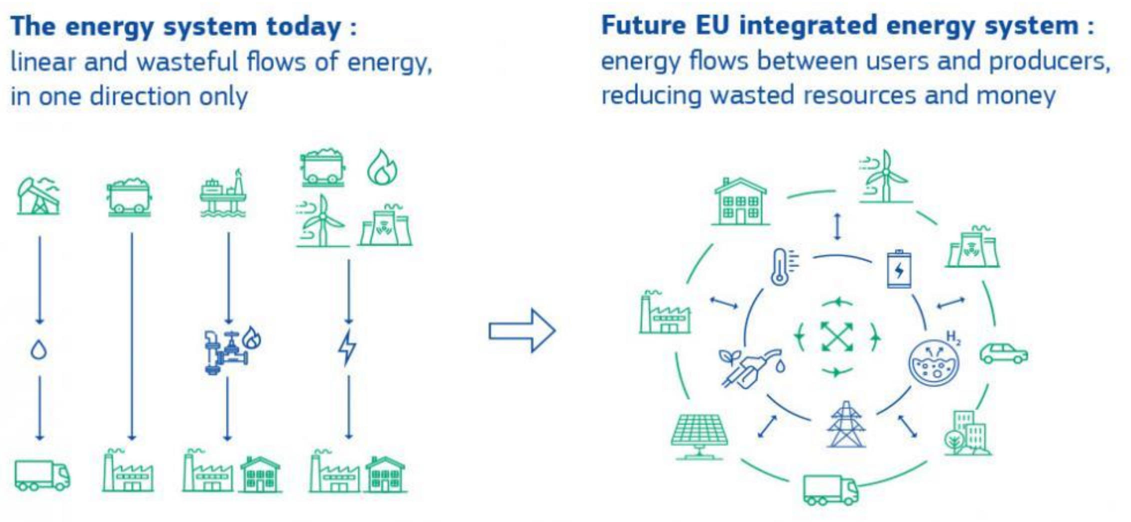



Figure 40. Visual representation of an integrated energy system [159]

In relation to hydrogen in the strategy, its capacity to store energy from renewable sources and its buffering ability are remarked, and so are its possible applications in heavy-duty road transport, rail transport, industrial processes and its use as synthetic fuel in maritime transport and aviation.

Finally, the Parliament:

*Notes that the development of the hydrogen economy can contribute to reducing imbalances in the energy system […]* [since] *hydrogen can play a key role in terms of storing energy to compensate for fluctuations in renewable energy supply and demand.*

*Highlights that an ambitious and timely strategy for energy storage through the use of hydrogen is required; notes, however, that the use of hydrogen for energy storage is not competitive yet.*

*Underlines […] the need to bring down costs for renewable hydrogen production […] therefore encourages the Commission to analyse options and capacities for hydrogen storage.*

The Commission is indeed taking an interest in analysing hydrogen storage, as proved by the report issued in February 2022 The role of renewable $H_2$ import & storage to scale up the EU deployment of renewable $H_2$ [161] by the Energy Transition Expertise Centre.

Some of the benefits of the deployment of hydrogen storage are recognised, such as:

- Security of supply, since having hydrogen stored allows for its use whenever needed.
- Enabling system flexibility; the $H_2$ storage can help maintain the stability of the network, can serve as a buffer in response to supply and demand variations, and can help to meet extreme or peak demands.
- Optimal development of infrastructure.

And for individual actors:

- For electrolyser operators, storage enables the decoupling of production and consumption times.
- For $H_2$ consumers, the stability provided by storage can prevent price fluctuations, and can also contribute to the deployment of end-uses affected by variations of demand.

Finally, although better detailed and explained in the correspondent document, the Figure 41 shows some of the barriers and measures to confront them that have been analysed in the report.

| BARRIERS FOR $H_2$ STORAGE DEVELOPMENT | MEASURES TO ADDRESS THESE BARRIERS |
|---|---|
| Hydrogen markets will develop slowly | Integrated planning of the hydrogen, gas and electricity systems |
| Energy sector planning may not consider storage characteristics | |
| The need for regulation of storage will vary across Member States and storage types | A clear, predictable regulatory framework for large-scale hydrogen storage |
| There is regulatory uncertainty concerning the conversion of currently regulated gas storages | |
| Market design and network tariffs may not reward the benefits of hydrogen storage | Development of hydrogen markets design and network tariff structures to value $H_2$ storage properly |

Figure 41. Barriers and measures regarding hydrogen storage [161]

From here on, the EU organisations and other involved actors need to carefully keep developing the hydrogen storage sector and market.

## 4.2 Precedents

Given the Commission's role of proposing and designing strategies, it is no surprise to learn that there already is a European strategy for hydrogen, particularly A hydrogen strategy for a climate-neutral Europe, developed by the Commission and issued in July 2020.

The documents considered are similar in theme, after all they are both European strategies for hydrogen. As seen in Figure 42, they have different structures but touch on many of the same topics.

One remarkable aspect is that in the first document the Commission is explaining certain circumstances regarding hydrogen and what they are doing or will about them. The Parliament's piece, however, is a constant appeal to the Commission and sometimes also to the Member States, calling on them to attend to several requests, as has been made evident in the previous section.

In terms of content, as mentioned before, there are clear similarities and that can be seen just by reading the section names; for example, the Commission's "Boosting demand and scaling up production" shares similarities with the Parliament's "Ramping up hydrogen production" and "Hydrogen demand", or so do the Commission's "The international dimension" and the Parliament's "International cooperation on hydrogen" amongst other sections.

Furthermore, the Parliament's strategy was released almost a year after the Commission's, and therefore the Parliament uses the latter as reference. That is why it is not rare to find the Parliament "welcoming" some of the Commission's proposals or ambitions.

Another instance is the direct reference to the Commission's hydrogen classification, which appears in its strategy, pointing out the double use of renewable and clean for the same category of hydrogen but welcoming it as a first step.


Figure 42. Schematic comparison of the two European hydrogen strategies [162] and [1]

Regarding the differences between the content of the strategies, it can be affirmed that the Commission's document is more thorough about the subjects it analyses and, even though it was issued previous to the Parliament's document, it covers some aspects that the former does not.

For instance, the Commission presents an investment agenda, giving estimations of the investments required for electrolysers (EUR 24-42 billion), renewable energy production (EUR 220-340 billion), retrofitting half of the CCS/U plants (EUR 11 billion), and HRS, transport, distribution and storage of $H_2$ (EUR 65 billion).

The Parliament does remark the importance of having an investment agenda but does not acknowledge the one just summarised.

Another aspect that the Parliament does not really acknowledge is the development of the hydrogen economy through phases the Commission defines. These phases express the renewable hydrogen electrolyser capacity for the coming years, as well as the development of infrastructure and applications.

Finally, it is interesting to list some of the documentation that was released in between the two strategies:

- European Parliament's resolution on a comprehensive European approach to energy storage [10 July 2020].
- European Parliament's resolution on the revision of the guidelines for trans-European energy infrastructure [10 July 2020].
- European Commission's communication "Stepping up Europe's 2030 climate ambition – Investing in a climate-neutral future for the benefit of our people" [17 September 2020].
- European Commission's report "2020 report on the State of the Energy Union pursuant to Regulation (EU) 2018/1999 on Governance of the Energy Union and Climate Action" [14 October 2020].
- European Commission's communication on an EU strategy to reduce methane emissions [14 October 2020].
- European Commission's Pact for Skills [10 November 2020].
- European Commission's communication on an EU strategy to harness the potential of offshore renewable energy [19 November 2020].
- UN Environment Programme's Emissions Gap Report 2020 [9 December 2020].
- European Commission's communication "Sustainable and Smart Mobility Strategy – putting European transport on track for the future" [9 December 2020].
- IRENA's report "Green hydrogen cost reduction – scaling up electrolysers to meet the 1.5°C climate goal" [December 2020].
- European Commission's adoption of the proposal to revise the regulation on trans-European networks in energy (TEN-E) [15 December 2020].
- European Commission's communication "Updating the 2020 New Industrial Strategy: Building a stronger Single Market for Europe's recovery" [5 May 2021].

Given all the reports, communications and resolutions issued from strategy to strategy, one can only imagine what changes will be implemented in the next hydrogen strategy type of document, especially after the scale up of the conflict with Russia, which has and will continue to affect the energy market and therefore the hydrogen economy development.

# 5 CHANGING THE SCOPE: INTERNATIONAL AND NATIONAL PROJECTS

So far most of the information presented has been linked to the European Union, which can be expected from a thesis focusing on the EU's strategy regarding hydrogen.

Nevertheless, it is always interesting to discover and analyse projects and hydrogen applications that are being developed in non-EU countries, as well as those being developed nationally in Spain.

## 5.1 International projects

Besides the European Union, there are other countries leading the way in the hydrogen sector. This can be seen just by looking at some of the column charts presented by the IEA such as those in Figures X1 and X2. Almost 70 MW of electrolysers were installed in 2020, and this can be seen in Figure 43: in 2019 the total capacity including all countries was about 225 MW and this number increases to almost 300 MW in 2020; however, looking at Europe it is noticeable that the increase in 2020 is less than 20 MW and, while it represents a 17% of the increase (40% of overall capacity), it shows that Europe is not the only actor to be taken into account in the sector.

In Figure 44 it can be seen that some of the regions that stand out in the FCEV sector (including fuel cell buses) are the US, Japan, China and South Korea. The latter country actually offered subsidies of even USD 30000 for the acquisition of FCEVs, which is the explanation behind its top position.

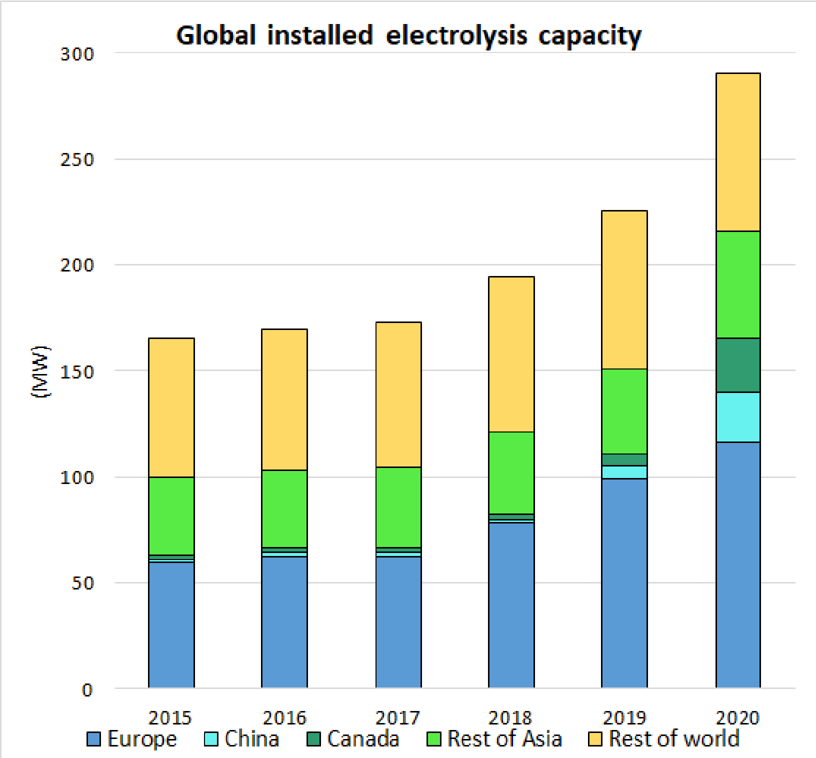



Figure 43. Global installed electrolysis capacity by region [37]

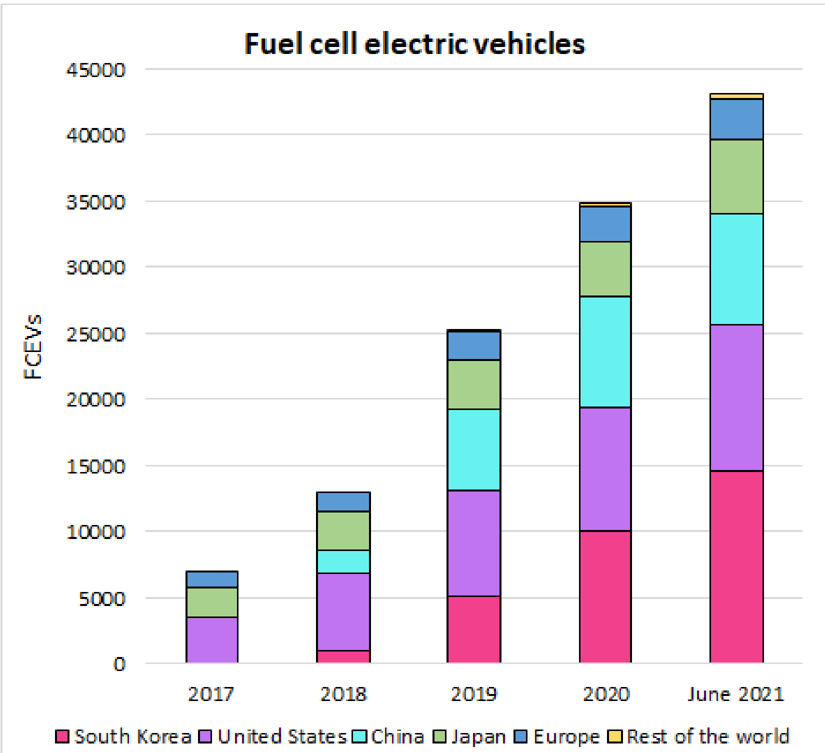



Figure 44. FCEVs stock by region [37]

A few international projects have been mentioned throughout the Final Degree Thesis such as Hydrogen Valleys or Global Ports Hydrogen, both including activities in the EU and other countries (Japan, China, US, Chile, Oman, Thailand, Australia, New Zealand).

The United States, for instance, has its particular hydrogen initiative, Hydrogen Shot, launched in June 2021; through it, the Department of Energy aims to reduce the cost of clean $H_2$ by 80% in 10 years. Some other projects also supported by the DOE include:

- [8]RH$_2$ Process for Producing Clean H2 with Autothermal Reforming and Carbon Capture.
- Investigation of Ammonia Combustion for Turbines.
- Advanced Mixed Mode Combustors for Hydrogen F-Class Retrofit.
- Demonstration of a Gas Turbine-Scale RDC Integrated with Compressor and Turbine Components at 7FA Cycle Conditions.
- Development of Hydrogen Burner for FT4000 Aeroderivative Engine.
- Low-NOx, Operable Ammonia Combustor Development for Zero-Carbon Power (LOAD-Z).

Another relevant country in the hydrogen sector, as seen in the previous figures, is China (People's Republic of China); just a few months ago, in March 2022 the country issued a 2021-2035 plan for $H_2$, explaining the phases to develop their hydrogen industry and decarbonise its economy.

The China Hydrogen Alliance has estimated a hydrogen demand of 35 million tons by 2030, and 60 by 2050; therefore, it is important for them to produce low-carbon and renewable hydrogen to mitigate their $CO_2$ emissions. Moreover, they expect to reach up to 200000 tons of renewable-based $H_2$ by 2025, and increase this number to 100 million tons by 2060.

Some of the projects developed in this country are:

- A steelmaking with hydrogen project of commercial scale in Hebei, by the steelmaking company HBIS Xuansteel.
- Hydrogen production through renewable energy sources projects by the company Sinopec: PV hydrogen production plant in Xinjiang and offshore wind power $H_2$ production plant in the Fujian Province.
- Sinopec is a Chinese oil company that is involved in many projects, including the two previously mentioned, and has also built 31 HRSs, appropriate given that China is the third country with the largest FCEV stock.
- A green hydrogen project with a 20 MW electrolyser to feed FCEVs at one of the Winter Olympic Games competition zones, the Zhangjiakou competition zone, commissioned by Zhangjiakou City Transport Construction Investment Holding Group and Shell China.
- Until a few months ago, the largest electrolyser in the world was a 30 MW electrolyser in China, operated by the company Baofeng Energy. This has changed since it was announced that this same company has been operating a 150 MW electrolyser since December 2021. This project, which is in the Ningxia region, is powered by a 200 MW PV plant that can be seen in Figure 45.
- This project will not be the world's largest for too long, since the previously mentioned Sinopec is building a 260 MW alkaline electrolysis plant in Xinjiang, where its PV and wind energy plants will be as well and will feed the facility.

Figure 45. PV plant to feed the 150 MW electrolysis facility by Baofeng Energy [169]

Finally, one last international project to remark is the NEOM project in Saudi Arabia; this USD 500 billion project aims to create the Neom smart city. Three main regions have been defined: Trojena, Oxagon and the line, the first being a mountain tourism destination, the second an innovation hub and home to clean industries, and the third, a no-carbon-emissions city.

What is interesting about this project is that it is expected to become a green hydrogen hub, combining it with desalination and renewable energy plants. The NEOM Green Hydrogen Company expects to be producing 650 tons of green $H_2$ per day, which will be accomplished thanks to over 2 GW of electrolysis provided by the company Thyssenkrupp and their 20 MW alkaline electrolysis modules.

As hydrogen technologies develop, the scale of the projects increases, and by the end of the decade there are projects planned to reach the giga-watt scale.

## 5.2 National projects

Spain has been mentioned a few times throughout this Final Degree Thesis, and it not rare given its potential in the hydrogen sector. It has quite the favourable location for renewable energy production and also land available, especially for solar but also for wind energy, although one issue that needs to be taken into account, particularly in southern Spain, is water scarcity.

Spain is also one of the Member States that has released a national hydrogen roadmap; that roadmap is aligned with the EU objectives, particularly with the Annual Sustainable Growth Strategy, the Green Deal and the Commission's Hydrogen Strategy.

The roadmap aims to remark the opportunities that the renewable hydrogen development presents for the country and be a reference point for said development.

It was issued in October 2020 and will be updated in three years; when the roadmap was released, hydrogen consumption in Spain was of about 500000 tonnes per year, which were used by the refining industry (70%), the chemical industry (25%), the steelmaking industry and some other minor uses. Most of it was produced by steam methane reforming.

In the roadmap, the Spanish government proposes 60 measures regarding a wide range of topics such as the hydrogen regulatory framework, the Guarantees of Origin, socioeconomical impact, Spain's role in the international $H_2$ market and green hydrogen research and innovation amongst other subjects.

However, probably one of the most interesting parts of the roadmap is the "Vision 2030 and 2050" section, in which the country's goals are explained, while taking into account the three time horizons and three phases defined by the Commission in its strategy.

The main characteristics of the roadmap for 2030 are:

- Install 4 GW of electrolysis capacity. By 2024 the installed capacity is expected to be about 300 and 600 MW.
- Renewable hydrogen is predicted to represent at least 25% of all the hydrogen consumed by industries.
- 150 to 200 fuel cell buses fed with renewable $H_2$ are planned to operate in the country, especially in bigger cities.
- 5000 to 7500 FCEVs (light and heavy duty) are expected to be used for transportation of goods.
- 100 to 150 HRSs of public access are predicted to be installed, with a maximum distance of 250 km between each one.
- Two commercial train lines, medium and long distance, in non-electrified tracks are expected to have trains powered by hydrogen.
- Handling machinery powered with fuel cells that consume green hydrogen is planned to be used, and supply sites are planned to be installed in the busiest ports and airports.
- The estimated investment for all aspects of green hydrogen developments is EUR 8900 million.
- The $CO_2$ emissions reduction by the end of the decade is estimated to be of 4.6 million tonnes of $CO_2$.

From 2030 on, renewable electricity capacity is expected to increase considerably, reducing electricity prices and enhancing renewable hydrogen's competitiveness. Renewable hydrogen consumption is predicted to grow and help decarbonise hard to abate sectors, since new hydrogen technologies will be developed.

In terms of projects in operation or under development in the country, a few have been mentioned throughout the Final Degree Thesis, and some also appear in the roadmap. These projects are:

- **HEAVEN** – This is a project aiming to develop a fuel cell based powertrain and cryogenic hydrogen storage for a 4 passenger aircraft and funded by the EU.
- **Basque Hydrogen Corridor** – A Project within the Hydrogen Valleys aiming to decarbonise sectors, covering the entire hydrogen value chain, therefore including $H_2$ production, storage, transport and uses in the industrial, residential and mobility sectors.
- **H2Ports** – This project aims to evaluate and demonstrate the use of Fuel Cells port equipment, and is co-founded by the European Union through FCH 2 JU.
- **SUN2HY** – Photoelectrochemical hydrogen production project (until 2020) by Enagás and Repsol, to make a demonstration of the technology.
- **SEAFUEL** – This project aimed to provide hydrogen as fuel for local transportation in Tenerife, producing it with an electrolyser fed by renewable energy sources and sea water.
- **HIGGS** – A project aiming to thoroughly analyse the gas infrastructure in Spain and the impact of injecting hydrogen, funded by FCH JU.

More projects are included in the roadmap and more are being developed; these projects entail topics such as: the production of renewable $H_2$ for industrial use, for steelmaking, for fertilisers production and for transport applications and the production of synthetic fuels with renewable hydrogen.

Finally, one of the most interesting projects in Spain in terms of renewable hydrogen is the Green Hysland project, which aims to develop a hydrogen ecosystem in Mallorca. It is included within the hydrogen valleys, and therefore covers the entire hydrogen value chain. The hydrogen hub created will be a blueprint for other islands to achieve decarbonisation; particularly, this model is to be replicated in the EU islands: Madeira, Tenerife, Ameland, the Greek islands, Aran, and also in islands in Morocco and Chile. The project is an answer to FCH JU Call for Proposals 2020, particularly to the proposal regarding the decarbonisation of islands through hydrogen, and was the recipient of a EUR 10 million grant from the EU. The project is also recognised under the name of Power to green hydrogen Mallorca, as Green Hysland is the EU initiative.

The consortium of this project is made up of 30 organisations that can be seen in Figure 46, including public organisations from the island and the cities and towns involved that are related to the end uses, Enagás, ACCIONA, Redexis (energy infrastructure, distribution networks), and Spanish hydrogen associations and research bodies.


Figure 46. Green Hysland logo (left) and consortium [175]

A schematic representation of the project can be seen in Figure 47.

Electricity will be produced by the two PV plants located in Lloseta and Petra, and they will feed the electrolyser located also in Lloseta, which will produce renewable hydrogen. Water required for the electrolysis will be taken from two wells in the site. It is estimated that about 300 tons of $H_2$ per year will be produced. To be more precise, the electrolysis capacity will be 7.5 MW, and the PV plants are of 8.5 MW (Lloseta) and 5.85 MW (Petra).

The distribution of that hydrogen will be by trucks as compressed gas (tube trailers), and there will also be a hydrogen pipeline to take it to the Cas Tresorer power station. In Cas Tresorer is the $H_2$ injection point into the gas grid, and $H_2$ will be injected first as $2\%_v$, eventually increasing to $4\%_v$.

One of the hydrogen end uses will be as fuel for a fuel cell based CHP system to supply power and heat to a municipal building in Lloseta. That same application will also be used in the Port of Palma for a ferry terminal and, also in Palma, for one or more hotels.

Finally, another location that will enjoy hydrogen applications is the bus station owned by the municipal company EMT; there, a HRS will be deployed so as to cover the demand of the mobility transport applications, which are a fleet of 5 fuel cell buses and a fleet of 10 rental FCEVs.

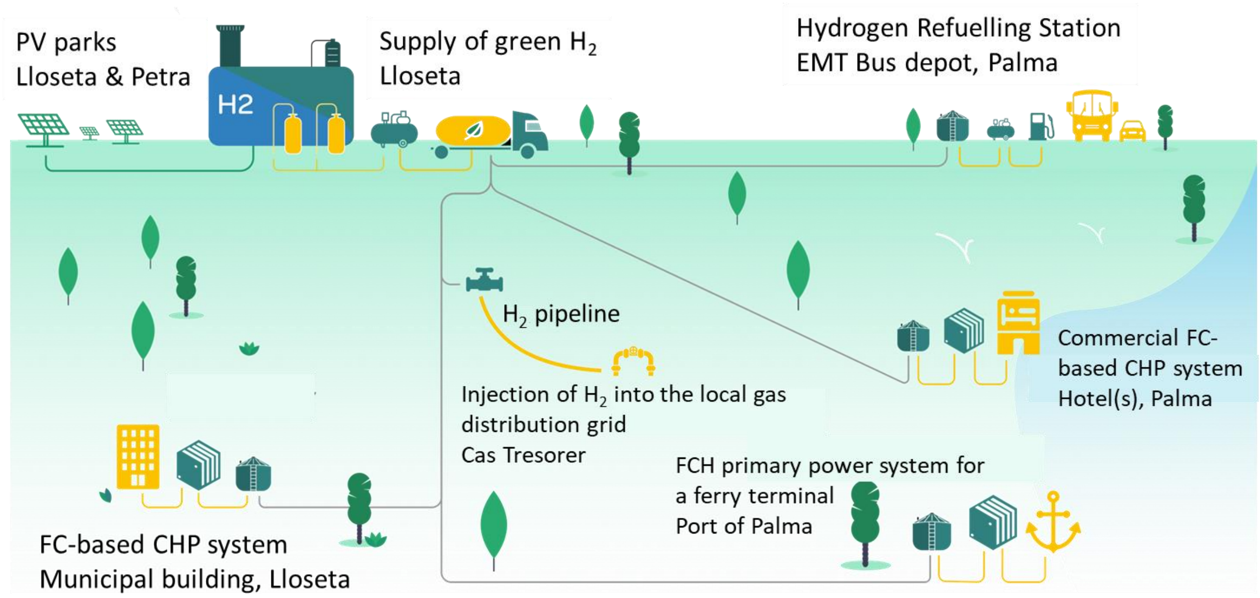



Figure 47. Schematic representation of the Green Hysland project sites [174]

The project officially started in January 2021, and in that year's summer construction of the PV plants started, and by December the electrolysis plant commenced its start-up tests. In February 2022 the municipal bus company of Palma chose the company Solaris Bus Iberica to supply the 5 fuel cell buses for the project.

In March 2022 the renewable hydrogen plant was inaugurated, and it will gradually produce hydrogen once the final applications are fully developed and deployed.

This large-scale project that covers the entire hydrogen value chain corroborates the potential of Spain in terms of renewable energy and renewable hydrogen projects, and how the country is collaborating to reach the objectives of decarbonisation set by the European Union.

# 6 CONCLUSIONS

This Final Degree Thesis has allowed for a general overview of the hydrogen sector, and particularly the European Union's position within it.

Concerning the Parliament's Hydrogen Strategy, it is appropriate to express its importance, since it is the document that gives the reader an understanding of how the EU intends to function in the hydrogen sector. Moreover, in the analysis elaborated, its effects can be recognised in terms of projects developed or policies adopted.

It is also remarkable that, in just a few pages the European Parliament manages to cover a wide range of topics, all of them significant to represent the entirety of the hydrogen sector. It touches on subjects such as $H_2$ demand, infrastructure, research, standards, etc., enabling a complete approach to the sector.

Another aspect that the Strategy mentions is the intention of the EU to be a leader in the hydrogen sector, and this purpose is corroborated by the large number of associations, strategies, plans and projects that are being established and developed by the European Union and have come up throughout this Final Degree Thesis.

It will be interesting to see how the EU updates its hydrogen strategy given the current context of energy prices inflation and the conflict with Russia.

Furthermore, the elaboration of this thesis has provided a complete perspective of the hydrogen sector, including technologies, projects, policies, organisations and more. Given the wide range of subjects discussed in the thesis it should not be surprising to learn that more than 150 information sources have been consulted, ranging from European laws and communications to the different projects' websites and the many hydrogen organisations' pages.

Finally, the most important conclusions to learn from this thesis are that hydrogen has many of the right characteristics to make it the key to decarbonisation, especially in hard-to-abate sectors, and that it is bound to be one of the main actors in the imminent green transition. Moreover, hydrogen seems to be having its breakthrough, particularly in Europe, and this field's development can have benefits not only from an environmental perspective but also from an economical one, enabling the European Union to lead the way into the green transition and the fight against climate change.

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Trabajo Fin de Grado

Grado en Ingeniería de la Energía

# Análisis de la estrategia europea para el hidrógeno

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# Resumen

Este trabajo de fin de grado persigue analizar las ambiciones de la Unión Europea dentro del sector del hidrógeno. Este objetivo se alcanza a través del análisis de la Estrategia Europea para el Hidrógeno presentada por el Parlamento Europeo, que además permite que el estudio abarque todos los campos del sector del hidrógeno.

El análisis es precedido por una contextualización del sector energético actual y por una descripción de las tecnologías del hidrógeno (para producción, transporte, almacenamiento, usos…), y también por una explicación de los planes y organizaciones más relevantes y que da forma al resto de leyes e iniciativas (Acuerdo de París, EU Green Deal…). Al análisis le sigue un resumen del desarrollo en materia de hidrógeno a nivel internacional y nacional (español), y finalmente las conclusiones obtenidas.

Cualquier documento que cumpla el papel de guía o estrategia para un determinado sector abarca inherentemente un amplio abanico de temas para reflejar el sector al completo, y este es el caso de la estrategia que se analiza. La Estrategia Europea para el Hidrógeno incluye temas como la demanda de hidrógeno, infraestructura, investigación e innovación, producción, políticas, etc. Este amplio rango de temas del documento estudiado implica un amplio rango de temas que explorar en este trabajo de fin de grado, lo cual ha resultado en la consulta de más de 150 fuentes de información para la elaboración del trabajo.

La Estrategia para el Hidrógeno es crucial para comprender el papel del hidrógeno en la UE y predecir su desarrollo en el futuro. Sin embargo, aunque fue publicada hace alrededor de un año, ya necesitaría una actualización para poder incluir los cambios del contexto energético que han tenido lugar en este corto periodo de tiempo (inflación en los precios de la energía, conflicto con Rusia…). Dada esta situación de falta de seguridad de suministro e inestabilidad, la necesidad de contar con un vector energético como el hidrógeno es más evidente que nunca.

Además, el hidrógeno puede ser clave en la transición verde y descarbonización de la UE, por lo que es muy importante continuar desarrollando las tecnologías del hidrógeno y cumplir esta estrategia.

***Palabras clave***: hidrógeno, hidrógeno renovable, Estrategia Europea para el Hidrógeno.

# 1 INTRODUCCIÓN Y OBJETIVOS

El objetivo principal de este Trabajo de Fin de Grado es analizar la posición y estrategia de la Unión Europea respecto al hidrógeno, que es ya que es vital para comprender el sector del hidrógeno y su evolución en el contexto de la transición verde. El motivo es que la UE es un participante muy importante en el sector, y las medidas que tome y los proyectos que desarrolle tienen una gran influencia en el avance del mercado del hidrógeno.

Este objetivo se alcanza consultando más de 150 fuentes de información, que se enumeran en la sección de Referencias.

Además, hay una breve explicación del estado del arte de las tecnologías del hidrógeno abarcando la cadena de valor (producción, almacenamiento, transporte y usos), de manera concisa, para dar al lector la información necesaria para seguir el análisis de la estrategia europea para el hidrógeno. También se repasan los distintos proyectos y estrategias desarrollados a nivel internacional y nacional (España).

En cualquier caso, como se ha comentado, el objetivo principal es estudiar cómo la UE se desenvuelve en el sector del hidrógeno a través del análisis de la Estrategia para el Hidrógeno del Parlamento Europeo.

Este trabajo de fin de grado se desarrolla en un contexto energético que tiene gran influencia en su contenido. Por tanto, es esencial considerar las circunstancias para comprender el papel del hidrógeno en ellas, por lo que el trabajo contiene en este apartado una breve contextualización del sector energético.

Además, se concluye comentando que la transición verde y la neutralidad climática no son solo la única manera de por lo menos mitigar los efectos del cambio climático, sino que también pueden ser una oportunidad para el desarrollo de tecnologías limpias y soluciones para la descarbonización que sean competitivas en el mercado y que constituyan la imagen de las tecnologías del futuro; en este contexto el hidrógeno tiene un papel crucial.

# 2 TECNOLOGÍAS DEL HIDRÓGENO

Es esencial analizar el estado del arte de las tecnologías del hidrógeno para interpretar la estrategia de la UE, por lo que en este apartado se explican de manera clara y concisa las tecnologías en los ámbitos de producción, almacenamiento, transporte, usos, etc.

El hidrógeno como elemento químico es el más abundante en el universo; para las aplicaciones de hidrógeno, este se requiere como gas diatómico $H_2$, pero este, a pesar de la abundancia del elemento, no se encuentra en la naturaleza como tal, pues se suele encontrar con otras sustancias (agua, hidrocarburos…). Por tanto, el $H_2$ tiene que ser producido con las tecnologías que se explican.

Su bajo peso molecular y baja densidad también son características relevantes, la última resultando ser un problema para el almacenamiento. Otra propiedad importante del $H_2$ es su alta densidad energética , siendo su poder calorífico inferior 120 MJ/kg $H_2$.

Es relevante destacar que hay importantes pérdidas de energía en las tecnologías del hidrógeno, y esta falta de eficiencia es un obstáculo que superar.

## 2.1. Producción de hidrógeno

### 2.1.1 Electrólisis

Es uno de los procesos de producción de hidrógeno más desarrollados y, aunque su uso no esté tan extendido, se espera que crezca ya que es la opción principal para la obtención de hidrógeno renovable.

La electrólisis consiste en una reacción para obtener hidrógeno usando electricidad para separar la molécula de agua, obteniéndose además oxígeno como producto. Los electrolizadores constan de un ándodo y un cátodo separados por un electrolito.

Existen diferentes tipos de electrolizadores, con diferentes electrolitos, funciones… Los electrolizadores más usados y desarrollados son el de membrana de intercambio de protones (PEM), el alcalino y el de óxidos solidos, aunque existen más en desarrollo.

La electricidad aportada al electrolizador puede venir de distintas fuentes, pero si estas son renovables se obtiene el hidrógeno renovable o verde.

### 2.1.2 Reformado

El proceso de reformado para obtener hidrógeno puede llevarse a cabo usando muchos combustibles como gas natural, carbón, biomasa, etc., aunque el más usado es el gas natural.

Existen más procedimientos pero la electrólisis y el reformado son los más representativos.

## 2.2. Almacenamiento de hidrógeno

El almacenamiento es una característica muy importante, crucial para dar flexibilidad al sistema energético y absorber las fluctuaciones de la generación renovable. Además, aporta seguridad de suministro y permite reducir la dependencia de los combustibles fósiles.

Existen varias tecnologías, las más representativas son: Como gas comprimido en tanques o cavidades naturales bajo tierra (cavernas), licuado, en compuestos orgánicos o como parte del amoniaco o en hidruros metálicos.

## 2.3. Transporte de hidrógeno

El transporte de hidrógeno es un aspecto crucial para el sector, pues el hidrógeno no siempre se produce en el lugar de consumo, aunque hasta hace poco este haya sido el caso en polos químicos o industriales, por lo que el transporte no se ha desarrollado tanto a gran escala.

Existen diferentes medios de transporte, que además llevan el hidrógeno en diferentes estados según se haya almacenado. Los más representativos son: el transporte por carretera (en camiones, licuado o comprimido), por hidroductos o en buques.

## 2.4. Usos del hidrógeno

En esta sección se explican los usos y aplicaciones del hidrógeno.

### 2.2.1 Usos del $H_2$ en la industria

El uso en industria es uno de los más consolidados.

Se puede usar en las refinerías, para producción de amoniaco, para la síntesis de metanol o para descarbonizar el proceso de producción de acero.

### 2.2.2 $H_2$ in the transport sector

According to the IEA, transport alone represented about 30% of the European Union's total GHG emissions in 2019, although this share has probably changed since COVID-19. It is therefore an important section to decarbonise.

Según la Agencia Internacional de la Energía, en 2019 el transporte supuso un 30% de las emisiones de gases de efecto invernadero en la UE, por lo que es un sector vital que descarbonizar.

Algunas de las aplicaciones son:

- Vehículos eléctricos con pila de combustible (ligeros, camiones, autobuses)
- Transporte marítimo
- Aviación
- Generación de energía
- Cogeneración con pila de combustible
- Inyección de hidrógeno en la red de gas natural

# 3 ORGANIZACIONES, INICIATIVAS Y PLANES EUROPEOS RESPECTO A LAS ENERGÍAS RENOVABLES Y EL HIDRÓGENO

A lo largo de este Trabajo de Fin de Grado aparecen multitud de organizaciones, planes, estrategias y demás, y en esta sección se recogen algunas.

Algunas de las más importantes, mencionadas en la Estrategia para el Hidrógeno y que son un marco de referencia para las demás son:

- **Acuerdo de París**
- **EU Green Deal**
- **REPOWEREU**
- **Objetivos para el Desarrollo Sostenible de Naciones Unidas**

Además se recogen el resto de organizaciones, planes, etc., la mayoría habiéndose establecido en los últimos años, confirmando el momento de auge que vive el sector del hidrógeno, de las energías renovables y en general de la sostenibilidad.

# 4 A EUROPEAN STRATEGY FOR HYDROGEN

Esta sección es el núcleo del trabajo, ya que consiste en el análisis del documento del Parlamento Europeo publicado el 19 de Mayo de 2021 "Una Estrategia Europea para el Hidrógeno". El documento muestra la posición del Parlamento respecto al hidrógeno, incluyendo sus objetivos y ambiciones, y consta de las siguientes secciones:

- Documentos, comunicados, Directivas y en general todos los documentos que se han consultado previos a la elaboración de la estrategia.
- Objetivos y situación del hidrógeno.
- Las declaraciones que expone el Parlamento Europeo.

En esta sección se realiza en primer lugar una explicación de los distintos organismos de la Unión Europea (Parlamento Europeo, Comisión Europea, Consejo Europeo, Estados Miembros), ya que aparecen reiteradamente en el texto.

Además, tras el análisis, se compara esta estrategia con la presentada por la Comisión Europea un año antes, analizando sus similitudes y diferencias y teniendo en cuenta que en varias ocasiones a lo largo de la estrategia del Parlamento Europeo se menciona la estrategia de la Comisión Europea, analizándose también qué documentos se publicaron entre ambas estrategias.

Las declaraciones se van analizando consultando los extractos de texto y desarrollando sobre los mismos. Están divididas temáticamente, y en cada apartado se tratan los siguientes temas:

- **General**: Se tratan la Estrategia Industrial de la UE, el liderazgo industrial de la UE, el concepto de Valles de Hidrógeno.
- **Clasificación y estándares del hidrógeno**: Las distintas clasificaciones del hidrógeno, la certificación, estandarización y certificación de origen.
- **Aumento de la producción de hidrógeno:** Marcos regulatorios para el hidrógeno, el uso de tecnologías del hidrógeno en islas, el aumento de capacidad de electrólisis, el aumento de generación renovable, particularmente eólica offshore, sistema de impuestos, recursos utilizados en la producción de hidrógeno.
- **Compromiso con la ciudadanía:** Comunidades de energía renovable, cultura de la seguridad respecto al hidrógeno.
- **Infraestructura para el hidrógeno:** Aumento y aprovechamiento de la infraestructura, marco legal referente a la infraestructura, reacondicionamiento y reutilización de infraestructura de gas, puertos.
- **Demanda de hidrógeno:** Competitividad del uso de hidrógeno y mecanismos para incentivar consumo, uso de hidrógeno en el sector del acero y ejemplos de proyectos, papel del hidrógeno en el sector del transporte.
- **Investigación, desarrollo, innovación y financiación:** importancia de investigación, desarrollo e innovación, instrumentos de financiación, Fuel Cells and Hydrogen Joint Undertaking.

- **Cooperación internacional para el hidrógeno:** liderazgo de la UE, asociaciones internacionales, uso de los estándares europeos para el hidrógeno.
- **El papel del hidrógeno en un sistema energético integrado:** Estrategia de la UE para la integración del sistema energético, beneficios del hidrógeno en este ámbito.

# 5 PROYECTOS A NIVEL INTERNACIONAL Y NACIONAL

En esta sección se cambia el ámbito de análisis, pasando de la Unión Europea a un marco internacional y de Esapaña.

## 5.1 Proyectos internacionales

Además de la Unión Europea, hay más países apostando por el sector del hidrógeno. Por ejemplo, China, Canadá y algunos países asiáticos están aumentando su capacidad de electrólisis.

Otro ejemplo puede ser el uso de vehículos eléctricos con pila de combustible, ámbito en el que la UE se ve adelantada por Estados Unidos, Japón, China y Corea del Sur.

A lo largo del Trabajo de Fin de Grado se mencionan varios proyectos internacionales como los Valles de Hidrógeno, que abarcan países como Japón, China, Estados Unidos, Chile, Omán, Tailandia, Australia y Nueva Zelanda.

Se comentan iniciativas y proyectos de Estados Unidos en el sector del hidrógeno.

También se analiza brevemente la situación de China, que en marzo presentó un plan para el hidrógeno; en este país se espera una demanda de 35 millones de toneladas de hidrógeno en 2030, por lo que poder producir hidrógeno con bajas o cero emisiones de gases de efecto invernadero es fundamental.

Se comentan posteriormente algunos de los proyectos en este país, incluyendo el uso de hidrógeno en la industria del acero, la creación de estaciones de repostaje de hidrógeno, plantas con generación renovable y electrólisis, etc.

Destacan una planta con 150 MW de electrólisis, la mayor del mundo hasta que fue anunciado que también en China se está desarrollando una planta de 260 MW de electrólisis.

Finalmente se destaca un proyecto en Arabia Saudí, el proyecto NEOM, que consiste en la creación de 3 áreas: una zona de montaña, una Smart city y una zona de desarrollo industrial e investigación, todo ello con el objetivo de la descarbonización en mente. Este proyecto pretende acoger una capacidad de electrólisis de 2 GW, combinándolo además con desalación de agua.

## 5.2 Proyectos nacionales

España ha aparecido varias veces a lo largo del Trabajo de Fin de Grado, lo cual no es de extrañar ya que el país tiene un gran potencial en este sector. Es destacable su localización favorable para la producción de energía renovable y espacio disponible, especialmente para producción solar y eólica.

Además, el gobierno español ha publicado una hoja de ruta para el hidrógeno, alineada con los objetivos de la Unión Europea. Se publicó en 2020 y sus características con visión para 2030 más representativas son: Instalar

4 GW de capacidad de electrólisis, implementar de 150 a 200 autobuses de pila de combustible, de 5000 a 7500 vehículos de pila de combustible y de 100 a 150 hidrogeneras.

Otros proyectos mencionados son:

- HEAVEN
- Basque Hydrogen Corridor
- H2Ports
- SUN2HY
- SEAFUEL
- HIGGS

Finalmente se habla con más profundidad del proyecto Green Hysland desarrollado en Mallorca y que pretende convertir a la isla en un proyecto de referencia para otras islas en el desarrollo de la cadena de valor completa del hidrógeno en islas.

Todos los proyectos en los que participa el país así como su hoja de ruta convierten a España en uno de los países que colaboran en alcanzar los objetivos de descarbonización y desarrollo del sector del hidrógeno de la Unión Europea.

# 6 CONCLUSIONES

Este Trabajo de Fin de Grado ha aportado una visión general del sector del hidrógeno y particularmente de la posición de la UE en el mismo.

Respecto a la Estrategia para el Hidrógeno del Parlamento Europeo, es apropiado expresar su importancia ya que es un documento que permite al lector comprender cómo quiere actuar la UE en el sector del hidrógeno. Además, en el análisis realizado, sus efectos se pueden apreciar en forma de proyectos desarrollados o políticas adoptadas.

También es destacable como en pocas páginas el Parlamento Europeo consigue abarcar un gran rango de temas, todos ellos importantes para dar una visión completa del sector. Trata temas como la demanda de hidrógeno, infraestructura, investigación, estándares, etc.

Otro aspecto que menciona la Estrategia es la intención de la UE de ser líder en el sector, y este propósito se corrobora con la gran cantidad de asociaciones, estrategias, planes y proyectos que se establecen y desarrollan por parte de la UE y que han aparecido a la largo de este Trabajo de Fin de Grado.

También será interesante ver como la UE actualiza su estrategia para el hidrógeno dada la situación actual, con la inflación de los precios de la energía y el conflicto con Rusia.

Además, la elaboración de este trabajo ha permitido obtener una perspectiva completa del sector del hidrógeno, incluyendo tecnologías, proyectos, políticas, asociaciones y demás. Dado el amplio rango de temas comentados en el trabajo, no resulta extraño que se hayan consultado más de 150 fuentes de información, incluyendo leyes y comunicaciones de la UE o las páginas web de los diferentes proyectos y organizaciones.

Finalmente, las conclusiones más importantes con las que quedarse son que el hidrógeno cumple con muchas de las características necesarias para convertirlo en la clave de la descarbonización, especialmente en los sectores difíciles de descarbonizar, y que se espera que sea uno de los participantes principales en la inminente transición verde. Además, el hidrógeno parece estar teniendo un nuevo momento de auge, especialmente en Europa, y el desarrollo de este campo no solo es beneficioso desde un punto de vista medioambiental, sino también desde un punto de vista económico, pudiendo convertir a la Unión Europea ser la guía en el camino de la transición verde y la lucha contra el cambio climático.