THESIS WORK FOR DUAL MASTER'S DEGREE

ITBA Mag. in Energy and Environment

KIT M.Sc. in Mechanical Engineering

An Economic Evaluation on Hydrogen Production Technologies and Hydrogen Applications

Javier F. Allende
Maritime Engineer
Instituto Tecnológico de Buenos Aires

Tutor
Dr. rer. nat. Dipl.-Ing. A.F. Badea KIT/IATF

Examiners
Prof. Dr.-Ing. Xu Cheng KIT/IATF
Prof. Dr.-Ing. Robert Stieglitz KIT/ ITES

Karlsruhe
02/04/2023

Institut für Angewandte Thermofluidik
Bereich Innovative Reaktorsysteme
Vincenz-Prießnitz-Str. 3
76131 Karlsruhe
http://www.iatf.kit.edu

Karlsruher Institut für Technologie

Erklärung

Master Thesis

von

Herrn Javier F. Allende

Matr.-Nr.: 2452559

An economic evaluation on hydrogen production technologies and hydrogen applications

Die Masterarbeit ist im engen Kontakt mit dem Institut auszuarbeiten und bleibt dessen Eigentum. Eine Einsichtnahme Dritter darf nur nach Rücksprache mit dem Institut erfolgen.

Ausgabetag: 03. Oktober 2022 Abgabetag: 02. Apr 2023

Betreuer:

____

Prof. Dr.-Ing. Xu Cheng

Bearbeiter:

____

Javier Allende

Karlsruher Institut für Technologie

Institute for Applied Thermofluidics
Innovative reactor systems division
Vincenz - Prießnitz -Str. 3
76131 Karlsruhe
http://www.iatf.kit.edu

Eidesstattliche Erklärung

Ich versichere hiermit, dass die vorliegende Bachelor-/ Masterarbeit selbstständig verfasst und keine weiteren als die angegebenen Hilfsmittel benutzt sowie die Stellen der Arbeit, die in anderen Werken dem Wortlaut oder dem Sinn nach entnommen sind, durch Angaben der Quellen sichtbar gemacht wurden.

Karlsruhe, den 02. April 2023

Javier Allende

Karlsruher Institut für Technologie

Institute for Applied Thermofluidics
Innovative reactor systems division
Vincenz - Prießnitz -Str. 3
76131 Karlsruhe
http://www.iatf.kit.edu

Requirements

for

Mr Javier F. Allende

Matriculation no.: 2452559

An economic evaluation on hydrogen production technologies and hydrogen applications

Task description: The use of hydrogen on large scale may be one of the ways to realize a future carbon neutral and carbon-free energy society, gaining nowadays in momentum, backed strongly by government financial support and regulations. The conversion of electricity into hydrogen is a process of storage and valorisation of excess electricity (as this is many times the case for renewables). In the next two decades the cost of renewable hydrogen is expected to successively break even those of low-carbon and grey hydrogen. The hydrogen may become in the mid-term future the most competitive low-carbon solution for many end applications, including commercial vehicles, trains, aviation and shipping. One should remind here also the paramount importance of hydrogen use in P2G and P2X technologies, and refinery, fertilizer and steel productions.

Tasks of the thesis:

- Literature review
- Explore the hydrogen supply sources and the hydrogen applications.
- Economic evaluations
- Conclusions and recommendations

Abstract

The main objective of the study is to present a comprehensive and, above all, updated overview of the hydrogen demand and supply situation. The physical and chemical properties of hydrogen are presented, together with an explanation of its major advantages and disadvantages as an energy carrier compared to other fuels currently in use. It also explains the importance of hydrogen on the world stage, as one of the main vectors for sustainable economic development worldwide.

There are numerous uses for hydrogen nowadays. It can be used, for example, as a feedstock in several industrial processes, as an energy carrier or reserve, and as one of the main fuels to decarbonise transport. This work explains the current situation of hydrogen demand, showing the most relevant applications at present and those that are emerging as highly probable alternatives in the short term. Furthermore, estimates of future hydrogen demand are also presented.

Regarding hydrogen production methods, firstly, a technical analysis is presented, explaining the characteristics of the different production methods available at present. Subsequently, an analysis of production costs is carried out, taking into account the main alternatives. A sensitivity analysis is also carried out on these alternatives to appreciate with clarity which are the factors that have the greatest impact on the final cost of hydrogen production for each method.

One of the most notable conclusions of the report is the fact that, at current fossil fuel prices and associated emissions costs, zero- or low-emission hydrogen production methods are cost-competitive against hydrogen produced from natural gas (the most widely used technology today). It is also highlighted how the global context of recent years has led to an accelerated development of hydrogen technologies and their deployment.

Kurzfassung

Hauptziel der Studie ist es, einen umfassenden und vor allem aktuellen Überblick über die Situation der Wasserstoffnachfrage und -versorgung zu geben. Es werden die physikalischen und chemischen Eigenschaften von Wasserstoff dargestellt und seine wichtigsten Vor- und Nachteile als Energieträger im Vergleich zu anderen derzeit verwendeten Brennstoffen erläutert. Außerdem wird die Bedeutung von Wasserstoff auf der Weltbühne als einer der wichtigsten Faktoren für eine nachhaltige wirtschaftliche Entwicklung weltweit erläutert.

Die Einsatzmöglichkeiten von Wasserstoff reichen von der Verwendung als Rohstoff in zahlreichen industriellen Prozessen über die Verwendung als Energieträger oder -reserve bis hin zu einem der wichtigsten Kraftstoffe für die Dekarbonisierung des Verkehrs. In dieser Arbeit wird die derzeitige Situation der Wasserstoffnachfrage erläutert und es werden die derzeit wichtigsten Anwendungen sowie diejenigen aufgezeigt, die sich kurzfristig als sehr wahrscheinliche Alternativen abzeichnen. Darüber hinaus werden auch Schätzungen des künftigen Wasserstoffbedarfs vorgestellt.

Was die Methoden der Wasserstofferzeugung betrifft, so wird zunächst eine technische Analyse vorgelegt, in der die Merkmale der verschiedenen derzeit verfügbaren Produktionsmethoden erläutert werden. Anschließend wird eine Analyse der Produktionskosten durchgeführt, wobei die wichtigsten Alternativen berücksichtigt werden. Für diese Alternativen wird auch eine Sensitivitätsanalyse durchgeführt, um klar zu erkennen, welche Faktoren den größten Einfluss auf die endgültigen Kosten der Wasserstoffproduktion für jede Methode haben.

Eine der bemerkenswertesten Schlussfolgerungen des Berichts ist die Tatsache, dass bei den derzeitigen Preisen für fossile Brennstoffe und den damit verbundenen Emissionskosten emissionsfreier oder emissionsarmer Wasserstoff gegenüber aus Erdgas hergestelltem Wasserstoff (der heute am weitesten verbreiteten Technologie) kostenmäßig wettbewerbsfähig ist. Es wird auch hervorgehoben, dass der globale Kontext der letzten Jahre zu einer beschleunigten Entwicklung von Wasserstofftechnologien und deren Einsatz geführt hat.

Resumen

El principal objetivo del trabajo es presentar un panorama completo y, sobre todo, actualizado de la situación de la demanda y oferta de hidrógeno. Se presentan las cualidades físicas y químicas del hidrógeno, junto con una explicación de sus mayores ventajas y desventajas como portador de energía, en comparación con otros combustibles utilizados actualmente. También se explica la importancia del hidrógeno en el escenario mundial, como uno de los vectores principales para lograr un desarrollo económico sustentable a nivel mundial.

Los usos del hidrógeno van desde materia prima en muchos procesos industriales, como portador o reserva de energía y como uno de los principales combustibles para descarbonizar el transporte. En este trabajo se explica la situación actual de la demanda de hidrógeno, mostrando las aplicaciones de mayor relevancia en la actualidad, y aquellas que se perfilan como alternativas ampliamente probables en el corto plazo. También se presentan estimaciones de la demanda de hidrógeno a futuro.

En cuanto a los métodos de producción de hidrógeno, en primer lugar, se presenta un análisis técnico, explicando las características de los distintos métodos de producción desarrollados hoy en día. Posteriormente se realiza un análisis de costos de producción teniendo en cuenta las principales alternativas. También se realiza sobre estas un análisis de sensibilidad para apreciar con claridad cuáles son los factores que mayor impactan en el costo final de la producción de hidrógeno para cada método.

Una de las conclusiones más notables del trabajo es el hallazgo de que, con los precios actuales de combustibles fósiles y los costos asociados a las emisiones, el hidrógeno de nulas o bajas emisiones tiene un costo competitivo frente al hidrógeno producido a partir de gas natural (la tecnología más utilizada en la actualidad). También se destaca como el contexto mundial de los últimos años ha conllevado a un acelerado desarrollo de las tecnologías de hidrógeno y su implementación.

Contents

Nomenclature

Symbol	Description
^{1}H	Protium
^{2}H or D	Deuterium
^{3}H or T	Tritium
AEL	Alkaline Electrolysis
AEM or AEM-EL	Anion Exchange Membrane electrolysis
BECCS	Bioenergy with Carbon Capture and Storage
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCSU	Carbon Capture, Storage and/or Utilization
CNG	Compressed Natural Gas
COP	Conference of the Parties
DAC	Direct Air Capture
DRI	Direct Reduction of Iron
Energy carrier	A transporter of primary energy to potential consumption points
FCEV	Fuel Cell Electric Vehicles
GHG	Greenhouse Gas
H_2	Hydrogen
H_2O	Water
HHV	High heating value
H-TCP	Hydrogen Technology Collaboration Program
IEA	International Energy Agency
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IRENA	International Renewable Energy Agency
LCOE	Levelized cost of Energy
LCOH	Levelized cost of hydrogen
LHV	Lower heating value
LNG	Liquified Natural Gas
NO_x	Nitrogen Oxides
O_2	Oxygen
O-H_2	Ortho-hydrogen
OPEX	Operational Expenditure

PEM	Proton Exchange Membrane fuel cell
PEM or PEM-EL	Proton Exchange Membrane electrolysis
P-H_2	Para-hydrogen
PSA	Pressure Swing Adsorption process
RES-E	Clean energies
RSOC	Reversibly Solid Oxide Cell
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyser Cell
SOFC	Solid Oxide Fuel Cell
UNFCCC	United Nations Framework Convention on Climate Change
WGS	Water-Gas Shift process

1.Introduction

The purpose of this work is to summarize the actual and short-term situation of the hydrogen industry by conducting a techno-economic analysis of its different ways of production. The report also presents an analysis of the current uses of this gas, the spectrum of new possibilities that new technologies offer, the strong relationship between this industry and countries' energy security and independence, and the relationship between this industry and environmental protection. This first chapter presents the current status of the hydrogen industry, the general physicochemical characteristics of hydrogen, and an explanation of why this substance is gaining importance nowadays.

1.1 Hydrogen Characteristics

Brief History

Henry Cavendish, an English chemist and physicist, discovered hydrogen in 1766 while performing an experiment involving mercury and sulfuric acid. He noticed tiny gas bubbles when the two came into contact. The gas was not recognized as one of the already known gases. Although he presumed that this gas was a component of mercury, he was able to correctly define its characteristics.

Separately, the same gas was discovered in 1787 by French chemist Antoine Lavoisier, who sought to demonstrate the universality of mass conservation in experimentation. He was able to demonstrate that no mass was lost after catching the non-condensed gas. He put the resulting gas through tests and showed that it was flammable. He gave the product the name hydro-gene because it was water (from the Greek words for water and generating, respectively). Only a few months after the English chemist William Nicholson had succeeded in electrolyzing water to produce hydrogen and oxygen, Johann Ritter improved on Carlisle and Nicholson's experiments in 1800. Ritter carried out the experiment again, but this time he set up the electrodes so he could collect the two gases separately.

In 1839, Sir William Grove showed how the opposite process (feeding electrodes with hydrogen and oxygen) could produce not only water but also an electrical voltage and current. He used sulfuric acid as electrolyte and platinum electrodes.

After Werner von Siemens discovered the dynamo electrical principle in 1866, the entire evolution of galvanic cells —including fuel cells— lost significance and alternating current power technologies long dominated direct current ones.

General Characteristics

Hydrogen (H) is the simplest chemical element of the periodic table, which, under standard conditions of pressure and temperature, combines to form a diatomic molecule (H_2). This results in a colourless, odourless, tasteless and combustible gaseous substance. The nucleus of the hydrogen atom is composed of a proton with one unit of positive electrical charge and an electron with one unit of negative electrical charge. Figure 1 shows the element data presented in the periodic table. Since the name hydrogen is derived from Greek words that indicate "creator of water," this is the first important chemical feature of hydrogen that is now recognized: H_2O.

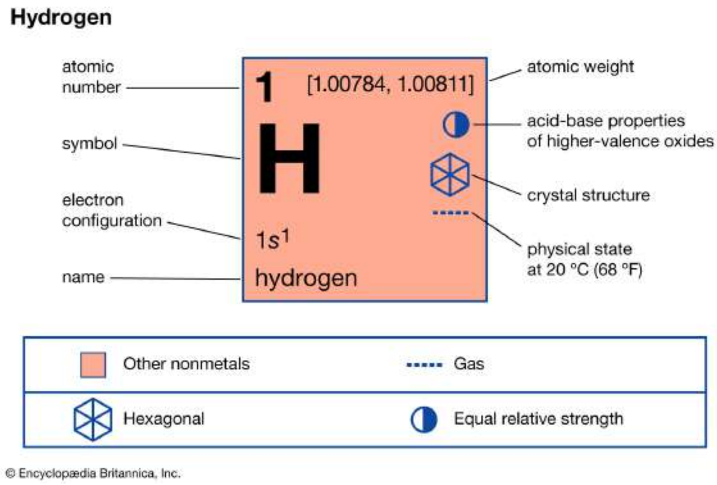

Figure 1 - Chemical Properties of Hydrogen (Source: Encyclopaedia Britannica, 2022).

Despite being the most common element in the universe and being three times as abundant as helium, the next most frequent element, hydrogen only represents about 0.14 percent of the weight of the Earth's crust. However, it is present in enormous amounts as a component of the water in oceans, icebergs, rivers, lakes, and the atmosphere. Hydrogen is a component of many carbon compounds and is found in all animal and plant tissues, as well as in hydrocarbons. Although it is sometimes stated that carbon has more known compounds than any other element, it is actually possible that hydrogen compounds are more numerous due to the fact that hydrogen is a component of nearly all carbon compounds and creates a wide variety of compounds with all other elements, except some of the noble gases. It is estimated to represent approximately 75% of all matter in the universe.

There are three known isotopes of hydrogen, with mass numbers of 1, 2, and 3. The most prevalent is protium (H or ^{1}H) with mass number 1 (only one proton and without any neutrons). Deuterium, also known as heavy hydrogen (symbol D or ^{2}H), is an isotope of mass 2 with a nucleus composed of one proton and one neutron. It constitutes 0.0156 percent of the common mixture of hydrogen. With one proton and two neutrons in each nucleus, tritium (symbol T or ^{3}H) is the mass 3 isotope and makes up less than 10^{-15} percent of all hydrogen. The fact that hydrogen isotopes have notable differences in their properties and applications is the reason why the scientific community has given them specific names.

Physical Properties

Hydrogen is the lightest element in nature. For this reason, hydrogen molecules can diffuse through many materials that are considered airtight or impermeable to other gases. However, in the event of a leak, hydrogen is rapidly dispersed into the atmosphere.

The boiling and melting points of hydrogen are, after helium, the second-lowest of all naturally occurring substances. The phase diagram of hydrogen in the Figure 2 shows that, at atmospheric pressure, hydrogen is liquid at temperatures below 20 K (-251.15 °C) and solid at temperatures below 14 K (-259.15 °C). At temperatures below 1 K, hydrogen has a face-centred cubic crystal structure, and above 5 K, it has a compact hexagonal structure. The triple point is at 0.0695 atm and 13.8 K. The boiling point varies with pressure and temperature, with hydrogen reaching the supercritical state above 13.8 atm and 33.2 K.

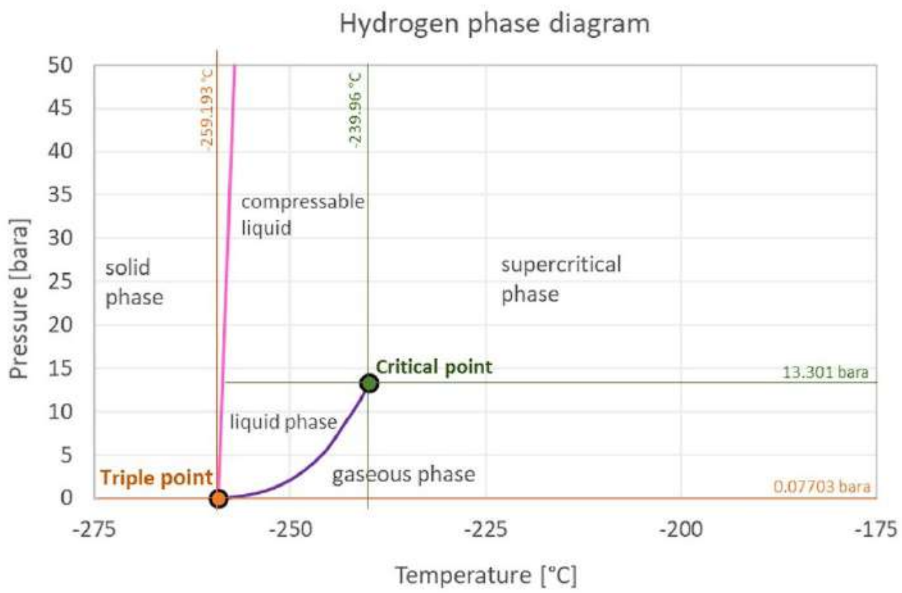

Figure 2 - Hydrogen Phase Diagram (Source: Engineering Toolbox, 2019).

Liquid substances generally take up less space than gaseous substances, so they are usually easier to transport and handle. For this reason, the boiling temperature of a substance is a critical parameter, as it determines the temperature to which it must be cooled to atmospheric pressure in order to be used in the liquid state. The boiling temperature of a pure substance increases with pressure until it reaches its critical point, above which an increase in pressure has no effect on the boiling temperature. The boiling temperature of hydrogen can only be increased to a maximum of -240 °C at a pressure of about 13 bar, which corresponds to its critical point. Due to the extremely low boiling temperature of hydrogen, obtaining liquid hydrogen is an extremely complex and energy-intensive process. Moreover, once in liquid form, hydrogen is highly volatile and evaporates quickly, so the container tanks must be perfectly insulated to avoid losses.

The volume occupied by hydrogen gas decreases with increasing pressure. It is clear that by pressurising the hydrogen gas, its volume can be substantially reduced, which can be useful for storage. In fact, the storage of pressurised hydrogen gas is the most common, even though the energy required for compression is considerable. It is observed that above 800 bar, an increase in pressure hardly affects the volume occupied by the hydrogen gas, so this value is not usually exceeded for storage or transport.

Molecular hydrogen comes in two configurations, depending on the direction of proton rotation. If the proton spin direction of both hydrogen atoms is the same, then it is called ortho-hydrogen (O-H_2). Otherwise, if both hydrogen atoms have opposite directions of rotation, then the molecule is called para-hydrogen (P-H_2). Figure 3 shows the proportions of each configuration for different temperatures.

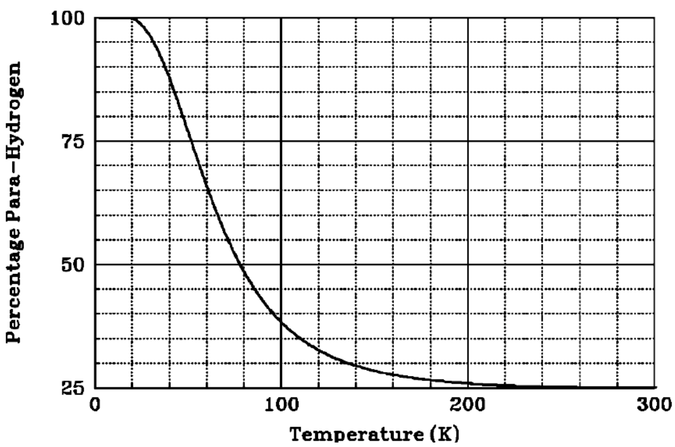

Figure 3 - Equilibrium para-hydrogen proportion (Source: Hydrogen Safety, 2003).

At room temperature (generally close to 300K) and above, molecular hydrogen is composed of approximately 25% para-hydrogen and 75% ortho-hydrogen. This is the equilibrium composition at room temperature and is called normal hydrogen. In liquid hydrogen, all hydrogen is in the form of para-hydrogen, which means that all ortho-hydrogen must be converted to para-hydrogen. When hydrogen gas (75% $O\text{-}H_2$) liquefies, the spin of each molecule does not change rapidly, and since $P\text{-}H_2$ has lower energy than $O\text{-}H_2$, this gradual change is exothermic, releasing energy (heat). This detail is important because when storing liquid hydrogen, this release of energy in the form of heat must be taken into account and compensated, to prevent the liquid from evaporating and dangerously increasing the pressure in the container.

Chemical Properties

On the Pauling scale, hydrogen has an electro negativity of 2.2. It reacts with all elements of the first group (alkaline), second group (alkaline earth), sixteenth group (chalcogen) and seventeenth group (halogenic elements). The alkaline earth elements cause a reaction that produces hydrides salts.

When hydrogen reacts with oxygen, a fixed amount of energy is released, and water is formed. This released energy is quantified as the high heating value (HHV) or the lower heating value (LHV). Both measures denote the amount of energy contained per unit mass of hydrogen. The difference between the HHV and LHV lies in the heat of vaporisation of water, so that in the HHV the formed water vapour is considered to condense. However, because the water produced in a combustion process or in an electrochemical reaction is in the form of vapour, the LHV represents the amount of energy available to do external work.

$$H_2 + 1/2\ O_2 \rightarrow H_20 \qquad H=286\ kJ/mol$$

The latent heat (approximately 44 kJ/mol) of the reaction is reduced if there is gaseous water on the right side. This explains how hydrogen serves as an energy carrier, as does the opposite reaction, or water splitting. It also reacts in air rather than just pure oxygen. In its stoichiometric combination with air, it contains 29.6%vol H2. There, it only needs a small amount of energy for ignition (10% less typically than for other burning gases), and it is inflammable in the range of 4% to 76% vol in air (the reaction is very slow in the absence of ignition or a catalyst).

The flammability limits must be considered to have little application in real-world scenarios. They are calculated under idealized laboratory circumstances with the gases at room temperature. The practical flammability range is typically much narrower. Ammonia, an important fertiliser precursor, is created with nitrogen when subjected to high temperatures and pressures. It is used for the synthesis of organic gases or liquid fuels in conjunction with carbon or carbon dioxide.

Energy Carrier

Due to the limited natural availability of H_2, it is not an energy source. However, hydrogen is considered an energy carrier (a transporter of primary energy to potential consumption points). Therefore, the quantity and quality of the energy contained in hydrogen is closely linked to that of the fuel or electricity used to obtain it.

Hydrogen has a high energy content by weight but not by volume. Liquids generally take up to 1,000 times less space than uncompressed gases. Figure 4 and Figure 5 present a comparison between different energy carriers' mass energy density and volume energy density.

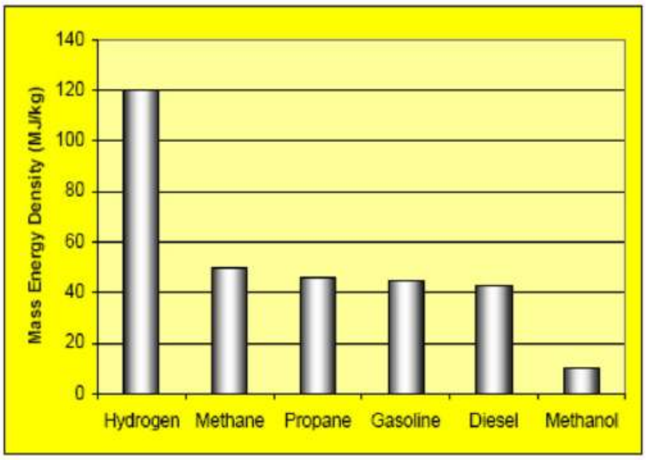

Figure 4 - Mass Specific Energy Density (Source: T. Jordan, 2012).

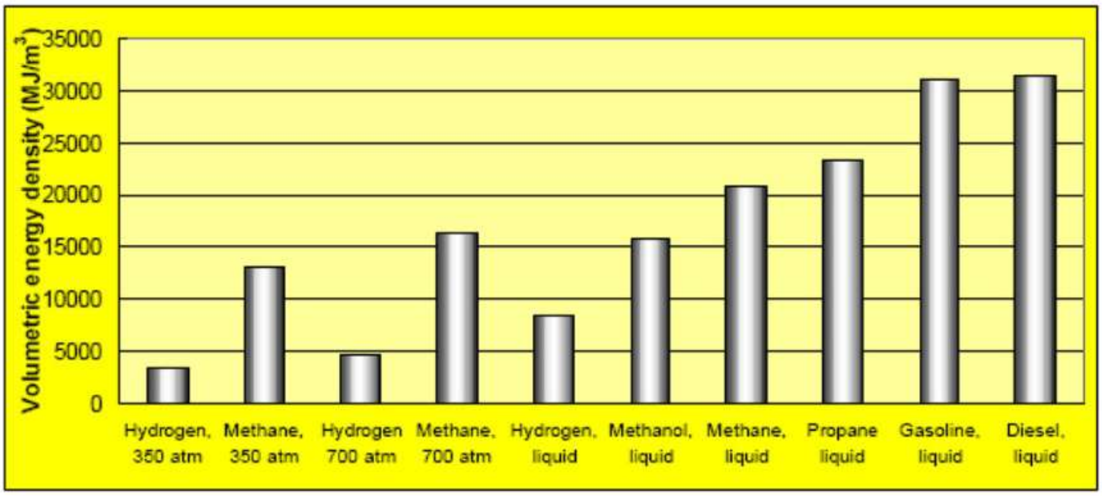

Figure 5 - Volume Specific Energy Density (Source: T. Jordan, 2012).

In the specific case of hydrogen, the volume ratio between its liquid and gaseous states is approximately 1:850, i.e., one litre of liquid hydrogen in uncompressed gas form would take up 850 litres. For this reason, it is compressed and stored at high pressures to obtain a higher energy density (amount of energy stored as H_2 per volume). However, being a small molecule with low viscosity and easy diffusion in the medium, it is prone to leakage. In an open environment, it will rise and disperse rapidly as hydrogen is 14 times lighter than air, which is a safety advantage. However, in an enclosed space, hydrogen leaks can accumulate, which, coupled with its high ignition rate and wide flammability limits in air, could cause the accumulation to reach a flammable concentration and is a hazard to be considered, especially in hydrogen mixtures in spaces such as pipes or ducts.

In order to summarise hydrogen characteristics and the comparison with other energy carriers, Tables 1 and 2 are presented below.

Table 1 - Hydrogen Properties (Source: Hydrogen Analysis Resource Center, 2020).

Properties	Values	Units
Autoignition temperature	500	°C
	932	°F
Boiling point (1 atm)	-252.9	°C
	-423.2	°F
Density (NTP)	0.08375	kg/m^3
	0.005229	lb/ft^3
Diffusion coefficient in air (NTP)	0.610	cm^2/s
	6.57×10^{-4}	ft^2/s
Enthalpy (NTP)	3858.1	kJ/kg
	1659.8	Btu/lb
Entropy	53.14	J/g-K
	12.70	Btu/lb-°R
Flame temperature in air	2045	°C
	3713	°F
Flammable range in air	4.0 - 75.0	vol%
Ignition energy in air	2×10^{-5}	J
	1.9×10^{-8}	Btu
Internal Energy (NTP)	2648.3	kJ/kg
	1139.3	Btu/lb
Molecular weight	2.02	
Specific gravity (air = 1) (NTP)	0.0696	
Specific volume (NTP)	11.94	m^3/kg
	191.3	ft^3/lb
Specific heat at constant pressure, C_p (NTP)	14.29	J/g-K
	3.415	Btu/lb-°R
Specific heat at constant volume, C_v (NTP)	10.16	J/g-K
	2.428	Btu/lb-°R
Thermal conductivity (NTP)	0.1825	W/m-K
	0.1054	Btu/ft-h-°R
Viscosity (NTP)	8.813×10^{-5}	g/cm-sec
	5.922×10^{-6}	lb/ft-sec

Notes:
NTP (normal temperature and pressure) = 20 °C (68 °F) and 1 atm;

Table 2 - Comparative Properties of Hydrogen and Fuels (Source: Hydrogen Analysis Resource Center, 2020).

Properties	Units	Hydrogen [1]	Methane [1]	Propane [1]	Methanol [1]	Ethanol [1]	Gasoline [2]
Chemical Formula		H_2	CH_4	C_3H_8	CH_3OH	C_2H_5OH	C_xH_y (x = 4 - 12)
Molecular Weight		2.02	16.04	44.1	32.04	46.07	100 - 105
Density (NTP)	kg/m^3	0.0838	0.668	1.87	791	789	751
	lb/ft^3	0.00523	0.0417	0.116	49.4	49.3	46.9
Viscosity (NTP)	g/cm-sec	8.81×10^{-5}	1.10×10^{-4}	8.012×10^{-5}	9.18×10^{-3}	0.0119	0.0037 - 0.0044
	lb/ft-sec	5.92×10^{-6}	7.41×10^{-6}	5.384×10^{-6}	6.17×10^{-4}	7.99×10^{-4}	2.486×10^{-4} - 2.957×10^{-4}
Normal Boiling Point	°C	-253	-162	-42.1	64.5	78.5	27 - 225
	°F	-423	-259	-43.8	148	173.3	80 - 437
Vapor Specific Gravity (NTP)	air = 1	0.0696	0.555	1.55	N/A	N/A	3.66
Flash Point	°C	< -253	-188	-104	11	13	-43
	°F	< -423	-306	-155	52	55	-45
Flammability Range in Air	vol%	4.0 - 75.0	5.0 - 15.0	2.1 - 10.1	6.7 - 36.0	4.3 - 19	1.4 - 7.6
Auto Ignition Temperature in A	°C	585	540	490	385	423	230 - 480
	°F	1085	1003	914	723	793	450 - 900

Notes:
[1] Properties of the pure substance
[2] Properties of a range of commercial grades
[3] NTP = 20 °C (68 °F) and 1 atmosphere
N/A - Not applicable

1.2 Importance of Hydrogen

Climate Crisis

In order to explain the importance of hydrogen in the global scenario, it is first necessary to explain the short- and medium-term international targets set to combat global warming. Globally recognised research shows that the temperature has risen by 0.8°C since the beginning of the 20th century and that most of the change has occurred in the last three decades, and that it is almost certainly mainly a change caused by an increase in atmospheric carbon dioxide (CO_2). As can be seen in Figure 6, concentrations of carbon dioxide in the atmosphere today are the highest that have been measured in 600,000 years.

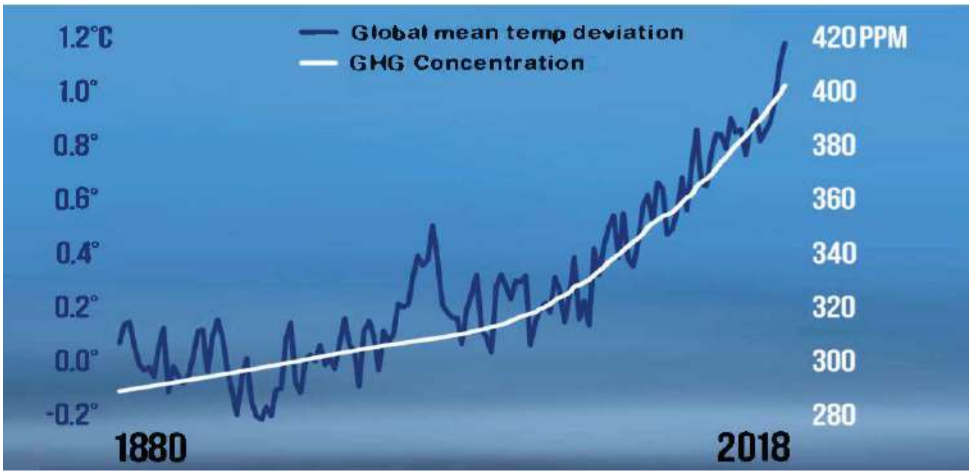

Figure 6 - Relation between GHG & temperature (Source: Cambio Climático Global, 2018).

The significant increase in greenhouse gases is due to the development of economic activity in modern societies. The production of electricity, the transport of goods, food production, human mobility and industrial activity are the main activities that, as a result of their current development, lead to the emission of these gases.

The emergency of climate change transcends national boundaries. To address the issue and assist nations in transitioning to a low-carbon economy, coordinated responses at all levels are needed.

The historic Paris Agreement, which was adopted on December 12, 2015, at the United Nations Climate Change Conference (COP21) in Paris, furthered progress in addressing climate change and its harmful effects.

The Agreement sets long-term goals as a guide for all nations:

- Substantially reduce greenhouse gas emissions to limit the global temperature increase this century to 2 °C and strive to limit this increase to even more than just 1.5 °C.
- Review countries' commitments every five years.
- Provide financing to developing countries to enable them to mitigate climate change, strengthen resilience and improve their capacity to adapt to the impacts of climate change.

Hydrogen role

Taking the context of the climate crisis into account, it is now possible to explain the role of hydrogen as part of the solution in order to achieve international goals.

Hydrogen is an energy carrier, i.e., it is a substance that stores energy in such a way that it can be released in a controlled manner at a later date. It can be used to produce heat through the combustion process (it is a fuel with a high calorific value), electricity (through an electrochemical process) or other products by using it as a raw material for different chemical reactions (synthetic fuels, fertilisers, etc.).

There are several methods to produce hydrogen, with the two most widely used and developed ones being steam methane reforming and electrolysis of water. Both processes aim to separate hydrogen from the elements with which it is combined.

The electrolysis process separates the water molecule into its components, hydrogen and oxygen, using electricity. If this electricity is of renewable origin, the hydrogen produced will be emission-free not only during its use but also during its production.

Hydrogen can be converted back into electrical energy through the use of fuel cells, which are devices capable of converting the chemical energy contained in hydrogen into electrical energy when needed. It is a highly efficient technology, free of noise and vibrations (as it has no moving parts) and free of pollutant emissions (the only associated emission is water).

In this way, hydrogen will allow greater penetration of non-manageable renewable energies in the electricity system. Solar and wind energy are intermittent and highly seasonal, so any electricity system with a high percentage of these technologies will require large-scale energy storage for long periods, and this will be one of the major roles of hydrogen in the energy transition.

The applications of hydrogen and fuel cell technologies are diverse, whether for stationary, portable or transport applications. According to the Hydrogen Council, hydrogen will play a key role in the energy transition to a more sustainable model based on renewable energies, with seven main roles:

- Enables greater penetration of clean energies (RES-E), integrating them more and better on a large scale.
- It allows a simple distribution of energy, between sectors and regions.
- Allows for a buffering of supply-demand differences in the grid (storage).
- It allows the decarbonisation of transport (cars, trains, ships and even aircraft).
- It serves as a raw material for different fuels, combining it with sequestered CO_2.
- It allows decarbonisation in industry, being used as a raw material or/and for the generation of process heat.
- It enables the decarbonisation of energy in households.

The fight against climate change and the imperative need to reduce carbon emissions suggest that hydrogen is key to the transition towards decarbonisation of industry, homes and transport.

Several countries have made a firm commitment to hydrogen (Japan and others on the Asian continent such as China and Korea; Canada; the USA, especially in the California area; some South American countries such as Chile, Argentina and Brazil; European countries such as France, Germany, the Netherlands and Scandinavia), proposing ambitious national development plans with strong support for their achievement. Europe wants to rapidly deploy hydrogen to decarbonise economic sectors that are particularly difficult to electrify and to store green energy to cover demand when there is no renewable generation (water, wind or sun).

Hydrogen technologies are continuously developing and evolving to become cheaper, and are key to improving business productivity and competitiveness, based on a system of renewable generation from non-manageable sources.

Current energy storage technologies, which are primarily based on batteries, cannot store large quantities of energy for extended periods. Hydrogen technologies will allow the storage of large amounts of energy (on the megawatt scale) for extended periods (seasonal storage).

The value added by hydrogen in this context centres on the great flexibility it presents:

- It can be produced from numerous resources, both on a large and small scale.

- It can be stored in gaseous or liquid form for long periods and transported over long distances.

- It can be used as a carbon-free fuel in multiple applications.

It offers numerous advantages that are key to the energy transition that needs to be undertaken in the coming years to meet global sustainability targets, such as increasing the penetration of renewable energy (it can be produced "on-site" from renewable energy), contributing to the development of the local economy and the creation of value-added jobs, linking the electricity sector to other sectors and contributing to the reduction of emissions.

Power-to-X technologies, which use electricity for the production of renewable hydrogen or its derivatives, increase the attractiveness of hydrogen production from surplus renewables, allowing for maximum energy efficiency and distribution across sectors and regions. These include Power-to-Gas, synthetic hydrogen or methane; Power-to-Fuel, synthetic fuels; and Power-to-Power to re-electrify stored hydrogen.

Hydrogen will also be a key alternative fuel in the mobility sector, which is responsible for a large amount of GHG emissions. There is a clear commitment to sustainable hydrogen-based transport, with a very promising present and future international scenario. Logically, supply infrastructures are required to supply fuel cell electric vehicles using hydrogen, and it is necessary to establish a minimum number of refuelling points that offer sufficient guarantees to users.

Figure 7 schematises the integration of hydrogen as an energy vector, with the previously mentioned applications.

Figure 7 - Hydrogen-energy flowchart (Source: The Cubix, 2022).

Current situation

The hydrogen industry is growing steadily. The sector is investing in large-scale projects to generate hydrogen via water electrolysis or traditional methods from fossil fuels, with the addition of the Carbon Capture and Storage stage (CCS). As a result, low-emissions hydrogen is now produced at costs that are competitive with conventional production, making it one of the present day's most practical solutions.

Many governments are looking at low-emission hydrogen as a means of reducing reliance on fossil fuels, especially in Europe. However, the implementation of low-emission hydrogen as a clean industrial feedstock and energy source is still in its early years. As with other clean energy technologies, it is important to effectively track development to determine whether it is moving forward at a pace that will allow hydrogen to contribute to the clean energy transition and improve energy security.

Hydrogen has another important characteristic that has been gaining importance in recent years. Unlike most energy carriers, hydrogen can be produced worldwide, using a variety of clean energy sources or low-emission methods. As a consequence, this energy option is intrinsically more secure, i.e., a country's energy matrix becomes less dependent on other countries that concentrate the largest proportion of resources used today for energy production (hydrocarbons). In this way, countries that do not have this natural resource can achieve energy independence through an even cleaner matrix. This advantage of hydrogen has recently become very important due to the energy crisis, mainly in Europe, as a consequence of the measures taken as a result of the conflict between Russia and Ukraine.

The number of demonstration projects is increasing, and some are expected to become commercially available earlier than previously thought. An example is the use of hydrogen in the Direct Reduction of Iron (DRI). Just one year after the first demonstration plant started to operate, plans for several commercial-scale DRI plants have been announced, mostly in Europe (IRENA 2021). Efforts to demonstrate hydrogen use in various sectors, in particular industry and transport, are expected to intensify, with the clear intent of reducing Europe’s dependence on imported oil and natural gas.

Along with technology adoption, policy areas have made progress in the past year. It is necessary to develop a regulatory framework that enables and promotes this development of the integral hydrogen economy, providing greater energy security and environmental quality, while guaranteeing its safety, quality and origin, and ensuring that all future hydrogen is green (from renewable sources to increase demand for hydrogen and to encourage early adopters, new policies have been announced, but few have been executed. The International Organization for

Standardization is working to create a Technical Draft Specification based on the IPHE Guidelines by the end of 2023 as part of the process of creating a global standard for carbon accounting (International Partnership for Hydrogen and Fuel Cells in the Economy).

Additionally, some governments have launched certification programs and developed regulatory instruments in order to promote the use of low-emission hydrogen as an energy source. The first steps toward hydrogen trade on a global scale have been taken. In a shipment from Australia to Japan at the beginning of 2022, the first international transport of liquefied hydrogen was accomplished.

2. Demand of Hydrogen

Hydrogen is a versatile and highly demanded product with a wide range of applications across multiple industries. The most important uses are represented in Figure 8. In recent years, the demand for hydrogen has been rapidly growing, driven by several factors, including the increasing demand for clean and sustainable energy sources, advancements in hydrogen production and storage technologies, and favourable government policies aimed at promoting the use of hydrogen.

This chapter presents the different uses of hydrogen, which can be divided into the following categories:

- Power generation
- Industrial uses of hydrogen
- Transport and mobility

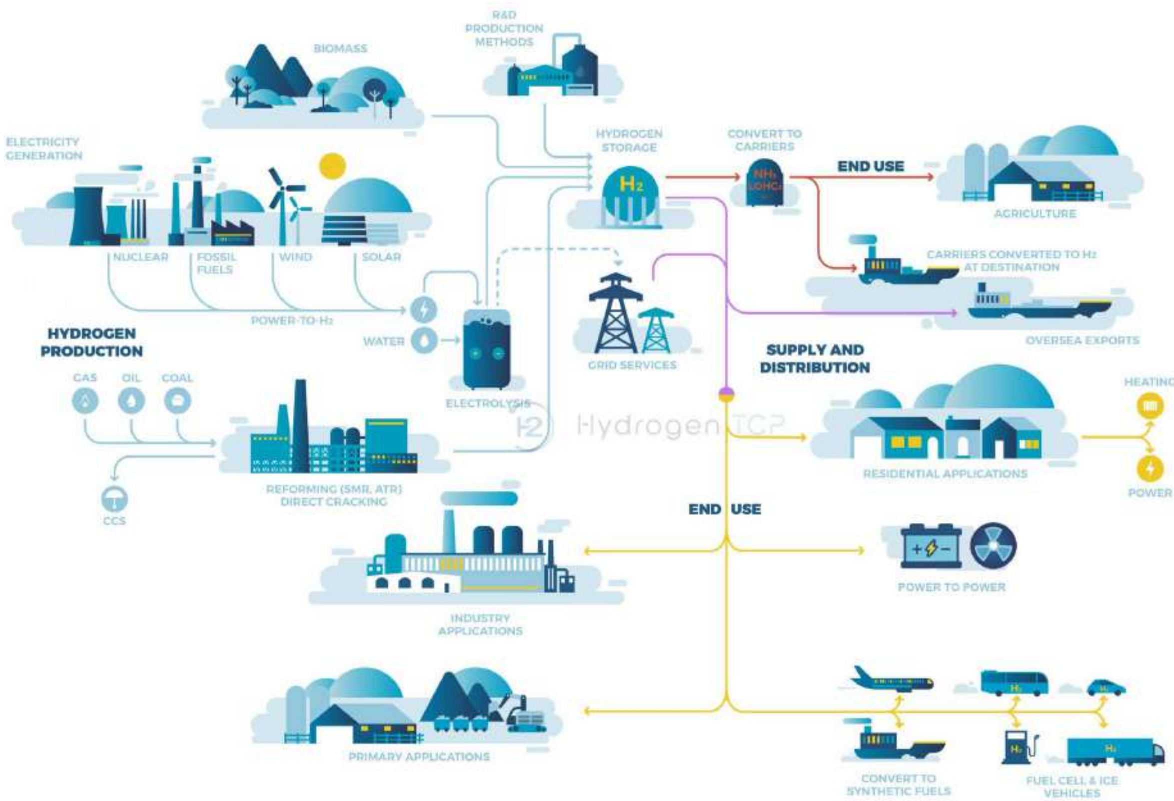

Figure 8 - Hydrogen value chain (Source: Hydrogen TCP, 2021).

2.1 Power Generation

The options of hydrogen for heat and electricity production are by combustion (without emissions) at high temperatures in the presence of air as a heat source or by using it as a reagent together with oxygen in fuel cells, where the hydrogen oxidation reaction takes place, leading directly to electricity and water.

By 2050, it is estimated that between 13% and 16% of the total electricity production generated will come from highly efficient cogeneration systems, with hydrogen from renewable sources as the main protagonist. Furthermore, according to the Power Generation Cost Study (IRENA 2021), this type of system will also cover between 19% and 27% of the heat demand of the different sectors.

2.1.1 Direct Combustion

H_2 when combined with oxygen in the air in a combustion reaction releases the chemical energy stored in the H-H bond, generating only water vapour as a by-product of the reaction. Given the differences between the physicochemical properties of natural gas and hydrogen, hydrogen presents certain changes when used directly without mixing in devices that were using natural gas like burners, turbines and internal combustion engines.

The industrial sector, in particular high temperature applications in the metallurgy or chemical sectors, is heavily dependent on fossil fuels for heat energy. As a possible solution, hydrogen could be used for industrial heat production by combustion in boilers, internal combustion engines or as a substitute for other fuel gases. Emission-free hydrogen is seen as the best option for heat-intensive thermal processes in a sustainable economy (Fraunhofer 2022).

Currently, heat is not produced from pure hydrogen in almost any process, but there are already tested alternatives of mixed combustion of natural gas and hydrogen, where hydrogen gas has a share of 15-20% and natural gas is the majority fuel. Compared to hydrogen combustion, natural gas improves flame detection and increases the calorific value of the mixture.

The use of hydrogen as a partial replacement of natural gas in domestic networks for heat generation is being evaluated in many countries to partially mitigate emissions related to this activity in particular. Studies indicate that mixtures of up to 20% hydrogen by volume could be carried by current gas connection networks, but this technology is being tested as a loss of hydrogen in the line could be very risky due to its high flammability.

2.1.2 Turbines

In terms of hydrogen power generation, there are two alternatives. On the one hand, there are the new turbine designs, designed to use only hydrogen as fuel, which would require much more infrastructure than at present, a competitive price for hydrogen, and a market that would allow the availability of the resource to be assured to a greater extent.

The other option that is much more feasible in the short term is the use of mixed gas turbines, which can operate with natural gas alone or with a mixture of natural gas and hydrogen in different proportions.

Currently, most gas turbines allow for a certain percentage of hydrogen blended into the fuel (mainly natural gas). Along these lines, in January 2019, members of the European industry association EU Turbines signed an agreement to gradually increase H_2 capacity in gas turbines by at least 20% by 2020 and 100% by 2030, with the aim of contributing to the transition to a carbon neutral economy by 2050.

Figure 9 - SGT-600 Turbine (Source: Siemens, 2019).

Table 3 presents four turbine models currently in operation on the market and the maximum percentage of hydrogen in volume of the mixture that they will accept. Figure 9 shows one of them (Siemens' model SGT-600).

Table 3 - Maximum percentage of hydrogen in volume of the mixture for different turbine models

Manufacturer	Mitsubishi	General Electric	Ansaldo Energia	Siemens
Model	M501JAC	6B, 7E, 9E	GT36-H	SGT-600
%H_2 in volume	30%	33%	50%	60%

This technology, which supports high amounts of hydrogen in the mix, is ideal to support the insertion of hydrogen into the power generation industry, providing the necessary conditions for a successful transition without requiring large additional expenditures or increased risk for investors.

2.1.3 Fuel Cell

The fuel cell is a device capable of generating electricity from the chemical reaction between the H_2 introduced into the fuel cell and the O_2 in the air, forming water vapour as a by-product. In other words, they perform the reverse process to that carried out by electrolysers.

Like a battery, it is based on several individual cells connected in series, each consisting of two electrodes (anode and cathode) separated by an electrolyte. Hydrogen is incorporated into the anode, where the H_2 oxidation reaction takes place, while oxygen from the air is supplied to the cathode, where the reduction reaction takes place. In this way, the electrochemical reduction-oxidation reaction takes place, generating a flow of electrons from those released at the anode to those collected at the cathode, which are collected by an external circuit, thus producing an electric current. Figure 10 schematizes the operation of a fuel cell.

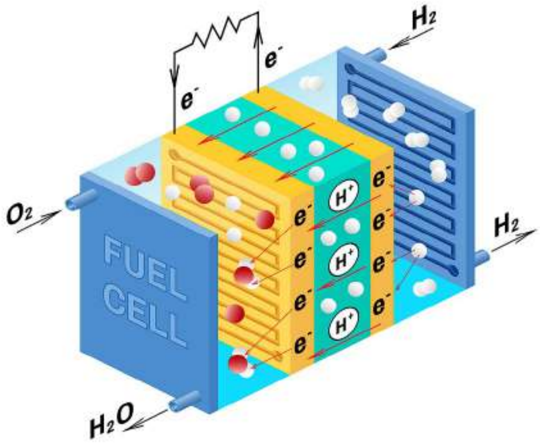

Figure 10 - Hydrogen fuel cell operation (Source: Airbus, 2020).

Its main advantage over direct H_2 combustion is that it has much higher efficiencies by eliminating the transformation steps (and thus the efficiency losses associated with these transformations) of the chemical energy contained in H_2 into thermal energy, of the thermal energy into mechanical energy by means of a turbine, and of the electromechanical transformation.

The current efficiency of PEM fuel cells (proton exchange membrane fuel cells) is 50%, which means that half of the energy contained in the H_2 fed into the fuel cell is not transformed into useful energy (electricity). For context, a small gas turbine has an efficiency of 25%, and a diesel cycle internal combustion engine has around 40%. Many companies are investing large amounts of money in improving this technology, so it is expected that the next decade will see a significant increase in efficiency and a reduction in the purchase price.

2.1.4 Hydrogen as a support for renewable electricity generation

One of the potential uses of hydrogen, and one that has received the most media attention, is as an energy storage system. Energy storage is essential for providing flexibility in electricity distribution and for the integration of renewable energies into the energy system.

Most of the renewable energies used today do not have an inherent possibility of storage, and their production depends on uncontrollable natural phenomena. They do not have constant or stabilised production over time and, when they operate, all their production must be fed into the grid. It is not logical for this technology to limit its production, as in other production methods (for example, to 80% of capacity), in order to be able to increase production at times of increased demand.

The option of being able to store this energy during a period of overproduction and reuse it in times of energy shortage would eliminate the need for fossil-fuelled generation and the associated carbon emissions. This solution is usually called Power-to-Gas, but there are similar solutions that do not involve hydrogen, so it is also called Power-to-Hydrogen. According to IRENA (2021), seasonal storage of renewable electricity will be a growth market after 2030, and hydrogen can play an important role.

Hydrogen, due to its energy capacity and its suitability for production by electrolysis of water, is, in theory, a basic element, not only to take advantage of infrastructures but also to increase the manageability of a system based on renewable sources such as wind and sun (shown in Figure 11). There is currently no significant need for seasonal storage as all renewable production directly replaces fossil fuel generation. However, energy policymakers should consider this possibility as a real opportunity to add to battery storage systems.

It is estimated that by 2050 the need for hydrogen storage to integrate large shares of solar and wind energy will grow significantly, as there will be an increasing electrification of demand in the different sectors to be supplied by renewable energies. This may be a solution to the problem of increased generation, as it may lead to saturation at the electricity interconnection nodes.

Figure 11 - Storage of superplus renewable energy in hydrogen (Source: Forbes, 2020).

2.2 Industrial uses of Hydrogen

2.2.1 Refineries

Crude oil is a substance based on a complex mixture of hydrocarbons that contains impurities such as sulphur, oxygen, nitrogen and heavy metals, mainly iron, nickel and vanadium. Hydrogen is used in various refinery processes, of which hydrotreatment is one of the most important, to eliminate environmentally harmful products. The process consists of adding hydrogen to induce hydrogenation and hydrogenolysis reactions, saturating aromatic compounds or eliminating elements such as sulphur, nitrogen or metals.

The refining process is the other main consumer of hydrogen. It allows the separation and classification of the different hydrocarbon fractions and then the addition of hydrogen to increase the production of the fractions that have the highest value in the market, such as liquefied natural gas, gasoline, diesel, jet fuel, lubricants and waxes. According to the IEA (2019), hydrogen demand in the oil industry has grown from 7 million tonnes per year in 1980 to 40 million tonnes in 2018.

2.2.2 Ammonia

The Haber-Bosch process, which involves the synthesis of ammonia from air nitrogen and hydrogen, was first demonstrated in 1909, using a metal catalyst at high pressure and temperature. This reaction is reversible and exothermic, requiring 1.5 H_2 molecules for each ammonia formed:

$$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g) \; \Delta H = -45{,}7 \text{ KJ/mol}$$

The ammonia produced can be neutralised with nitric acid in a spontaneous and irreversible reaction to yield ammonium nitrate, which is used as a source of nitrogen in fertilisers. This revolutionised the agricultural industry, as the manufacture of synthetic fertilisers increased field productivity and helped produce enough food to supply the world's growing population. At present, they account for about two-thirds of the fertilisers on the market. Ammonia production accounts for 27% of today's demand for hydrogen. A large variety of products, including ammonium nitrate, calcium ammonium nitrate, urea, ammonium sulphate, and others, are derived from ammonia synthesis as a source of agricultural nitrogen. About 80% of the world's ammonia production is used as a source of nitrogen for fertiliser synthesis.

The process has high energy requirements due to the high operating pressures and temperatures, which, added to the hydrogen needs, mean that the environmental impact of the standard process from natural gas reforming is very significant in terms of greenhouse gas emissions. At the technological level, there are already various initiatives that have incorporated capture units or that have replaced reforming plants with green hydrogen as a solution for decarbonising ammonia production.

Ammonia has industrial applications other than fertiliser production, which account for 20% of demand. Ammonia is used directly in environmental protection measures, e.g., to remove NOx from flue gases or as a solvent in cleaning products or refrigerants. Liquid ammonia is a prominent solvent used as a refrigerant. It is also used as a raw material in the production of plastics, synthetic fibres, explosives, dyes and pharmaceuticals.

In addition to its properties as a solvent, refrigerant or nitrogen carrier, ammonia has an energy density of 18.6 GJ/tonne, about half that of oil and comparable to that of biomass, so its use as an energy carrier is also being considered. In this case, it would be a carbon-free fuel, like hydrogen, and would allow the chemical storage of surplus renewable energy, such as methane and methanol, as well as hydrogen. However, there are technical barriers, such as toxicity to living beings and water, or potential NO_x emissions during reforming or combustion, which currently limit its implementation.

2.2.3 Steel

Direct reduction of iron (DRI) is a process that uses solid reducing agents like coal or gaseous reducing agents like hydrogen or synthesis gas to produce steel from iron ore (iron oxides like magnetite or hematite) at temperatures much lower than those of conventional blast furnaces (800–1,200 °C).

Table 4 below shows the chemical reactions depending on the reducing agent used.

Table 4 - Direct Reduction of Iron reactions

Reducing with H_2	Reducing with CO	Reducing with Carbon
$3Fe_2O_3 + H_2 \rightarrow 2Fe_3O_4 + H_2O$	**$3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO$**	**$C + CO_2 \rightarrow 2\ CO$**
$Fe_3O_4 + H_2 \rightarrow 3FeO + H_2O$	**$Fe_3O_4 + CO \rightarrow 3FeO + CO_2$**	…then reduction with CO
$FeO + H_2 \rightarrow Fe + H_2O$	**$FeO + CO \rightarrow Fe + CO_2$**	

Because of these reactions and taking into account that the hydrogen usually used in this industry is produced from fossil fuels, the steel industry is one of the largest generators of greenhouse gases.

According to Guidehouse (2021), it is estimated that 100 kg of hydrogen is required to produce one tonne of steel. If the annual steel consumption (1.800 Mt in 2018) and the procurement method had been fully DRI using hydrogen, the demand would have amounted to 180 Mt H_2 per year. Considering that one tonne of hydrogen can replace 5 tonnes of coal (coke), using hydrogen produced without emissions would have a major impact in terms of reducing direct CO_2 emissions.

The steel industry is currently the fourth largest source of hydrogen demand (4 MtH_2 per year), accounting for 3% of total consumption, either in pure form or as a mixture of gases. Taking into account global growth and the need for new infrastructure in developing countries, steel demand is estimated to increase by 6 % by 2030, and therefor, hydrogen demand is going to increase at least proportionally, or even more if it replaces carbon in the new projects, as is intended.

2.2.4 Methanol

To satisfy the demands of international markets, methanol is a chemical that is produced on a large scale. It is a basic alcohol and is liquid at room temperature. It is a precursor to many other industrially important substances, including formaldehyde, acetic acid, methyl tert-butyl ether, dimethyl ether, and other chemicals. It is also used as a refrigerant and as a solvent. Like the liquid hydrocarbons mentioned above, it is valued energetically as a fuel (40% of total consumption) in addition to its uses as a feedstock. Its energy density is 80% higher than that of liquid hydrogen. New pathways for using methanol as a precursor for aromatics, olefins, and value-added chemicals have recently been postulated. Therefore, the production of methanol can be seen as the starting point for the production of many different compounds that require hydrogen.

The methanol synthesis process consists of the synthesis gas reaction, with a stoichiometry of two moles of hydrogen per mole of carbon monoxide. It is estimated that about 12 MtH_2/year (11 % of demand) is used for methanol synthesis alone.

2.2.5 Other industrial uses

Apart from those mentioned above, hydrogen has countless uses in industry.

- Synthetic hydrocarbons: defined as hydrogen-based fuels that are liquid at room temperature. They are also referred to as electro-fuels, and the compounds proposed are in the form of methanol, gasoline, paraffin and light diesel (schematized in figure 12). The most foreseeable market niche for synthetic liquid fuels is transport that is more difficult to electrify, such as air and maritime transport. It should be borne in mind that, by using these liquid fuels in internal combustion engines, only the problem of net CO_2 emissions is avoided but not that of pollutant emissions such as NOx or carbon monoxide.

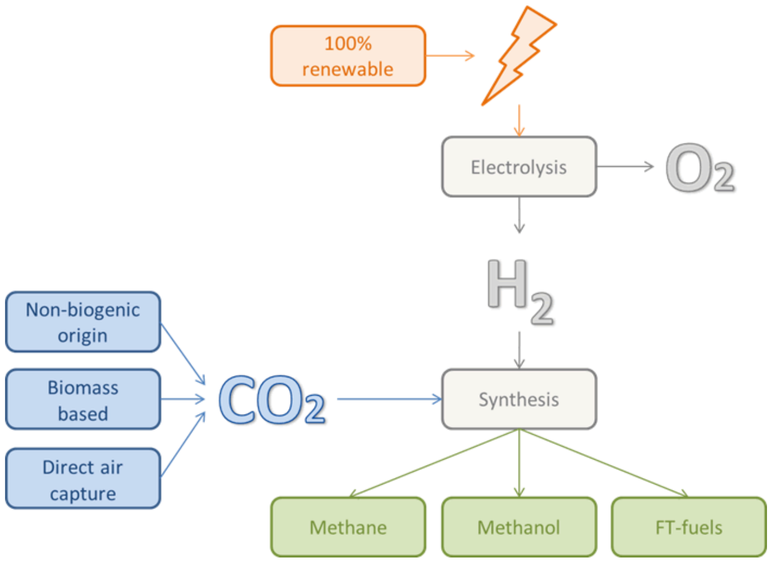

Figure 12 - Explanatory diagram of the production of electrofuels (Source: European Technology and Innovation Platform, 2019).

- Industrial process heat: At present, the role of hydrogen producing heat for industrial processes is very low. In the near future in Europe, although full electrification is expected for low-temperature heat due to the availability of suitable technologies and the associated efficiency gains compared to combustion processes, hydrogen will play a more important role in the decarbonisation of medium and especially high-temperature processes.

- Other chemical products: The two most important basic chemicals obtained from hydrogen are ammonia (55%) and methanol (10%), in addition to all the organic compounds produced in refineries by hydrogenation reactions discussed above (25%). Hydrogen is also used as feedstock for the production of other basic chemicals such as hydrochloric acid (HCl), hydrogen peroxide (H_2O_2), various alcohols, aromatics and amines, among others.

- Polymers: Olefins (ethylene, propylene, butylene, etc.) are basic compounds that are used on a large scale in the chemical industry to produce more complex molecules such as plastics, polystyrene (PS), polyethylene terephthalate (PET) and polyvinyl chloride (PVC), everyday products. For example, ethylene is the most widely consumed petrochemical product in the world. Traditionally, they have been obtained from refineries using petroleum as feedstock. However, the high global demand for olefins cannot be met in the long term by thermal cracking of hydrocarbons. Instead, alternative processes for the manufacture of carbon-neutral plastics are based on the Fischer-Tropsch reaction, in which carbon monoxide is combined with hydrogen to generate more complex molecules, such as olefins. Products that require hydrogen addition are called synthetic chemicals (in this case, synthetic plastics).

Figure 13 shows the expected hydrogen demand in Europe for 2030, disaggregated by type of final use.

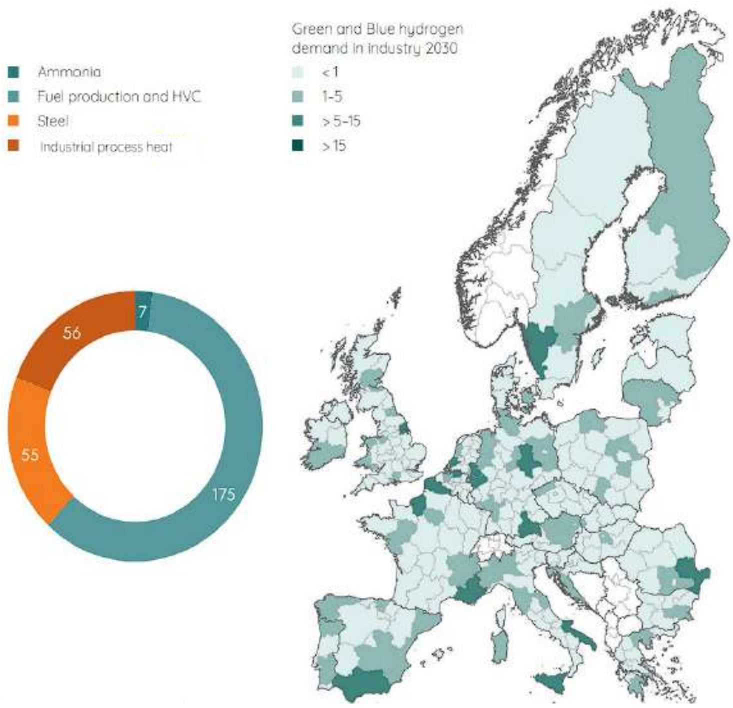

Figure 13 - Expected industrial green and blue hydrogen 2030 demand based on industry decarbonisation roadmaps of existing installations (in TWh/year) (Source: Guidehouse, 2021).

2.3 Transport and mobility

As one of the main energy sources that can be used to reduce the carbon footprint of transportation, hydrogen competes with and complements natural gas (CNG and LNG), biofuels (like biomethane) and electric vehicles.

The range restrictions and extended refuelling times associated with battery electric vehicles are overcome by hydrogen vehicles. In comparison to biofuels, it doesn't require as much land and doesn't have the same negative effects on air quality, especially in densely populated urban areas.

The European Air Quality Agency (EAQA 2016) has estimated that more than half a million premature deaths in Europe are caused by elevated levels of particulate matter and NO_x, above those recommended by the World Health Organisation, to which more than 90% of the world's population is exposed. The use of hydrogen for transport can secure future energy supply while minimising this environmental impact.

When low-emission hydrogen is used in fuel cells, as in mobility applications, the only waste produced is water, which helps to address two significant problems: global warming and air quality. With transportation accounting for 20% of global energy consumption, its use is establishing the foundation for a sustainable energy economy. Through a number of demonstration projects, transportation was one of the first industries to adopt hydrogen-based technologies. It has been obstructed until now by the immaturity of the underlying technologies, the associated costs, and the insufficient infrastructure, but the situation is starting to change. Toyota and Hyundai own more than 65% of the fuel cell market, which has a combined capacity of 1.1 GW, and they are mostly used in the production of their hydrogen-vehicles. Although it can be implemented through various solutions for light or heavy transport, the suitability of hydrogen-based solutions depends on each type of transport.

According to Guidehouse's report (Wang A. et al., 2021), the demand for direct hydrogen in Europe in 2030, 2040, and 2050 is forecasted to be 21 TWh, 131 TWh, and 217 TWh, respectively for heavy road transport, approximately 3%, 25%, and 60% of the total heavy road energy demand and 0 TWh, 9 TWh, and 68 TWh for aviation, approximately 0%, 1%, and 9% of aviation energy demand.

There are several works related to the implementation of hydrogen-powered vehicles in Europe because it is one of the most prominent solutions in order to achieve international environmental objectives. In summary, here are the most relevant applications of hydrogen in transportation:

- Light road vehicles: The decarbonisation of transport must focus on the transition of the private car, as its emissions account for around half of the emissions generated by the sector.

  At present, the clearest example of hydrogen-based light mobility is the fuel cell-powered electric car. Although externally, and in the way they drive, they are exactly like a battery electric car, the core engineering of these vehicles is a stack of fuel cells. This stack of fuel cells converts hydrogen into water, combining it with oxygen from the air and releasing the electrons that will provide the power needed to drive the electric motor.

  Light transport with fuel cells has, in the coming years, a very specific field of application because they mean a high investment for users, and electric cars are currently a more economical option. However, a more extensive deployment in the longer term is not ruled out, as various analyses suggest a clear reduction in vehicle cost when they are mass-produced. The expected reduction in the price of hydrogen will bring the total cost of ownership in line with other existing mobility alternatives.

- Heavy road transport: In heavy mobility and heavy-duty transport, such as buses and cargo trucks, the fuel cell electric vehicle prevails over the battery-powered vehicle due to its greater autonomy. Its operation is very similar to that described for the private passenger vehicle, but in this case, its consumption is expected to be 10 to 15 times higher. Several models are already operational around the world, as in the case of the bus CITARO (Figure 14).

  Buses and waste collection trucks, as vehicles that always operate in a closed and known circuit, always returning to the same base, are an ideal case for boosting hydropower infrastructure with a minimum investment, allowing the deployment of a large fleet of vehicles. Their impact and social visibility, as they are widely used by the population, are factors that favour their development, and they are currently at a very high level of technological maturity, with many success stories in different parts of the world, mainly Europe, the USA and Japan.

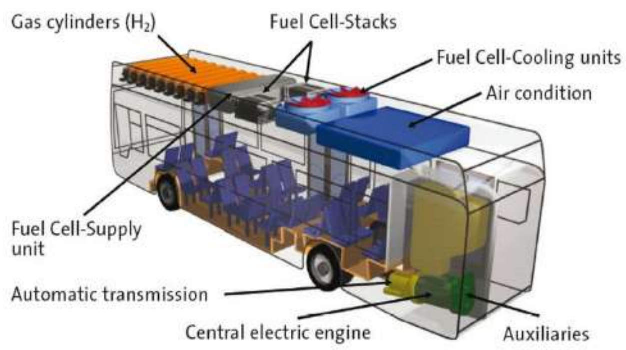

Figure 14 - Components of fuel cell bus CITARO (Source: Clean Urban Transport for Europe, 2016).

- Maritime and river transport: Maritime applications of hydrogen have already been tested in the propulsion of small and medium-sized vessels, including ferries, but the reality is that their commercial deployment is still at a very early stage. There are exceptions, such as in the Baltic or the North Sea, where some countries have started to regulate ferries to require them to be powered by 100% renewable energy, which has promoted the emergence of fuel cell-powered vessels.

One of the main problems with the transition of large ships is that they have very long lifetimes and relatively small production volumes, which slows down deployment. The high fuel consumption, which can reach or even double a tonne of hydrogen per day, would require the adoption of onboard cryogenic storage, which is a factor against the transition. However, for the same reason, it is even less likely that this industry will achieve decarbonisation from battery-powered electric vehicles, as these would be unfeasible in terms of cost and size.

In the short term, the most viable option, and one that is currently being employed to meet emission reduction requirements in the shipping industry, is the use of hydrogen/natural gas fuel blends in ships that were originally operated only on natural gas. Blends of up to 20% hydrogen by volume do not require major system changes, and some engine manufacturers have been preparing engines to run on this fuel mix for more than a decade.

- Rail transport: The future potential of the hydrogen fuel cell train lies in new routes or non-electrified routes. It is difficult to imagine hydrogen trains replacing the thousands of kilometres of electrified rail transport that already exist, but it does present an opportunity to generate new routes at a lower cost than electrification, such as in urban areas.
  One of the first demonstrations has taken place in Germany, where Alstom has developed the train called Coradia iLint, which has been running the passenger route between the Lower Saxony cities of Cuxhaven, Bremerhaven, Bremervörde and Buxtehude since 2018, and dozens of units have been built.

- Air transport: As in the case of maritime transport, there is particular interest in this alternative for air transport, since the use of batteries is not feasible for aircraft. At the same time, air transport is one of the industries that receives the most social pressure regarding its emissions. This is why most of the major aircraft manufacturing companies nowadays have departments dedicated to the development of new alternatives to reduce emissions. In this scenario, there are several options that take into

Figure 15 - Hydrogen powered aircraft concept (Source: Airbus, 2020).

account hydrogen as the aircraft's main energy reserve. One of the most developed solutions so far is the use of fuel cells to produce electricity to run the engine, as in the previous cases. Another solution being evaluated in this particular case is the use of hydrogen-powered turbines. However, only prototypes (as the one shown in Figure 15) and a few-passenger aircraft have been produced so far.

2.4 Summary and Analysis of Demand

At present, hydrogen is used primarily for industrial purposes, with approximately 95% of the hydrogen produced being used in the production of fertilizers, chemicals, and petroleum products. In addition, hydrogen is also being used as a fuel for transportation, particularly for fuel cell vehicles, and is also being used for energy storage, particularly in the form of hydrogen fuel cells. Although these applications of hydrogen are relatively small at present, they are expected to grow in the future as the demand for clean and sustainable energy sources continues to increase.

In 2021, there was evidence of accelerated implementation of certain critical hydrogen technologies. It was a record year for electrolysis deployment, with more than 200 MW of extra installed capacity, three times more than the previous record year (2020), pushing total operating capacity above 500 MW. If all the currently starting projects are completed, electrolysis capacity might range from 134 to 240 GW by 2030 (Wang A. et al., 2021).

In 2021, global hydrogen demand was over 94 million tonnes (Mt), a 5% rise over the previous year. The conventional uses of hydrogen, mainly in refining and industry, accounted for the majority of this demand growth. Yet, several emerging uses, such as fuel cell electric vehicles (FCEVs), are enjoying rapid adoption. By the end of 2021, the global FCEV stock had risen to over 51 000 units, up from over 33 000 in 2020, indicating the greatest annual deployment of FCEVs since they were commercially available in 2014. The majority of FCEVs are passenger cars, but many demonstration projects for fuel cell trucks, as well as a significant push in China, are expected to put roughly 800 hydrogen fuel cell heavy-duty trucks into service by 2021.

There are several factors that are driving demand for hydrogen in the near future, including:

1. Increasing concern about climate change: As global temperatures continue to rise, there is growing concern about the impact of human activity on the environment. This has led

to increased demand for zero-emission hydrogen, which produces no greenhouse gas emissions when used.

2. Growing demand for clean and sustainable energy sources: The demand for clean and sustainable energy sources is growing globally, as more and more countries adopt policies to reduce greenhouse gas emissions and transition to a low-carbon economy. This is driving demand for hydrogen, which is a clean and sustainable energy source that can be produced using renewable energy sources.

3. Advances in hydrogen production technology: Advances in hydrogen production technology are making it possible to produce hydrogen more efficiently and at a lower cost, making it a more attractive energy source for a wider range of applications. In particular, the development of renewable hydrogen production methods, such as electrolysis, is making it possible to produce hydrogen using renewable energy sources, further increasing the appeal of hydrogen as a clean and sustainable energy source.

4. Government support for hydrogen: Several governments around the world are offering financial and regulatory support for the development of hydrogen technologies, as part of their efforts to transition to a low-carbon economy. This support is helping to drive demand for hydrogen as it makes it easier for businesses and individuals to adopt hydrogen technologies.

5. Energy crisis: The conflict between Russia and Ukraine has led to an increase in geopolitical tensions and Eastern Europe's energy dependence on Russian natural gas. It has highlighted the importance of energy security and independence and has led many countries to seek more secure and sustainable energy alternatives, resulting in an increased interest in hydrogen development and accelerated research and investment in the technology.

In conclusion, the demand for hydrogen is growing, driven by increasing concern about climate change, the need for clean and sustainable energy sources and its potential to store energy. As advances in hydrogen production technology continue, and as more and more governments offer support for the development of hydrogen technologies, the demand for hydrogen will likely continue to grow in the coming years.

3. Hydrogen Production

This chapter presents the different hydrogen production methods used today or technologies that have a high probability of being used in the near future and have already proved to be technically feasible. It also explains the classification of hydrogen by colour according to its production method and the current situation of hydrogen production in the world.

Although hydrogen itself is a zero-emission fuel, its production can result in substantial upstream greenhouse gas emissions, depending on the method used to produce it. As mentioned above, hydrogen is an energy carrier because it requires an energy input to obtain it. Therefore, it will be a sustainable vector or not, depending on whether the primary energy sources and production processes used are sustainable. Around 95% of current global hydrogen production is based on fossil fuels, and according to the report “The Future of Hydrogen” by the International Energy Agency (IEA 2019), in 2018, this production caused the emission of 830 million tonnes of CO_2 (2.2% of global emissions).

Hydrogen can be produced by using different processes like electrolysis, steam methane reformation, or gasification fed either by the direct combustion of fossil fuels or electricity generated from renewable, fossil, or nuclear energy sources. The climate impact of the different hydrogen production methods differs. There are numerous classification schemes to distinguish between hydrogens produced from various fuels and electric sources. A colour-code system for identifying hydrogen's source is currently gaining popularity. Based on the initial energy source and production method, this code divides hydrogen into various "colours", as shown in Figure 16.

	Terminology	Technology	Feedstock/ Electricity source	GHG footprint*
PRODUCTION VIA ELECTRICITY	Green Hydrogen	Electrolysis	Wind | Solar | Hydro Geothermal | Tidal	Minimal
	Purple/Pink Hydrogen		Nuclear	
	Yellow Hydrogen		Mixed-origin grid energy	Medium
PRODUCTION VIA FOSSIL FUELS	Blue Hydrogen	Natural gas reforming + CCUS Gasification + CCUS	Natural gas | coal	Low
	Turquoise Hydrogen	Pyrolysis	Natural gas	Solid carbon (by-product)
	Grey Hydrogen	Natural gas reforming		Medium
	Brown Hydrogen	Gasification	Brown coal (lignite)	High
	Black Hydrogen		Black coal	

*GHG footprint given as a general guide but it is accepted that each category can be higher in some cases.

Figure 16 - The hydrogen colour spectrum and indications for carbon emissions (Source: National Hydrogen Strategies, World Energy Council, 2021).

Black or brown hydrogen, for example, is produced by heating hard coal or lignite (two types of coal) to over 700 °C. This produces a gas from which hydrogen is extracted. It is the oldest form of production and, due to its CO_2 emissions, is the most harmful to the environment.

Grey hydrogen refers to hydrogen gas that is produced through a process known as steam methane reforming, where natural gas is heated with steam to produce hydrogen and carbon dioxide. This process is currently the most common method used for producing hydrogen and is considered a conventional method. However, the production of grey hydrogen is associated with high greenhouse gas emissions, as carbon dioxide is released during the production process. Therefore, grey hydrogen is not considered a sustainable or environmentally friendly option for hydrogen production.

However, during the production of grey hydrogen, it is possible to prevent these greenhouse gases from being released into the atmosphere. In this case, it is considered blue hydrogen. In fact, any black, brown or grey hydrogen that incorporates a carbon capture and storage process is now considered blue hydrogen.

Recently, a new technique has been developed to produce hydrogen from methane that, instead of generating a CO_2 by-product as in grey hydrogen, produces solid carbon waste that does not contribute to the greenhouse effect. This process, called "methane pyrolysis", requires a temperature of over 1000 °C and is what gives rise to turquoise hydrogen.

The rest of the hydrogen colours are based on the hydrolysis technique: using electricity to split water molecules into oxygen and hydrogen, which is then captured. When it is generated using electricity from renewable sources (wind, solar or other) green hydrogen is obtained, which, as its name suggests, is considered the most environmentally friendly. Many projects are being developed nowadays regarding green energy. Hydrogen is a really good way to store the green energy produced during low-demand periods (for example, wind farms produce lots of energy during the night when it is not demanded).

When the energy for hydrolysis comes from nuclear generation, it is classified as pink hydrogen. One of the advantages is that it is a non-GHG emitting source and produces steadily, so the producer can either maintain a constant and stabilised production or use periods of low energy demand to produce the hydrogen. Another great advantage of using this energy source is that it does not simply use hydrolysis but also uses techniques (explained later in this chapter) that use high temperatures to increase efficiency, in this case using thermal energy directly from the reactor.

Finally, when the electricity used for hydrolysis comes from a mix of different sources (renewables or not), the product is labelled as yellow hydrogen. How environmental-friendly is the yellow hydrogen depends on the composition of the grid generation, which changes drastically from country to country.

At present, the most common industrial form is grey hydrogen: molecules of methane (the principal component of natural gas) contain hydrogen atoms that can be extracted by the "steam reforming" technique. It is an energy-intensive process because it requires very high pressures and temperatures of 800-900°C, and to make matters worse, it releases a lot of greenhouse gases.

Figure 17 presents an organize overview of the different hydrogen production methods.

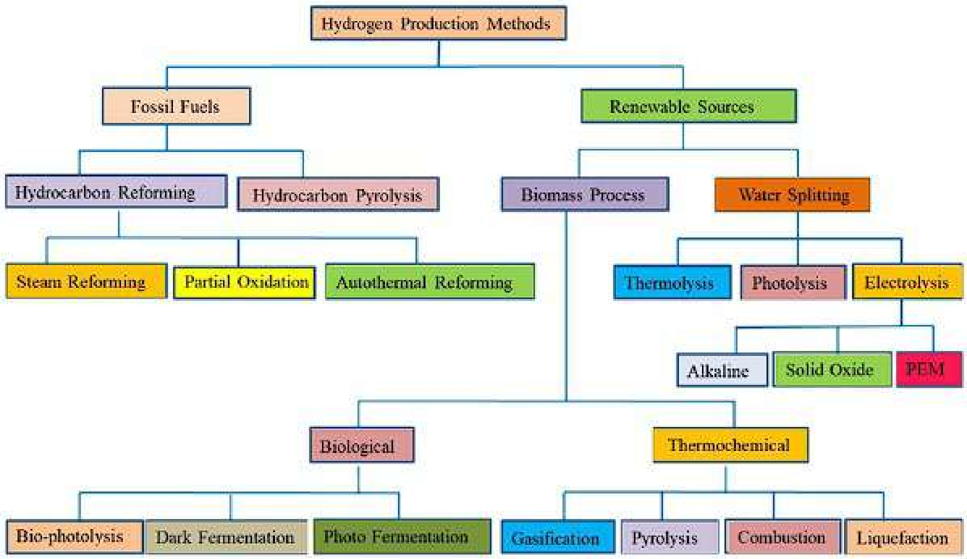

Figure 17 - H_2 production methods (Source: Materials Science for Energy Technologies,2019).

The following sections will provide a detailed technical explanation of the most popular hydrogen production methods, divided into the following categories according to the nature of the process:

- Thermochemical processes
- Electrochemical processes
- Photochemical processes
- Biochemical processes

As mentioned above, hydrocarbons are currently the most widely used raw materials, and hydrocarbon reforming is the most widely used and economical method for industrial hydrogen production, but substantial amounts of CO_2 emissions are produced as a consequence of using carbon-based raw materials and energy sources. Therefore, the generation of hydrogen from renewable sources will be one of the main priorities in the future due to its clean and environmentally sustainable characteristics.

3.1 Thermochemical processes

The most common hydrogen production processes are thermochemical, such as gasification and reforming. The fuel used is the one with the highest atomic H/C ratio (ratio of hydrogen (H) to carbon (C) atoms) in order to achieve a higher production of H_2 per fuel consumed. Its relatively low cost compared to other processes and its chemical composition make natural gas the world's leading source of energy from which hydrogen is produced. Natural gas consists mainly of methane (CH_4), whose molecules consist of 4 hydrogen atoms (H) for each carbon atom (C) so that a larger amount of H_2 is generated in the extraction of H_2 from its chemical structure compared to other longer-chain hydrocarbons and much more than with coal or biomass, where H_2 comes mainly from using water as an oxidising agent.

3.1.1 Natural gas reforming

Reforming is the chemical process by which hydrogen is extracted from a gaseous fuel (usually natural gas). There are three methods, depending on the oxidising agent used in the reaction, and the most widely used is known as Steam Methane Reforming (SMR). The method is schematized in Figure 18 for a better understanding.

SMR is a mature production technology that requires high temperatures (700–1100 °C) in the presence of a catalyst to accelerate the reaction and water as the oxidising agent. The high temperatures required in the reformer are achieved by burning external fuel (natural gas or other hydrocarbons) and are necessary to carry out the highly endothermic chemical reaction of partial decomposition of natural gas (CH_4) into CO and H_2, an energy-intensive reaction. To increase the amount of H_2 formed, syngas must undergo the Water Gas Shift (WGS) reaction. This slightly exothermic chemical reaction allows the H_2/CO ratio to be adjusted by reacting the CO in the synthesis gas with water vapour to form CO_2 and H_2. In this way, hydrogen with a high degree of purity can be obtained from WGS after the subsequent removal of the CO_2 formed in the reaction of the synthesis gas with water vapour. Natural gas reforming can achieve efficiencies of between 74% and 85%, according to a study published in the scientific journal Materials Science for Energy Technologies (2019).

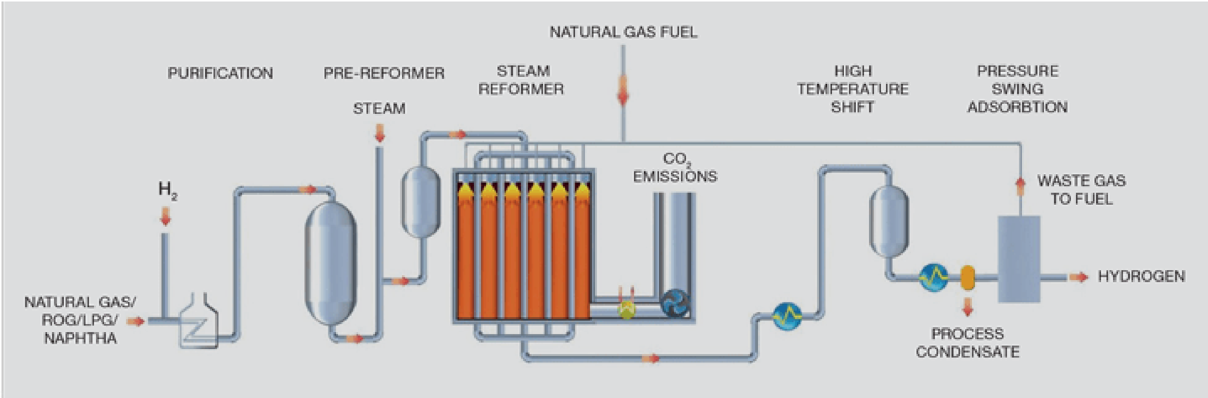

Figure 18 - Hydrogen production using SMR technology (Source: Bill Cotton, The Chemical Engineer, 2019).

Like the gasification process (explained in the next section), SMR is a production method that releases CO_2, in addition to other GHGs, with the environmental impact that this entails. It is estimated that for every tonne of hydrogen, between 9 and 11 tonnes of CO_2 are emitted, taking into account only energy use and emissions from the reforming process, disregarding possible methane leakage. About 33% of the final emissions are due to the burning of fossil fuels for the production of the heat needed in the reforming process. Globally, hydrogen generation from natural gas reforming accounts for 630 Mt of emissions per year (2017).

Carbon Capture

A carbon capture and storage (CCS) and/or utilisation (CCSU or CCU) system can be incorporated into the H_2 gasification or reforming processes to reduce their associated environmental impact. If the CO_2 is captured from the emission of biomass sources, it is known as bioenergy with carbon capture and storage (BECCS), and if it is with direct air capture, it is known as DAC (Direct Air Capture).

These systems use expensive, immature and unproven technology on a large scale. In addition, their CO_2 capture rates have been low, leak gas into the atmosphere and consume substantial amounts of electricity to capture and store CO_2. Many of the CCS projects funded by the European Union have been discarded and labelled as failures. Current state-of-the-art CCS projects only achieve around 63% capture of contaminant gases, despite predictions of an 85–95% target for the future, meaning that between 5% and 15% of all CO_2 hypothetically captured will leak and escape back into the atmosphere.

The combustion process also emits other gases and particles that deserve special attention, as the ultimate goal is the overall reduction of GHGs and improvement of air quality. This system involves not only CO_2 capture but also transport and storage, which is why the carbon capture system is as important as the efficiency of the storage and/or use of the captured CO_2. For example, in order to inject CO_2 into certain geological formations (gas fields, depleted aquifers or salt caverns), gas compression is required to reach such depths, which requires high energy consumption. Studies carried out to determine the environmental impact of this alternative usually establish a storage period of at least 100 years, a dangerous baseline consideration because it may jeopardise all efforts to decarbonise the economy. As an alternative to CCS storage, the main applications proposed for CCU are to store carbon dioxide captured in old oil wells to enhance oil recovery or to use it to produce synthetic fuels, which, ironically, means increasing the availability of polluting fuels.

Hydrogen obtained from natural gas reforming has been assigned the colour grey, and if the process includes CCSU, it is assigned the colour blue or the low emission label. Grey hydrogen's historical price is around 1-1.5 €/kgH_2, not including carbon capture. That makes it difficult, albeit on an inhomogeneous calculation basis, to migrate towards more sustainable models of production that are not dependent on fossil fuels and, therefore, emission-free. However, they will gradually catch up as their price increases through the incorporation of the associated environmental impacts and the costs of renewable alternatives are reduced through the development of technology.

3.1.2 Gasification

Gasification is a process by which liquid or solid fuels rich in carbon (biomass, coal, oil derivatives, etc.) are converted into gas, known as syngas. Synthesis gas (or syngas) is a gas whose main composition is a variable mixture of quantities of carbon monoxide (CO) and H_2, with other gases such as CO_2, CH_4, water vapour, etc. often present in smaller proportions. During this gasification process, **partial oxidation** takes place for incomplete combustion at very high temperatures (between 800 and 1800 °C, depending on the process and feedstock), by controlling the amount of the oxidising agent (oxygen and/or steam) used in the reaction. In general, water vapour (H_2O), due to the presence of H_2 in its molecule, is usually added as an oxidising agent to increase the hydrogen composition of the syngas produced after gasification.

This reaction is carried out in the presence of a catalyst to increase the gasification reaction rate and decrease the time required. Depending on the type of catalyst, lower or higher pressure and temperature are required to carry out the process. On the other hand, depending on the composition and quality of the feedstock, as well as the type of gasifier, the resulting syngas will contain low levels of hydrocarbons and traces of various components from the feedstock or formed during gasification (especially in the case of biomass).

The presence of inert molecules affects the purity of the synthesised H_2 and must be eliminated by pre-treatment of the raw material prior to gasification and subsequent conditioning of the synthesis gas produced to separate the unwanted components. Due to the low hydrogen/carbon (H/C) ratio of coal and biomass, the syngas obtained is rich in carbon oxides (CO and CO_2) and deficient in hydrogen. Therefore, as after the methane reforming process, methane has to undergo the Water-Gas Shift (WGS) process to react the main components of the produced syngas with water vapour to increase the amount of hydrogen formed. The efficiency of the H_2 synthesis process is higher for coal gasification than for biomass gasification. In general, based on the lower calorific value of the fuels, gasification can achieve efficiencies in the order of 30% to 40%. The hydrogen obtained from coal gasification has been assigned the colours black or brown and its production generates 20 $tonCO_2/tonH_2$. Therefore, one option presented by this process is the possibility of being able to capture and store this CO_2 and thus reduce emissions into the atmosphere.

3.1.3 Pressure Swing Adsorption (PSA)

This is not a production method itself, but it is a necessary process in several cases to purify the output hydrogen to a high percentage of the product. It is important to add it to the analysis because the percentage of hydrogen in the final product has to be close to 100% in order to be efficiently used in energy generation and other industrial uses, so the cost of this process must be added to the economic analysis in the next chapters.

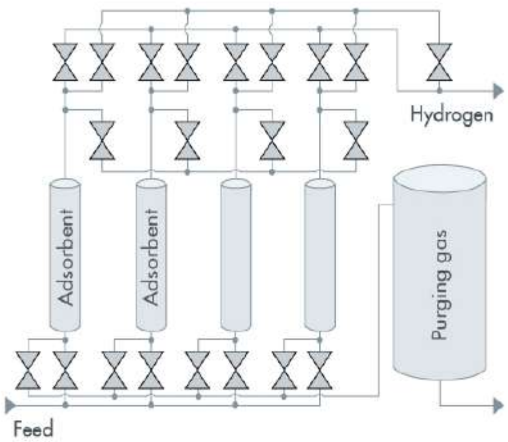

Figure 19 - Pressure Swing Adsorption System (Source: Samson Group, 2020).

According to Samson Group (PSA-systems manufacturer), the adsorption process is based on the binding of gas molecules to an adsorbent material. The adsorbent bed is specially selected depending on the gas to be adsorbed. Ideally, only the gas to be separated is adsorbed, while all other gases pass through the adsorbent bed without being trapped. The purity of the adsorbed gas depends not only on the adsorbent used but also on the temperature and pressure during the process. Therefore, the control valves used also contribute considerably to the quality of the final product. Figure 19 presents the scheme of a PSA system for better understanding.

The pressure swing adsorption process is divided into four stages that occur in cycles:

1- Adsorption: Adsorption takes place at high pressure (up to 40 bar). The gas mixture passes through a bed of adsorbent. The adsorbent traps easily adsorbable gas molecules, while gas molecules that are not easily adsorbable (or not adsorbable at all) pass through the bed. The adsorbent bed continues to adsorb gas molecules until it reaches its maximum capacity.

2-Depressurisation: Depressurisation is the first step in the regeneration (desorption) of the adsorbent bed. As the pressure drops, the gas molecules in the adsorbent bed are released, and the target gas is discharged from the adsorption tank.

3- Purge: The adsorbent bed is purged with the target gas to regenerate it completely.

4- Repressurisation: Repressurisation is done with the gas mixture or with the target gas until the adsorption process conditions are restored.

3.1.4 Pyrolysis

As an alternative to conventional H_2 synthesis processes based on thermochemical methods, there is a novel technology whereby methane or various fuels, such as biomass or different hydrocarbons, are subjected to pyrolysis (a process at high temperatures, between 800°C and 1,200°C, in the absence of oxygen), giving rise to carbon in solid form as a by-product. Similar to the gasification process, the efficiency of the process in converting the fuel used into hydrogen is between 35% and 50%.

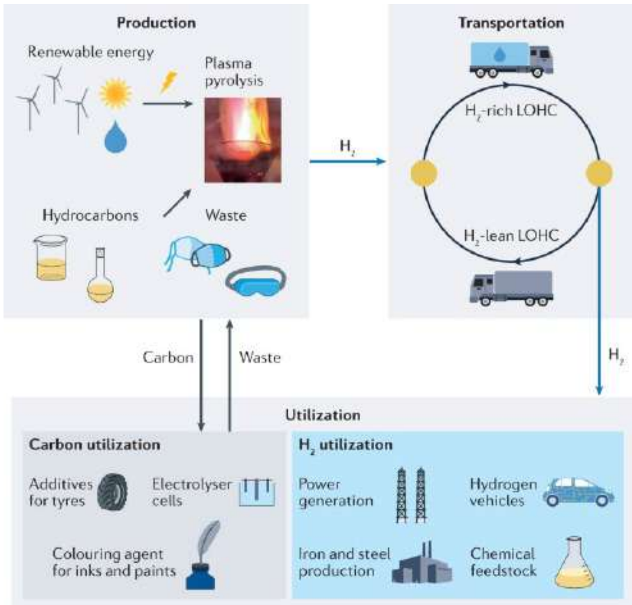

Figure 20 - pyrolysis for a sustainable hydrogen economy (Source: Chen, G., Tu, X., Homm, G. et al., 2022).

The diagram in Figure 20 illustrates the implementation of this system in the economy. Unlike methane reforming, by not using an oxidising agent (and therefore no chemical compound containing oxygen in its molecule) in the decomposition of methane, the possibility of producing carbon oxides (CO_2 or CO) is reduced and, as the carbon is in a solid state, there is no need to separate it from the gaseous H_2 gas. This method produces three tonnes of pure carbon residue in a solid state for every tonne of hydrogen, a by-product that could be used in different industrial processes, such as the production of pigments or polymers, among others.

The hydrogen obtained from the pyrolysis of natural gas has been assigned the colour turquoise and is also labelled in the literature as low/medium-emission H_2. One important thing to take into account related to this method is where the energy for the high temperatures comes from because that is the main source of emissions and cost in this process.

3.1.5 Thermolysis

Thermolysis is a process based on the splitting of the water molecule by an exothermic chemical reaction called hydrolysis, whereby the water molecule (H_2O) dissociates (separates) into its constituent elements H_2 (resource) and O_2 (as a by-product of the chemical reaction). Thermolysis is a way of producing hydrolysis of water, whereby the energy required to carry out this reaction is delivered solely as thermal energy, which requires very high temperatures of approximately 2,500 °C. The overall efficiency of the process is between 20% and 45%.

This method is not currently in use in the industry, but several projects are researching how to produce hydrogen in an economically feasible way with this method.

3.2 Electrochemical processes

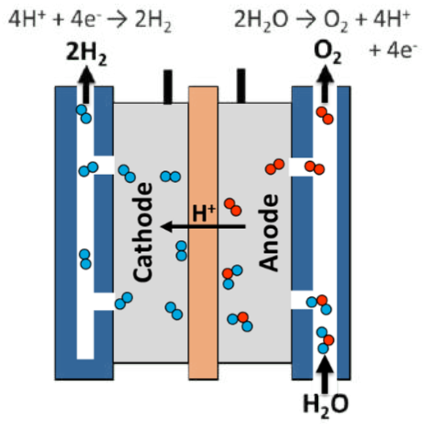

Figure 21 - Functioning of an electrolyser (Source: U.S. Energy Department, 2018).

Electrochemical processes are based on the hydrolysis of water, a reaction using electrical energy known as the electrolysis of water, whereby a direct electric current flows from the positively charged electrode (anode) to the negatively charged electrode (cathode) immersed in water mixed with a substance (electrolyte) that improves the electrical conductivity of the water by reducing the resistance to the passage of current through the water (illustrated in Figure 21).

As in thermochemical reactions, in electrochemical reactions, catalysts (electrocatalysts) may also be added to the electrode surfaces to increase the rate of chemical reactions by improving the transfer of electrons between the electrodes and the reactants.

The electric current separates (dissociates) the water molecule (H_2O) into its constituent elements H_2 (resource) and O_2 (as a by-product of the chemical reaction), which are released at the electrode surface (hydrogen is produced at the cathode surface, while oxygen will appear at the anode) in a gaseous state. After the sum of the chemical reactions taking place at both electrodes (cathode and anode), the number of H_2 molecules produced is twice the number of O_2 molecules. Moreover, the number of electrons transported across the electrodes is twice the number of H_2 molecules produced and four times the number of O_2 molecules obtained.

In water electrolysis, electrical energy is the main source driving the endothermic electrochemical reactions. Due to the stability of the water molecule, high consumption of electricity is required. Therefore, electrolysers are not always proposed to operate with water at room temperature. Thermodynamically, high operating temperatures are beneficial as they reduce the electrical current needed to carry out the electrolysis, increasing the kinetics (speed) of the hydrolysis reaction and decreasing the electrical losses in the cell.

Thermoelectrolysis, therefore, allows a significant fraction of the energy required to carry out the reaction to be delivered as thermal energy so that the demand for electrical energy is considerably reduced, and consequently, the cost of hydrogen production (compared to low-temperature electrolysis). The electrolysis process requires demineralised water (to avoid mineral deposition and thus undesired electrochemical reactions) as raw material, electricity and/or a thermal energy source.

The electrolysis process is carried out in electrolysers, of which there are two main categories according to their operating temperature: the so-called high-temperature electrolysers (700-1000 °C), working with water vapour, and the low-temperature electrolysers (70-80 °C) using liquid water.

Low-temperature electrolysers are divided into two types: low-temperature electrolysers operating in an acidic medium and those operating in a basic medium. The latter are the most abundant as they do not need precious metals such as platinum or iridium, which are essential for the former. Figure 22 presents the principal configurations, which are the Alkaline Electrolysis Cell (AEC or A-EL), the Proton Exchange Membrane (PEM or PEM-EL), Anion Exchange Membrane (AEM or AEM-EL) and the Solid Oxide Electrolyser Cell (SOEC).

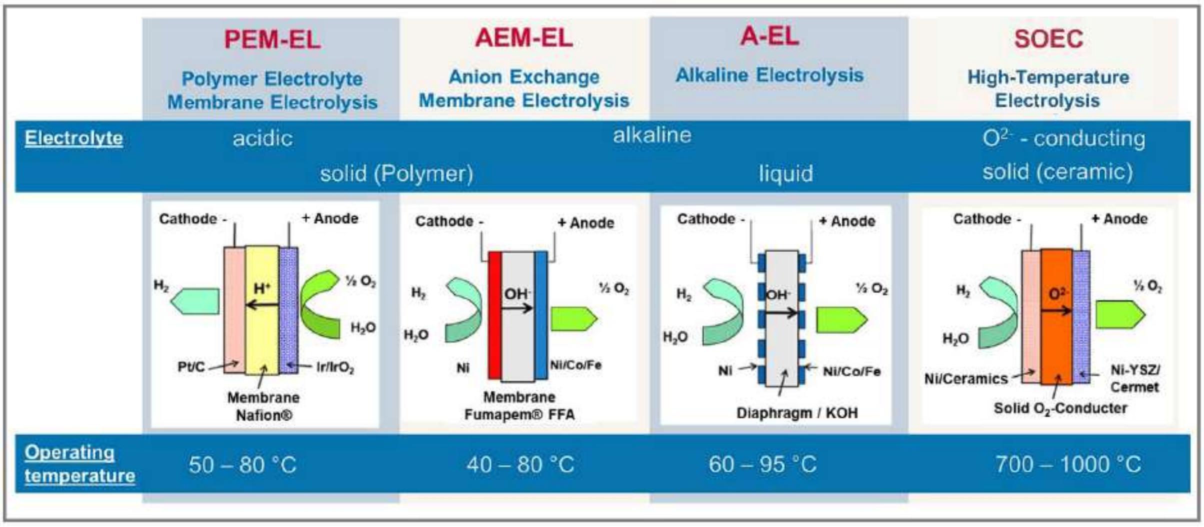

Figure 22 - Comparison of the electrolysis technologies PEMEL, AEMEL, AEL and SOEC (Source: Chemie Ingenieur Technik, 2021).

The main difference between them is due to the material used as the electrolyte. The most developed electrolyser technology at present and the one with the lowest investment cost is the AEC system. However, due to the characteristics of the electrolyte used in this electrolyser, low H_2 yields are achieved compared to other electrolysis technologies.

The industry is increasingly opting for PEM technology, although it currently has half the lifetime and is more expensive than the alkaline alternative. That is because both have similar performance, but PEM has greater flexibility of operation and a shorter response time, as well as a greater capacity to produce H_2 already compressed (around 30 bar). But, above all, it is the flexibility of operation, considering the use of electricity generated with renewables in over-powered hybrid systems and applications in which H_2 is required at high pressures (such as in mobility), that favours its application in those cases in which the higher capital cost associated mainly with more expensive components used in its production is compensated.

Finally, SOEC electrolysers are the least mature of these technologies and require the highest initial investment, but they have the greatest potential for improving energy efficiency among the commercial configurations because, in contrast to the two previous electrolysers, these systems operate at very high operating temperatures (650-1,000 °C). An additional advantage is their ability to operate reversibly (RSOC) in both electrolysis (SOEC) and fuel cell (SOFC) modes, producing electricity from hydrogen.

The high electricity consumption of an electrolyser increases the cost of hydrogen production. This cost could be minimised, and would be competitive, only if the necessary input energy were supplied from low-cost renewable energy sources. This H_2 obtained from the electrolysis of water with electricity from 100% renewable sources has been assigned the green colour (or pink in case of nuclear generation) or just renewable label, as it does not generate any CO_2 emissions in its entire production chain. Renewable hydrogen has room for improvement by increasing the capacity and diversity of electrolysers, reducing the still high costs of its components, and addressing its low energy efficiency, measured as kg of hydrogen produced per kWh of electricity consumed. At present, large amounts of electrical energy are required due to the low efficiencies of electrolysers.

Electrolysers operating at temperatures well above ambient temperatures will additionally require a thermal energy source. To ensure that the thermal energy supplied to the electrolyser is of renewable origin, proximity to renewable heat sources such as concentrating solar thermal energy, high temperature geothermal energy or through synergies with other processes from which waste heat can be utilised is necessary.

Nuclear power plants are a good example of this because they can utilize energy from the heat they produce in an efficient way. As a result, pink hydrogen now has access to an entirely new economic reality. According to the World Nuclear Association, nuclear power plants could produce zero-carbon hydrogen using four different methods:

- **Cold electrolysis**, which uses only electricity
- **Low-temperature steam electrolysis (LTSE)**, which uses both electricity and heat
- **High-temperature steam electrolysis (HTSE)**, which uses both electricity and heat
- **High-temperature thermochemical production**, which uses only heat

Although they may be constrained by materials limits, processes that use heat benefit from higher efficiencies and potentially lower production costs. That is because the high temperatures can quickly degrade the membranes used in HTSE. The currently under development next-generation nuclear reactors may offer practical manufacturing routes by the next decades.

To summarise, Table 5 presents technical and economic values associated with the various electrolyser models analysed.

Table 5 - Comparison of the electrolysis technologies PEMEL, AEMEL, AEL and SOEC. (Source: Chemie Ingenieur Technik, 2021).

	AEL	AEM	PEM	SOEC
System efficiency [%][a)]	up to 65	up to 68	Up to 65	up to 82
Current densities [A cm^{-2}]	0.2–0.6	0.5–2	1–3	0.3–1
Operating temperature [°C]	60–95	40–80	50–80	700–1000
Operating pressure [bar]	atm. – 32	30–35	atm. – 40 (demon-stration up to 700)	1–3
Module size [kW]	5–6000	up to 5	5–2500	–
System size [MW]	up to 100	–	up to 100	up to 0.15
CAPEX costs [€ kW^{-1}]	500–1200	–	1000–1800	1200–2000

3.3 Other processes

Many other production methods are being investigated nowadays, but they have not achieved even comparable production costs, so in this project, some of them are going to be reviewed only from the technical point of view, without considering them for the economic analysis.

Photochemical processes

Instead of applying electrical energy to provide the energy needed to carry out hydrolysis, the use of direct solar irradiation (rather than harnessing photons to produce electricity through the photoelectric effect on which photovoltaic panels are based and thus powering the electrolyser) to break down the water molecule is being studied. This process is known as photolysis, which attempts to mimic the process of photosynthesis (artificial photosynthesis). Photocatalysis, photoelectrolysis or photocatalytic decomposition, among others, are processes based on solar irradiation as the source of energy to synthesise H_2 from water. Nevertheless, these methods are still at an early stage of development with a wide range of improvements in their conversion efficiency.

Biophotolysis: Hydrogen is extracted from water using sunlight and specialised micro-organisms such as green algae and cyanobacteria. These micro-organisms consume water and generate hydrogen as a by-product of their natural metabolic processes, although at rates too low for commercial production and with limited conversion efficiencies.

Photoelectrolysis: This is the electrolysis of water caused by the potential difference due to the incidence of solar radiation on electrodes made of certain semiconductor materials, each of which operates optimally at a particular wavelength. This process has great potential for cost reduction, with higher efficiency than electrolysis powered by photovoltaic cells.

Biochemical processes

Biological processing is another alternative for the production of carbon-neutral hydrogen. The main methods are direct and indirect biophotolysis, photofermentation, dark fermentation and metabolic processing. However, these techniques are underdeveloped, under research and generally have low efficiencies, and H_2 production volumes are lower compared to other production methods.

4. Economic Analysis

This chapter develops the economic analysis of the main hydrogen production methods in order to determine, at present and in the near future, which technologies will be used for production and whether a change towards production with cleaner energies is indeed economically viable.

All the processes analysed in this section have already passed the technical analysis stage and, therefore, will be studied in this chapter from an economic feasibility point of view. In the first section, there is a general explanation of the methodology implemented, and in the following ones, each step of the study.

4.1 Methodology and General Considerations

In this case, it is particularly important to describe precisely the methodology used for the analysis so that the results can be properly interpreted. This section explains, as a roadmap, the general guidelines and steps to be followed in the following sections of the research, but the particularities and exhaustive explanations of each one will be duly explained in the corresponding section.

4.1.1 Economic Parameters

The research takes into account a bibliography from around the world but takes into account that, as well as with all the work, the study focuses on the European Union, as it is one of the most developed regions in the field of hydrogen production using alternative and more environmentally friendly techniques. It is important to clarify that it is not based on a specific country but on the economic values of the region as a whole. These are the economic parameters used in this work (unless otherwise stated):

- **European inflation rate (2002-2022) average**

The calculation is the average of the last 20 years in the European Union according to Eurostat (the statistical office of the European Union). Figure 23 shows the average inflation of the region for the period of interest. This data has been corroborated with Statista.

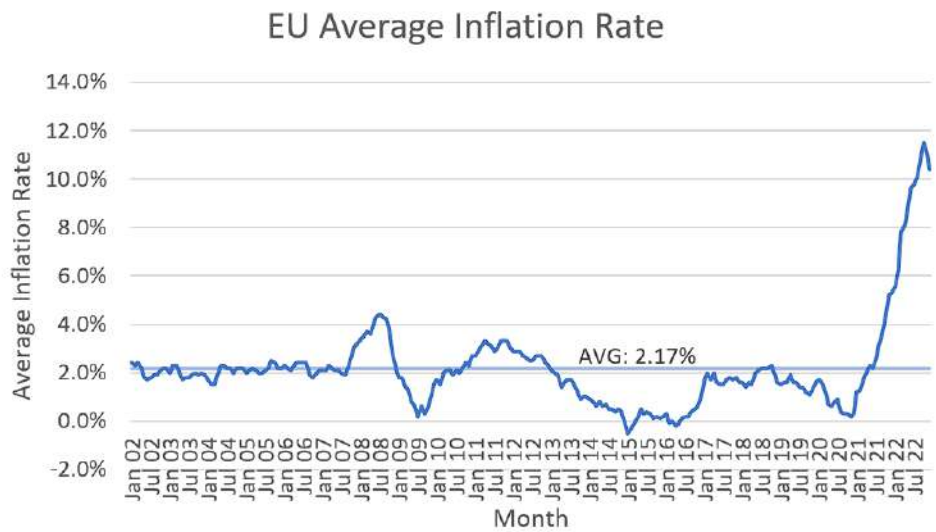

Figure 23 - European Union Average Inflation Rate (Data source: Eurostat, 2022).

The inflation rate has been increasing in the late period because of the energy crisis but has started to go down. Eurostat also provides a projection for the following years in which a stabilization close to 2% can be observed (see Figure 24), so it seems sensible to use the average of **2.17%** for the feasibility analysis.

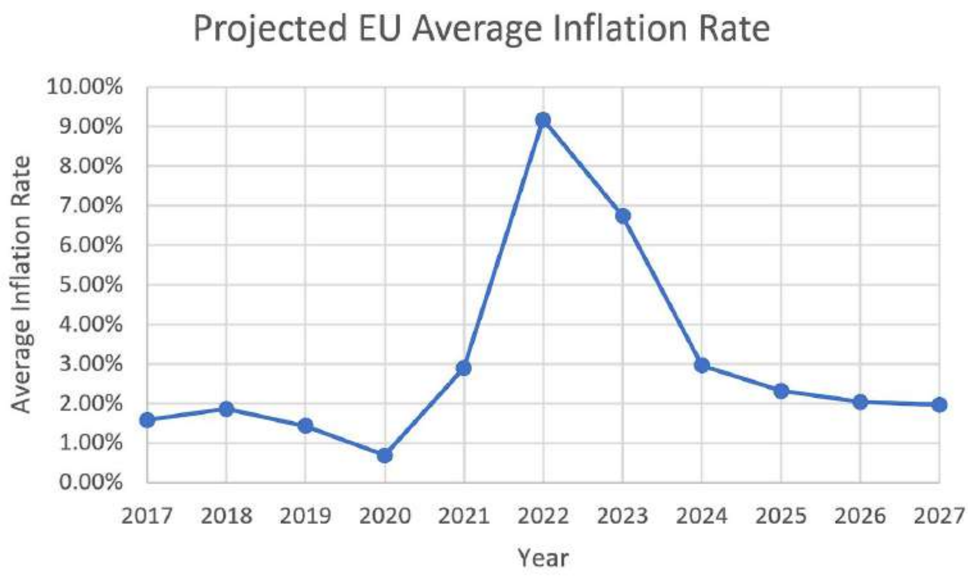

Figure 24 - Projected European Average Inflation. (Data source: Eurostat, 2022).

- **EUR/USD Exchange Rate**

According to Eurostat, the 20-year average exchange rate of EUR/USD is 1.24. The average value during 2022 was 1.06, and projections estimate that this tendency is going to continue in the following years. In general, the prices indicated in this work will be converted to EUR when needed, following the values informed in Table 6. For future estimated values, an exchange rate of **EUR/USD=1.10** is going to be considered.

Table 6 - Average Exchange Rate EUR/USD Evolution (Data source: Statista, 2023).

Year	Average Exchange Rate EUR/U$D
2013	1.328
2014	1.329
2015	1.110
2016	1.107
2017	1.130
2018	1.181
2019	1.120
2020	1.142
2021	1.183
2022	1.053
Jan-2023	1.07

- **Weighted Average Cost of Capital (WACC):**

In this case, WACC is understood as a measure of the hydrogen producer company's average cost of capital, which includes both the cost of equity (money from investors) and the cost of debt (borrowed money). It is calculated with the following equation:

$$WACC = c_e \times \frac{E}{D+E} + c_d \times (1-t) \times \frac{D}{D+E}$$

Where

- c_e = Cost of equity
- c_d = Cost of debt
- D = Market value of debt
- E = Market value of equity
- t = Corporate income tax rate (assuming notional taxes on EBIT in cash flow projection)

The cost of debt is the rate of interest that has to be paid back to the creditor, either by way of a bank loan, bond issue or by the mechanism by which the company finances itself. The cost of equity is the return that investors expect to get for the money they invest in the company (after Taxes). In Europe, according to diverse sources (Eurostat, Lazard and KPMG), the cost of debt is close to 7%, and the cost of equity is close to 10%. Considering a proportion of 40% of the capital as equity (leaving 60% as debt), the WACC is between 5% and 7%. This number is important to calculate the levelized cost of hydrogen because it is the one that is going to be used as the nominal return rate of the projects, which means that the investors receive the return they wanted for their investment.

- **Tax rate**

The tax rate that is going to be considered in this project is **t = 35%**, as taxes on revenue in Europe are, in general, between 30% and 40%.

- **Real WACC**

Real prices and rates consider the inflation rate in the analysis. In plain words, if WACC is lower than the inflation rate, then the project is producing less value than the devaluation of that currency.

The real WACC is calculated with the following formula:

$$Real\ WACC = \frac{1 + Nominal\ WACC}{1 + inflation\ rate} - 1$$

Summary of economic parameters considered

Table 7 presents the values used in the study for the economic parameters explained before.

Table 7 - Economic Parameters used in the analysis (European averages).

Economic Parameters	Abbreviation	Value
Inflation	inf	2.17%
Tax Rate	t	35%
Cost of Equity	C_e	10%
Cost of Debt	C_d	7%
Proportion of Equity	E	40%
Proportion of Debt	D	60%
Weighted Average Cost of Capital	WACC	6.73%
Real WACC (adjusted by inflation)	Real WACC	4.46%

v

4.1.2 Production methods considered in the economic analysis

The selected methods were chosen for the economic analysis because they present a mature enough technology that has proven to work well for the production of large quantities and are either currently used for industrial production or are presented in the diverse bibliographic sources as one of the main alternatives for more sustainable production. Some other production options seem also feasible in the future (like turquoise hydrogen), but there are no industrial productions or prototypes already working to consider them for this analysis.

1- Steam Methane Reforming (SMR) from natural gas without Carbon Capture and Storage (Grey Hydrogen)
2- Steam Methane Reforming (SMR) from natural gas with Carbon Capture and Storage (Blue Hydrogen)
3- Gasification (Black Hydrogen)
4- Electrolysis using renewable energy (Green Hydrogen)
5- Electrolysis using Nuclear Energy (Pink Hydrogen)

4.1.3 Analysis Structure

First, research about the current values of production costs of one kilogram of hydrogen (kgH_2) with the different methods is carried out, for which bibliographic investigation is conducted only considering actual production cost values (meaning that future estimates in projects that have not yet started production are not considered). It is important to clarify this and to base it on the fact that it has always been the main objective of this work to present the current and short-term situation of hydrogen production objectively and realistically so that technologies and values that are not supported by hard evidence such as production plants or functioning real-size prototypes cannot be considered. However, future estimates will be considered when there is enough evidence (i.e., the decreasing acquisition cost of electrolysers, which has been on a marked trend for many years due to the continuous development in the production of this relatively recent technology).

At this stage, values relative to the past four years are being considered, although, for some future analysis, the evolution over time of the cost is also presented, allowing the analysis of which factors affect it to a greater or lesser extent. It is important to keep in mind that the prices of everything related to energy have recently been affected by the conflict between Russia and Ukraine, so having values prior to the conflict and being able to analyse the evolution of production costs can provide relevant information about which factors impact the most in hydrogen production costs. Also, different prices related to this study will be analysed in order to be used in the following sections, such as the Natural Gas price and the cost of Electrolysers.

After presenting the current production values according to the literature, an economic feasibility analysis of different production alternatives is carried out. In the previous chapters, it was explained that the demand for hydrogen would probably increase in the coming years and decades. It is, therefore, appropriate to carry out a project analysis for each production method studied in order to determine whether alternative production methods can indeed compete with those used in the last decades to cover the increase in production in the short term. More than one possible scenario will be considered in order to present how each of the projects would evolve according to the different boundary conditions in which it is found.

To perform the economic analysis, the concept of Levelized Cost of Hydrogen (LCOH) will be used, which is an economic instrument to translate the cost of production over the life of the project to a discounted value, taking into account inflation, rate of return, and the economic values previously mentioned. This tool is already widely used to calculate energy production values and to be able to compare different technologies in a fair way, as each has its own characteristics, such as different lifetime or maintenance costs. In this project, a calculation tool is developed using the Excel program to calculate the LCOH of the analysed technologies.

First of all, the average economic parameters of the European Union will be considered (explained in the specific section), and no aid, subsidies or economic penalties will be considered in any of the methods, either from the state or from external organizations. Subsequently, scenarios will be presented, taking a realistic and conservative approach, in which methods that avoid or reduce greenhouse gas emissions receive government support (as is currently the case with these projects). Penalties due to emissions are not considered in the first approach but will be added to the analysis later. The objective of this is to create a fair comparison of technologies nowadays, without external factors, and then add the factors to see how they impact the cost of each technology.

Finally, a sensitivity analysis of the different costs in relation to different variables, such as the overall cost of gas, carbon credits and the rates used in the analysis, will be carried out. Finally, the most important conclusions of the economic analysis are presented.

4.2 Current prices and short-term projections

As explained above, this section presents costs for recent years of hydrogen production by various means. The price analysis of other assets that are important for the analysis is also presented.

Figure 25 presents a graph from the "Global Hydrogen Review" (IEA 2022) which compiles and condenses information on production costs of different production methods from 2021 and estimates for 2030 and 2050, based on its own database of companies, a McKinsey study and information provided by the Hydrogen Council.

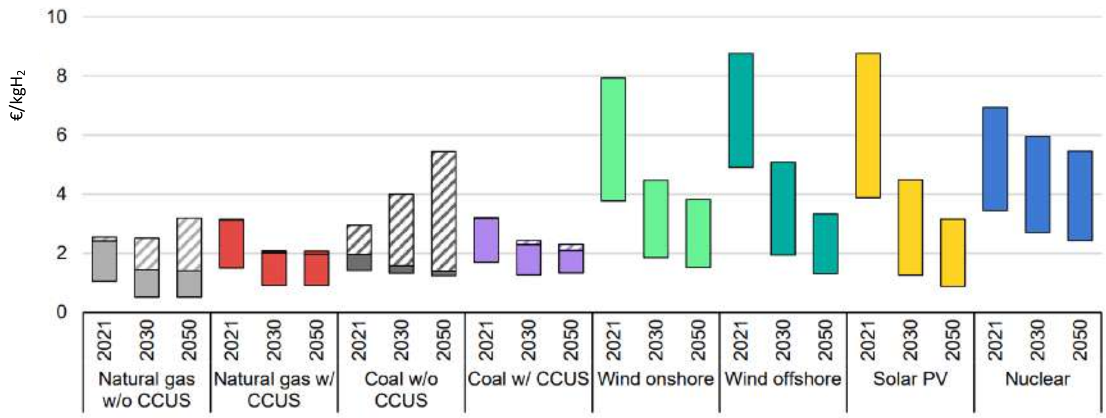

Figure 25 - Levelized cost of hydrogen production by technology (Source: Global Hydrogen Review, IEA, 2022).

To understand the graph, it is necessary to explain what **Carbon Credits** are. Carbon Credits (also called Carbon Permits) are defined as permits that allow the owner to emit a certain amount of carbon dioxide. These credits are regulated and priced by the market. In other words, emitting greenhouse gases entails a direct economic cost for companies because they have to buy them in order to be able to emit them. If they avoid emissions, they could sell non-used permits. In the graph above, the dashed area represents the cost added to that production method due to emissions. It can be seen how it does not affect technologies that avoid greenhouse gas emissions. For 2021, the IEA considers a Carbon Credit cost of 15 €/tonCO_2, which is currently well below the current value (in February of 2023: 100€/tonCO_2).

As can be seen, in 2021, the costs per kg of hydrogen are not significantly affected by emissions (due to the low cost of Carbon Credits, consistent with that time). It also highlights that the most favourable average production cost is that of natural gas, with values between 1.4 €/kgH_2 and 2.7 €/kgH_2, while renewable energy costs are the highest (3.6 - 8.2 €/kgH_2).

The report itself specifies that by taking values from the beginning of 2021 and earlier, the impact on natural gas and Carbon Credit prices changes due to the energy crisis is not reflected. In fact, in June 2022, the cost of grey hydrogen production in Europe was three times higher than in 2021 (4.4–7.1 €/kgH_2), and it has now stabilised at 4.8–7.9 €/kgH_2 for blue hydrogen and 3.7–6.8 €/kgH_2 for grey hydrogen. Figure 26 presents a graph showing the production cost of blue hydrogen as a function of the price of natural gas and, in comparison, the green hydrogen production costs in specific areas.

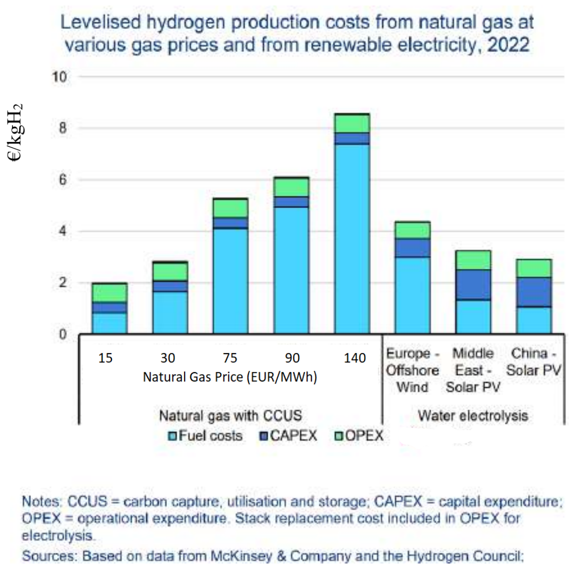

Figure 26 - Cost of grey hydrogen production for different natural gas prices and green hydrogen options (Source: Global Hydrogen Review, IEA, 2022).

Two important graphs for the analysis can be seen below, both from the organization Trading Economics, but similar ones could be found from other sources. Figure 27 presents the evolution of gas prices over the last few years. It is currently around 50 €/MWh, far from the value of 2021 (20 €/MWh), but also recovering from the record prices presented in 2022. Estimations for the next two years indicate that the price will probably stabilise between 30 and 70 €/MWh. Figure 28 shows a similar graph that shows the evolution of the price of carbon credits. This price is rising even faster than expected in the past years, and new estimations indicate that this tendency is going to continue in the following years.

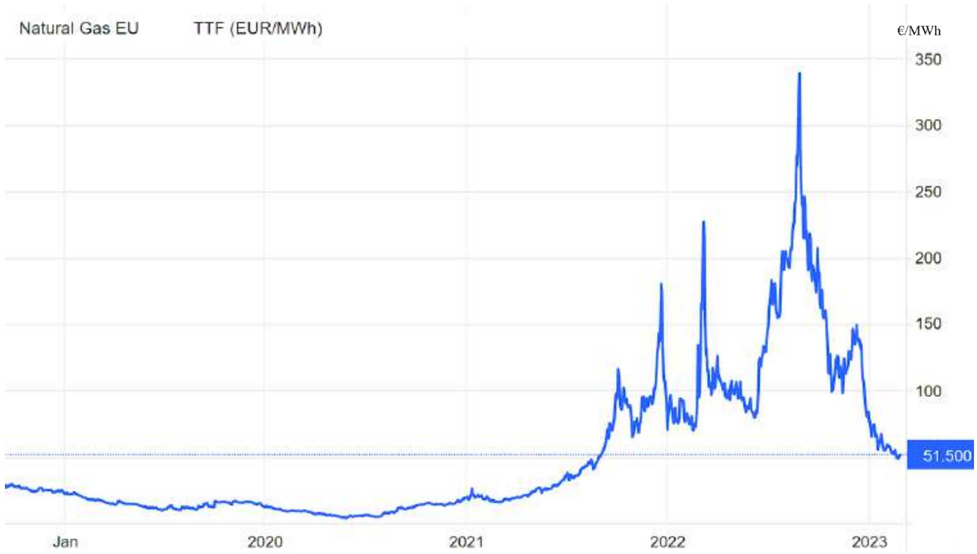

Figure 27 - Natural Gas Price Evolution (Source: Trading Economics, 2023).

Figure 28 - Carbon Credits Price Evolution (Source: Trading Economics, 2023).

According to ACER (European Union Agency for the Cooperation of Energy Regulators), the price of Liquified Natural Gas imported into Europe during the first two months of 2023 was between 45 and 55 €/MWh (ACER Spot LNG price assessment for EU. 2023)

In 2019, a special report named "The Future of Hydrogen" (2019) was presented at the G20 reunion in Japan. In that report, the price of producing grey hydrogen in 2018 in Europe was around 1.6 €/kgH_2 and blue hydrogen around 2.1 €/kgH_2, considering the natural gas price of 15 €/MWh. In contrast, the price of green hydrogen was 2.8, considering renewable energy cost 30 €/MWh.

Other relevant information in this report is the characteristics of electrolysers in 2018:

- Alkaline Electrolysers: Efficiency: 63-70%; Load Range: 10-110% of nominal power
  operating hours: 60000 – 90000; CAPEX: 450-1250 €/kW
- PEM Electrolysers: Efficiency: 56-60%; Load Range: 0-160% of nominal power.
  operating hours: 60000 – 90000; CAPEX: 1000-1650 €/kW
- SOEC Electrolysers: Efficiency: 74-81%; Load Range: 20-100% of nominal power
  operating hours: 10000 – 30000; CAPEX: 2500-5000 €/kW

Although the values are old, they serve as a reference. SOEC technology is the newest technology and is expected to improve significantly in the coming years, especially the cost of production, which is related to the high prices of materials that can withstand the high temperatures required for this method of hydrogen production. (600-1000 ºC). Nuclear power plants and solar thermal are the energies more related to this process because they could provide both the electricity and the heat for this type of electrolyser. The key is that this type is allowed to operate in reverse (as a fuel cell), so during the moments of low demand, it could use the extra energy to produce hydrogen, and during high demand periods, both the generator and the electrolyser can produce electricity. According to the Department of Energy of the United States of America, research is underway to develop materials for SOEC electrolysis that are well suited to the temperature levels of nuclear energy heat sources (US-DOE. 2018). Small modular reactors could also have a role to play in SOEC electrolysis in the future.

Several reports make short-term estimates of hydrogen production costs using various methods. Bloomberg's report "Hydrogen Project Evaluation" (2020) indicates a green hydrogen production cost of 2.3-4.1 €/kgH_2 in 2019 and 1.1-2.4 €/kgH_2 in 2030. Their estimates indicate that by then, it would already be competitive with blue hydrogen (1.3-2.5 €/kgH_2 in 2019 and 1.2-2.4 €/kgH_2 in 2030). They also indicate that the cost of electrolysers has fallen by 40% on average in recent years, and even by 80% cheaper, according to Chinese producers (300 €/kW). The report "Analysing future demand, supply, and transport of hydrogen" (Guidehouse 2021) focused on Europe projects that 150 TWh of green hydrogen can be produced at 1.5-2.0 €/kgH_2. According to this report: "green hydrogen delivered at 2.0 €/kgH_2 can compete with grey hydrogen at a CO_2 price of around 100 €/tonCO_2 in 2030", and that is the current price of carbon, as stated before.

It is important for this work also to investigate the price of energy. Every year, the consulting firm Lazard presents valuable reports on energy costs depending on their origin. In the "Levelized Cost of Energy (LCOE) Analysis V15", they present the following energy production costs at the end of 2021 (see Figure 29), without considering any subsidies or aid, with an estimated gas cost of only 12 €/MWh, far from actual prices. As can be seen, some renewable energy sources are already competitive with conventional production methods. These energy prices have been corroborated with the International Energy Agency's database and will be the ones considered in further analysis. Lazard also presents a "Levelized cost of hydrogen analysis V2" (2021) in which a similar unsubsidized cost of green hydrogen analysis is made, showing prices between 2.2-3.7 €/kgH_2 considering electricity costs of 36 €/MWh and a project lifetime of 20 years (considering stack replacement).

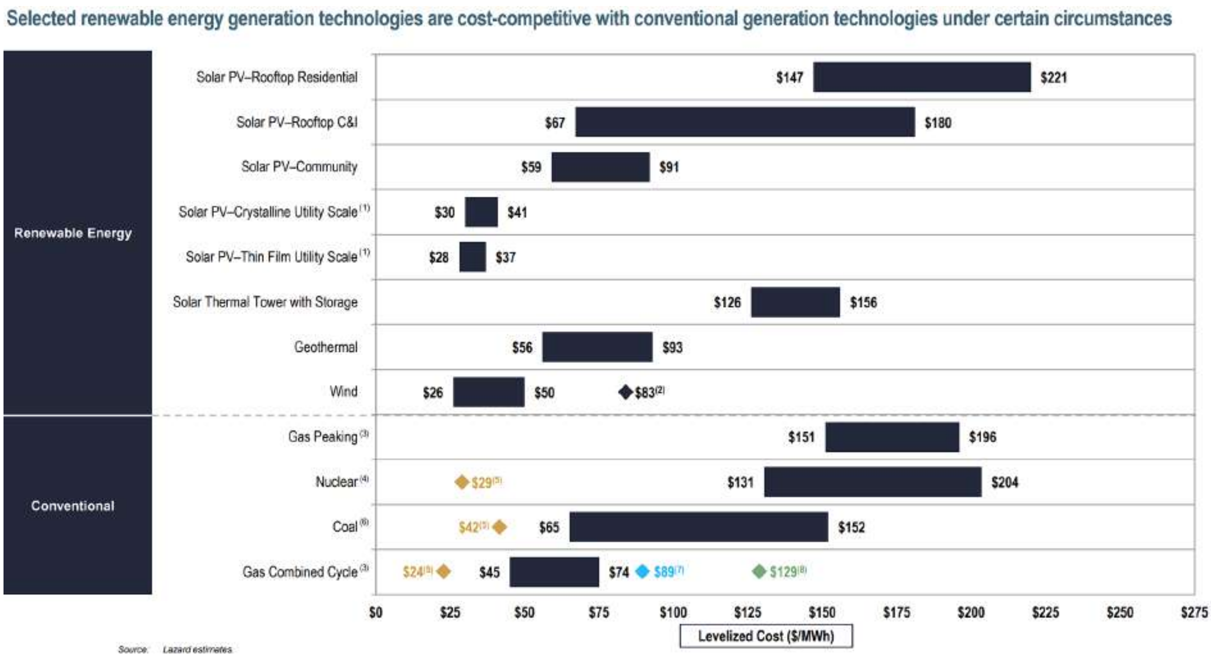

Figure 29 - Levelized Cost of Energy Comparison - Unsubsidized Analysis (Source: Lazard Consulting, 2021).

Also, Figure 30 shows the evolution of the LCOE for the different technologies over the past decade, in which it is possible to highlight that the price of renewable energy has decreased between 72% (for wind) and 90% (for solar photovoltaic) in 12 years.

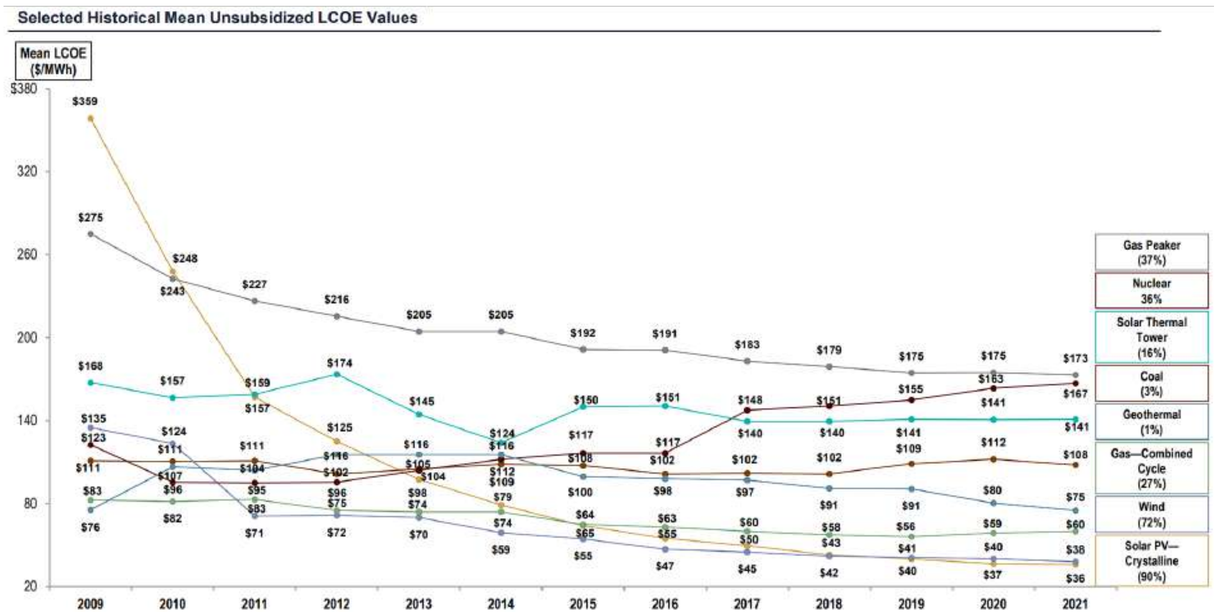

Figure 30 - LCOE Unsubsidized Evolution for Different Technologies (Source: Lazard Consulting, 2021).

After all the analysis made and the research on costs and prices of the past four years among the mentioned bibliography, Table 8 condenses the average values relevant to this work and the minimum and maximum values that are going to be considered in the sensitivity analysis.

Table 8 - Average costs and prices of hydrogen and different assets.

	Cost / Price (2020-2022 average values)			
	Min considered	Average	Max Considered	Units
Grey Hydrogen	1.0	1.8	2.8	€/kgH_2
Blue Hydrogen	1.6	2.5	3.4	€/kgH_2
Black Hydrogen	1.5	2.2	2.9	€/kgH_2
Green Hydrogen	2.0	2.8	3.6	€/kgH_2
Pink Hydrogen	3.5	4.8	6.1	€/kgH_2
Natural Gas (2023)	15	40	75	€/MWh
Coal (2023)	90	172	220	€/ton
Carbon Credit (2023)	20	100	180	€/tonCO_2
Renewable Electricity	20	40	80	€/MWh
Electrolyser	300	600	900	€/MWh
Electrolyser efficiency	60%	70%	90%	

4.3 Production Methods Economic Analysis

In this section, the Levelized Cost of Hydrogen (LCOH) is calculated for each of the technologies that are going to be compared. As the different technologies have different and particular conditions, a tool for each one has to be programmed in order to calculate the costs properly. The particularities of each analysis will be explained in the correspondent sub-section, explaining the reasons for the values selected for each parameter. The technical particularities of each technology are not going to be explained in this section because they were already explained in the previous chapter.

4.3.1 Levelized Cost of Hydrogen Calculation

The simplest way to explain how a levelized cost calculation works is with the following equation:

$$Cost = \frac{Net\ Present\ Value\ of\ Total\ Cost}{Hydrogen\ Production}$$

$$Cost = \frac{\sum_{i=0}^{n} \frac{I_i + M_i + O_i}{(1+r)^i}}{\sum_{i=0}^{n} E_i}$$

Where:
I_i: investment in year i, (€).
M_i: maintenance and service cost in year i, (€).
O_i: operational cost in year i, (€).
E_i: energy (hydrogen) output in year i, kg.
r: discount rate, %. In this case is going to be equal to WACC, in order to provide the return expected by the investors and repay the debt.
n = lifetime of the project.

This is a simple calculation, and it is possible to add to the calculation the effect of other project evaluation parameters, such as the tax on the income, the effect of different types of assets depreciation, the tax life of the assets and the degradation of the facility in terms of the original efficiency.

Validation of the calculator

The LCOH calculator developed in this project has been validated by comparing the resulting cost values to those from other reports that made available the parameters used in their calculations, arriving at similar values (Lazard (2021) LCOH-V2; IEA (2019) Future of Hydrogen). Figure 31 shows the comparison between the original costs presented in the reports and the calculated ones in this work.

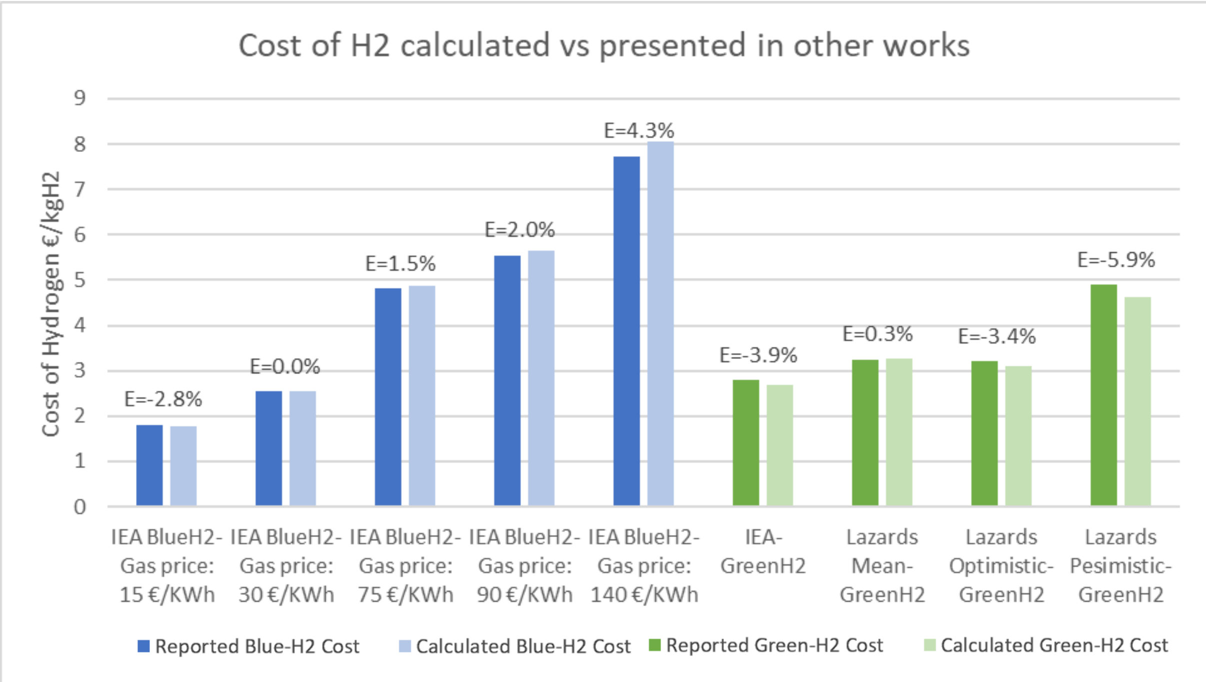

Figure 31 - Cost of H_2 calculated vs presented in other works.

The average absolute error was 2.7% and may be due to various factors, e.g., differences in the inflation rate considered or methods of taking into account the depreciation of assets.

General parameters considered in all further studies

The studies to be referred to in the next paragraphs are:

- Grey hydrogen cost calculation
- Blue hydrogen cost calculation
- Black hydrogen cost calculation
- Green hydrogen cost calculation
- Pink hydrogen cost calculation
- Sensitivity analysis

Input variables that are common to all the further studies (unless stated otherwise) are explained in this section.

Emissions:

Emissions are going to be computed as tonnes of CO_{2eq} considering the following factors provided by the International Energy Agency (condensed in Table 9).

Table 9 - Emissions factors related to each method (Data source: IEA, 2021).

Method	Emissions Factor	Units
Grey Hydrogen	8.9	$kgCO_2/kgH_2$
Blue Hydrogen	0.9	$kgCO_2/kgH_2$
Black Hydrogen	20.9	$kgCO_2/kgH_2$
Green Hydrogen	0.2	$kgCO_2/kgH_2$
Pink Hydrogen	0.2	$kgCO_2/kgH_2$

Emissions cost:

When the emissions are considered in the cost analysis, they are going to be computed as an operational cost following this equation:

$$Emissions\ Cost = ton\ of\ CO_2\ * price\ of\ Carbon\ Permit$$

This work considers initially no cost for emissions in order to compare the technologies without this recently incorporated instrument. This is an important parameter for sensitivity analysis. The current price of carbon permits is 100 €/$tonCO_2$, which is higher than the expected price for 2023. In fact, that is the expected price for 2030 in several past analyses.

Water consumption:

All the methods use water, in different proportions, as one of the inputs. In this analysis, water consumption is considered for two reasons. Firstly, even though water is considered cheap, it has a cost, and the amounts of water used in these processes tend to be huge. The other important aspect is the impact of using that water for this purpose. Some regions do not have enough water to conduct these projects, and the impact on society and the environment could also make the project unfeasible. At present, the cost in the European market is 0.8 € per tonne of water (2023).

Parameters considered for Levelized Cost of Grey Hydrogen calculation

Project lifetime: 20 years

The project lifetime can change from project to project, but in general, the past analyses made by the IEA and Lazard considered this lifetime.

Gas Price: 20 €/MWh and 40 €/MWh

The gas price is one of the most influential parameters. Two prices are going to be considered in the initial analysis. 20 €/MWh is the average price of the last years and is the one considered in other works. It is important to corroborate the calculations made in this work with past works.

The value of 40 €/MWh is also going to be considered because that is the current price of gas in Europe (2023), so it will lead to the actual LCOH. Nevertheless, a sensitivity analysis is going to be conducted regarding this item, with values between 15 and 65 €/MWh. In 2022, the price overpassed the 200 €/MWh mark, but it is not very probable to reach that price again, and in that case, the production of hydrogen or electricity from gas would be unfeasible.

CAPEX: 600 €/kW

Capital expenditure (CAPEX) of this type of plant can be presented in many different units. In this work, the CAPEX is standardized on kW for the plant at full capacity. The value of 600€/kW is the average for this technology, according to the IEA.

Production factor: 42 kWh/kgH_2

The production factor is correspondent to efficiency. It means that to produce one kg of hydrogen, the amount of energy required from the fuel is 42 kWh. Considering that one kg of hydrogen has a low heating value of 33.33 kWh, this means an efficiency of 79% for energy conversion. The value of 42 kWh/kgH_2 comes from the IEA's reports performing similar calculations (IEA 2022).

Load Factor: 98%

One advantage of these plants is their unabated production, which means that they produce almost all the time. Most reports consider a load factor of 98%, leaving a 2% margin to compensate for some losses during maintenance and not full power production.

OPEX: 4.5% of CAPEX

All the reports considered for this technology, based on the already operational plants, place the values for the operational expenditure (OPEX) between 4.5 and 5% of the CAPEX. Working with fossil fuels and high temperatures usually leads to high OPEX proportions for the maintenance and operation of the plant.

Parameters considered for Levelized Cost of Blue Hydrogen calculation

For this particular technology, two cases are considered:

1- Capture 48% of emissions: this consists of partially capturing emissions only related to the reforming process and is the technology currently applied in most of the projects in operation and is easier to implement in already working grey hydrogen plants.

2- Capture 90% of emissions: this consists of capturing emissions from the entire plant process, including the generation of heat to reach the temperatures necessary to carry out the reforming process. This process is called total capture, although there is a small portion of the emissions that cannot be captured, considering that the capturing process has an internal capture efficiency involved. In this work, unless specified otherwise, blue hydrogen refers to this case, as in all the bibliography.

With regard to grey hydrogen, the only project values that change are the following:

CAPEX:

The carbon capture and storage (CCS) plant in the 48% case is considered to lead to an increase in CAPEX of 50%, while for the 90% emissions capture case, the increase in CAPEX is 100%, according to reports from the international energy agency (IEA 2019).

Production factor

The implementation of the CCS system leads to more energy consumption, which can be directly accounted for as part of the production factor, implying a reduction in the efficiency of the energy conversion to hydrogen. A value of 48 kWh/kgH_2 is considered for the first case and 52 kWh/kgH_2 for the total capture system.

Load Factor:

A small reduction of the load factor is considered in these processes because a more complex system leads to more downtime throughout the year. Therefore, values of 97% for the first alternative and 96% for total capture are considered.

Parameters considered for Levelized Cost of Black Hydrogen calculation

Project lifetime: 20 years

The project lifetime can vary from project to project, but in general, the past analyses made by the IEA have considered 20 years.

Coal Price: 11€/MWh

The fuel price is one of the most influential parameters for this technology. The cost of coal considered in this work is the European stabilised price pre-conflict, which means 80 €/tonne of coal, or the equivalent value of 11€/MWh.

CAPEX: 1800 €/kW

The coal gasification process requires higher temperatures and more stages than the SMR process. According to the Global Hydrogen Review (IEA 2022), this leads to a CAPEX three times higher than SMR plants.

Production factor: 56 kWh/kgH_2

The production factor value of 56 kWh/kgH_2 comes from the IEA's reports performing similar calculations (IEA 2022).

Load Factor: 98%

Most reports consider 98%, leaving a 2% margin to compensate for losses during maintenance and not full power production.

OPEX: 5% of CAPEX

The value considered for the OPEX in this report is 5% of the CAPEX. The maintenance of these plants is more expensive than the maintenance of SMR plants because the temperatures are higher and fuel management is more difficult.

Parameters considered for Levelized Cost of Green Hydrogen calculation

Project lifetime: 20 years

The project lifetime of this type of plant will probably increase in the following years with the development of more suitable materials for electrolysers. Twenty years generally means that the stack must be changed in the middle of the project. The new projects are estimated to have a 25- or even 30-year lifetime.

Electrolysers capacity: 100 MW

The electrolysers capacity is the full capacity of all the electrolysers in the plant working at the same time, and the value of 100 MW is an already accomplished capacity in working projects.

Type of Electrolyser: Alkaline

The electrolysers considered in this analysis are alkaline because that is the most mature technology and, therefore, the one with the lowest production costs at the moment, but if another type of electrolyser seems more suitable in the future (like PEM or SOEC), the analysis is similar. Only the technical values must be changed in the calculation program.

Electrolysis Efficiency: 70%

Electrolysis efficiency is the amount of energy stored in the hydrogen produced according to hydrogen's LHV (33.33 kWh per kilogram) divided by the electricity input. 70% is a value already achieved in the new projects, so it is going to be the value to consider. The tendency is that this value is going to continue developing. PEM efficiency is expected to be better than alkaline (which will improve but still be close to 70%), and for that reason, PEM technology is gaining importance. The SOEC technology is immature but is expected to achieve 90% efficiency by 2030 and is the only one that can technically achieve 100%, according to the bibliography (N. Norouzi, 2021. Assessment of Technological Path of Hydrogen Energy Industry Development: A Review).

Some texts define this efficiency in kWh/kgH_2, which means the same thing but in terms of the amount of electricity demanded and the amount of hydrogen produced. With this definition, an efficiency of 70% is equal to 47.6 kWh/kgH_2, and an efficiency of 60% is equivalent to 55.6 kWh/kgH_2. In other words, lower efficiency means that more electricity is required to produce one kilogram of hydrogen.

Load Factor: 50%

The load factor is the amount of time that the electrolyser is working. It depends on the maintenance and operation. When using renewable energies, this value can change significantly. Diverse sources use high values of this parameter in their calculations (Lazard 96%, EdBodm 98%), but in this study, the value of 50% is chosen for the general analysis. Nevertheless, a sensitivity analysis is going to be conducted with values from 20% to 100% (100% is not possible because of maintenance).

CAPEX: 600 €/kW

The CAPEX is the total capital expenditure, including the entire installation and not only the electrolysers acquisition. For large production projects, the industry has already achieved a low CAPEX of 300 €/kW, but only in specific projects outside Europe. The initial analysis will consider a value of 600 €/kW because that is the average according to the mentioned bibliography. Nevertheless, it is important to consider that there is a lot of investigation and development regarding this subject and that the price of electrolysers (production and installation) has been descending in the last decade, and this tendency is expected to continue.

Stack Lifetime: 90 000 hours

This method has the particularity that the stack of the electrolyser must be replaced after some time in order to maintain efficiency. The old bibliography indicates values between 60 000 and 90 000 hours, but new projects have already accomplished 120 000 (N. Norouzi, 2021). It is also possible to link the lifetime of the project to two times the lifetime of the stack. In that way, there is enough time to completely use two stacks.

Stack Replacement Cost: 30% of CAPEX

It is considered that the stack value represents around 40% of the CAPEX. When it has to be replaced, the replacement cost (considering a residual value for the original stack and moderate technological advances) is estimated at 30% of the initial CAPEX.

Cost of Green Electricity: 40 €/MWh

In Europe, the analysis in the previous section shows the average price of renewable energy is between 30 and 50 €/MWh and is expected to descend in the following years. The value considered in the first approach is 40 €/MWh, but a sensitivity analysis is going to be conducted. The Power Generation Costs report (IRENA 2021) shows that the average price of all the on-shore wind generation projects in 2020 was 30 €/MWh.

Parameters considered for Levelized Cost of Pink Hydrogen calculation

This method is similar to the green hydrogen analysis because it produces hydrogen from electricity. The most important differences are associated with the cost of nuclear energy and the fact that the most efficient type of electrolyser could be the SOEC, which requires higher temperatures. This technology is not a possibility right now, but it is expected to be one of the best no-emission solutions in the near future. Therefore, this technology merits a cost analysis. The values presented below are from recent studies on electrolysers (IEA-Electrolysers, 2021; N. Norouzi, 2021).

Type of Electrolyser: SOEC

The electrolysers could be of any of the types mentioned, but with the SOEC type, there is a particularity. Both the thermal and electrical energy needed for this electrolyser could be provided by the nuclear reactor, including harnessing energy at the end of the nuclear generation process to provide the heat (that is usually wasted or converted with low efficiency). Another particularity is that the SOEC electrolyser can operate in reverse, using hydrogen to produce electricity.

Electrolysis Efficiency: 75%

These electrolysers have the highest expected efficiency. For the first analysis, the efficiency of 75% already achieved in tests is going to be considered, but it is expected to reach the 90% value in 2030.

Load Factor: 97%

This technique has the advantage that it can produce hydrogen almost uninterruptedly, just like the fossil fuel-based methods used today.

CAPEX: 2400 €/kW

Despite the high CAPEX required for nuclear power plant construction, this cost is taken into account in this study when computing the levelized cost of electricity provided to the electrolysers. In the other reports, the cost of the SOEC electrolysers is not accurately informed, as it is a more immature technology than the other systems analysed, and no production projects are operating at industrial levels. The cost is expected to be between 1800 and 4200 €/kW in the next few years, dropping to values of up to half over a period of 10 to 20 years. This work will consider 2400€/kW as the general value.

Stack Lifetime: 60 000 hours

The elevated temperature involved in this method leads to a shorter stack lifetime. The 60000 hours value comes from a recent study of different types of electrolysers (N. Norouzi, 2021).

Cost of Nuclear Electricity: 65 €/MWh

In Europe, the average cost of nuclear electricity is between 60 and 90 €/MWh. According to the French multinational electric utility company report (EDF 2023), some of their reactors produce electricity at a value of 42 €/MWh. Also, Lazard's study (LCOE-V15 2022) shows that using the nuclear plants that are not operating nowadays, the energy production would have a marginal cost close to 30 €/MWh. In this work, an initial value of 65 €/MWh is considered, but a sensitivity analysis with prices between 30 and 120 €/MWh is conducted.

4.3.2 Results of the analysis for each technology

General Results

The grey hydrogen cost is 1.24 €/kgH_2 with a gas price of 20 €/MWh and 2.08 €/kgH_2 considering a gas price of 40 €/MWh. For the same prices of gas, the costs of blue hydrogen with 48% of Carbon Capture and Storage are 1.65 €/kgH_2 and 2.61 €/kgH_2, respectively, and the costs of blue hydrogen with 90% are 2.07 €/kgH_2 and 3.11 €/kgH_2.

Black hydrogen cost is 2.23 €/kgH_2 considering the average price of carbon at 80 €/tonne, far from the current price. In Europe, this technology is not in use because it is not competitive even against grey hydrogen without considering emissions costs, but in some regions is one of the most feasible options.

Green hydrogen has a cost of 2.59 €/kgH_2 considering electricity at 40 €/MWh and a 50% load factor. As can be seen, in this particular case, green hydrogen is competitive against blue carbon without considering emissions costs and considering the current price of gas (which is above 40 €/MWh).

Finally, the cost of pink hydrogen is 4.82 €/kgH_2 considering the price of nuclear energy at 65 €/MWh. It is important to clarify that this pink hydrogen price, unlike those mentioned above, has not been achieved in any project yet, since the industrial production of SOEC electrolysers has not started (although there are companies arranging production lines). The electrolyser parameters considered are average values according to the cited literature. In the next decade, they are expected to greatly improve efficiency, production cost and lifetime.

Considering Emission Cost

When the cost of emissions is considered, the price of grey, blue and black hydrogen changes significantly. The current price of carbon credits in Europe is above 100 €/tonCO_2, and that is a value that was expected to be reached in 2030. Past reports mentioned in this work considered a price of 15 €/tonCO_2, and therefore the costs in this report are considerably higher. Figure 32 presents the result of a cost analysis of different types of hydrogen considering different carbon credits prices.

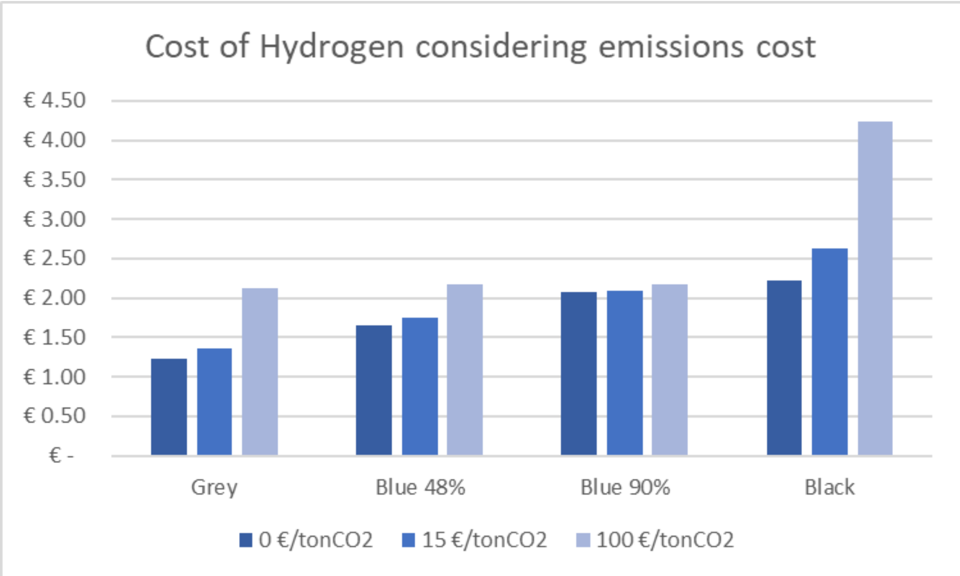

Figure 32 - Cost of Hydrogen considering emissions costs (Gas price: 20 €/MWh; Coal Price: 80 €/ton)

As can be seen in Figure 32, the current cost of black hydrogen is not competitive in Europe with the cost of grey or blue hydrogen, even without considering the cost of emissions, and is not competitive against green hydrogen if the current emissions cost is taken into account. This alternative is not going to be analysed in the sensitivity analysis because the price considered in the analysis is already a low value for the European market, and the correspondent price is not competitive with the other technologies (and it has no technical advantages over the other technologies).

It is noticeable how influential the cost of emissions is on the final cost of these hydrogen variants. The analysis highlights that, at current carbon credit values (100 euros/tonCO_2), blue carbon is competitive with grey carbon, which almost doubles its cost due to the cost of emissions.

Figure 33 shows the cost of grey and blue hydrogen (considering the current price of 40€/MWh and the average price of 20 €/MWh) with the cost of green hydrogen (considering electricity at 40 €/MWh and a 50% load factor) for different carbon credit prices. It is evident that, with the current value of the carbon credit and gas price, the cost of green hydrogen calculated above is even lower than that of hydrocarbon-based hydrogen. Nevertheless, it is important to say that with the current prices of gas, electricity is expensive, so considering that renewable energy is going to be converted into hydrogen is not the best scenario because it would probably be injected into the grid as electricity (because it would be cheaper than the energy coming from gas power plants). Therefore, the comparison with the average pre-conflict price of gas is also shown.

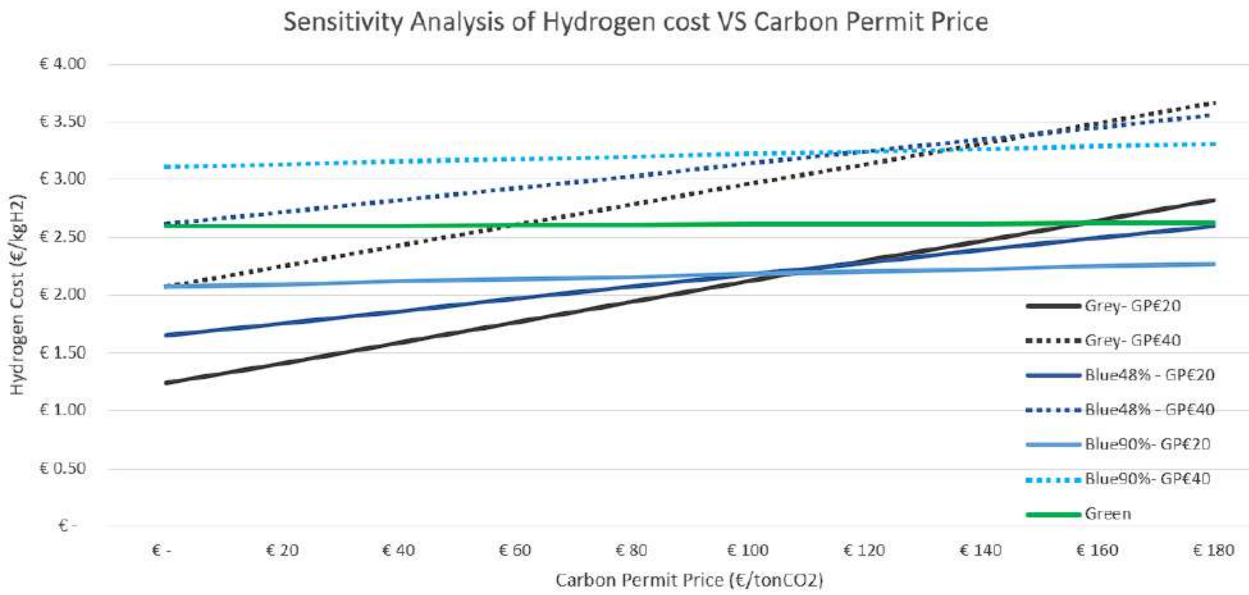

Figure 33 - Hydrogen cost for different technologies and carbon prices

Sensitivity Analysis – Green Hydrogen

The cost of each technology presented in the general section is a particular case considering mean values for the many parameters that determine the final value. For example, the cost of green hydrogen presented in the general section is a particular case, with mean values for efficiency (70%), load factor (50%), price of electricity (40 €/MWh), CAPEX cost (600 €/kW) and many other parameters mentioned before.

Maintaining all the other parameters constant, Figure 34 presents several graphs showing the sensitivity analysis of the green hydrogen cost for the most influent parameters in the final cost. As can be seen, the price of green hydrogen varies greatly depending on these parameters, and for each particular project, special attention should be paid to these.

Low load factor values make this option uncompetitive, so it is necessary to have access to various renewable energy sources that are highly likely to exceed 20%. Currently, many projects are carried out with wind energy in places with load factors between 40 and 50%, or a combination of different renewable energies to reach even higher values.

Another significant measure where advancements are anticipated over the next ten years is electrolyser efficiency. Although values close to 80% are expected to be attained in the medium term, and new technologies promise higher values, the efficiency of 70% is already a fact today. This parameter is crucial because it significantly lowers the amount of electricity needed, and electricity costs are the main factor in the end price of green hydrogen.

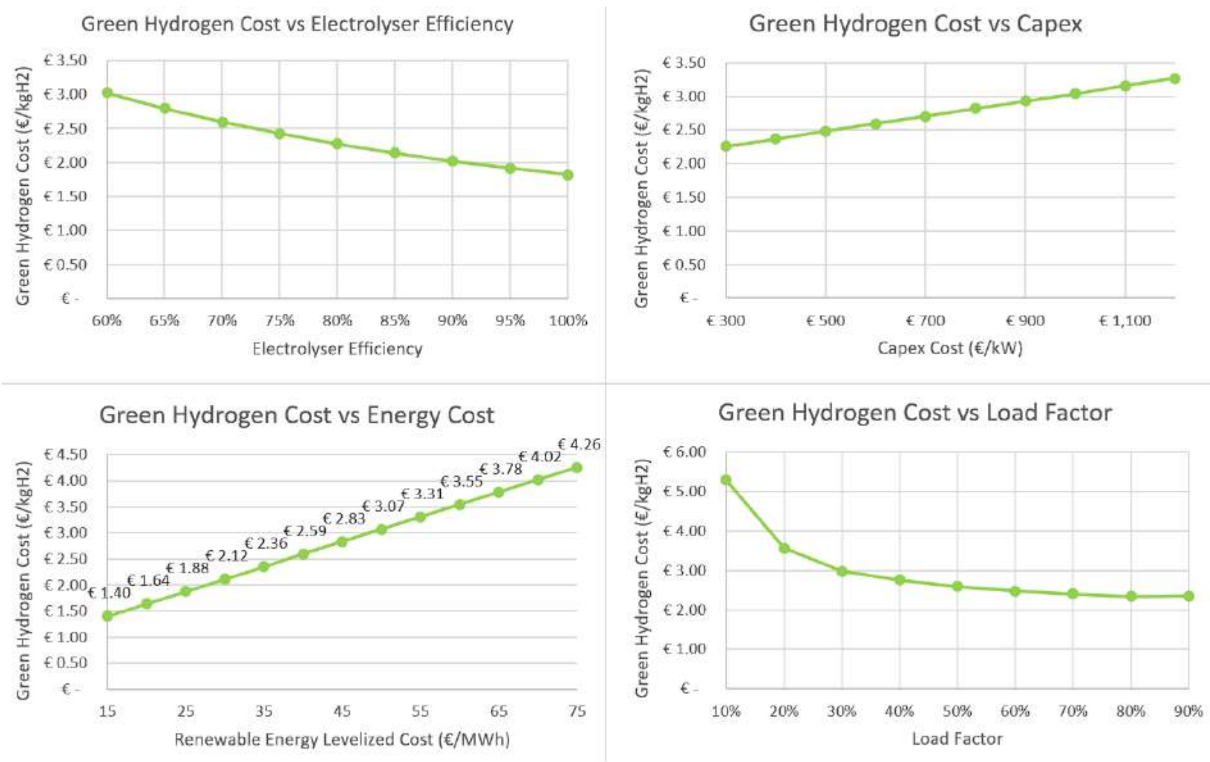

Figure 34 - Sensitivity analysis of green hydrogen price.

CAPEX is also a value that strongly influences the final cost of hydrogen. The reduction in the manufacturing cost of electrolysers over the last three decades and the increase in efficiency are the main reasons why this technology has become competitive today.

The most significant and direct factor affecting the overall cost of hydrogen is the cost of renewable energy. One of the biggest obstacles to humanity's ability to develop its activities in a more sustainable way is the availability of this energy source at reasonable prices and with adequate load factors. In some projects, values of 30 €/MWh and even lower have been reached, and it is anticipated that this cost will continue to fall over time, as it has over the past few decades, thanks to the advancement of technologies.

Considering that the most influential factors in the final cost of green hydrogen, which can vary the most between regions, are the CAPEX and the cost of energy, a bivariate analysis is conducted on these parameters in order to present the cost in different scenarios. The result can be seen in Figure 35.

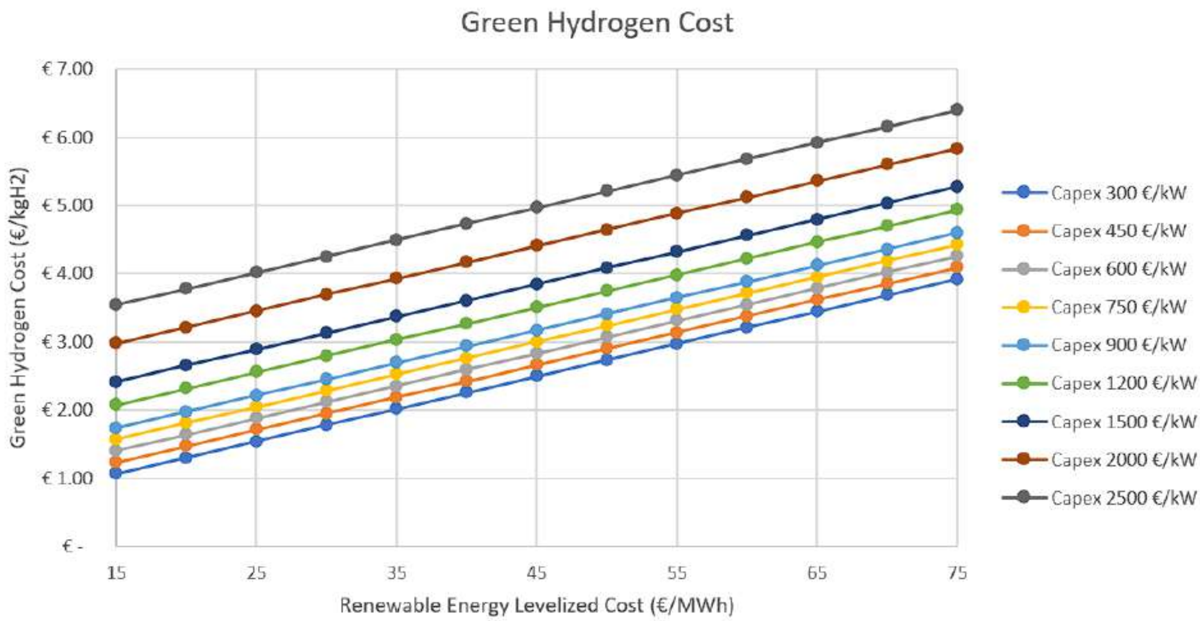

Figure 35 - Green Hydrogen Cost for different scenarios

Sensitivity Analysis – Grey and Blue Hydrogen

The sensitivity analysis concerning the most influential parameters on the cost of hydrogen from natural gas is shown in Figure 36 and Figure 37.

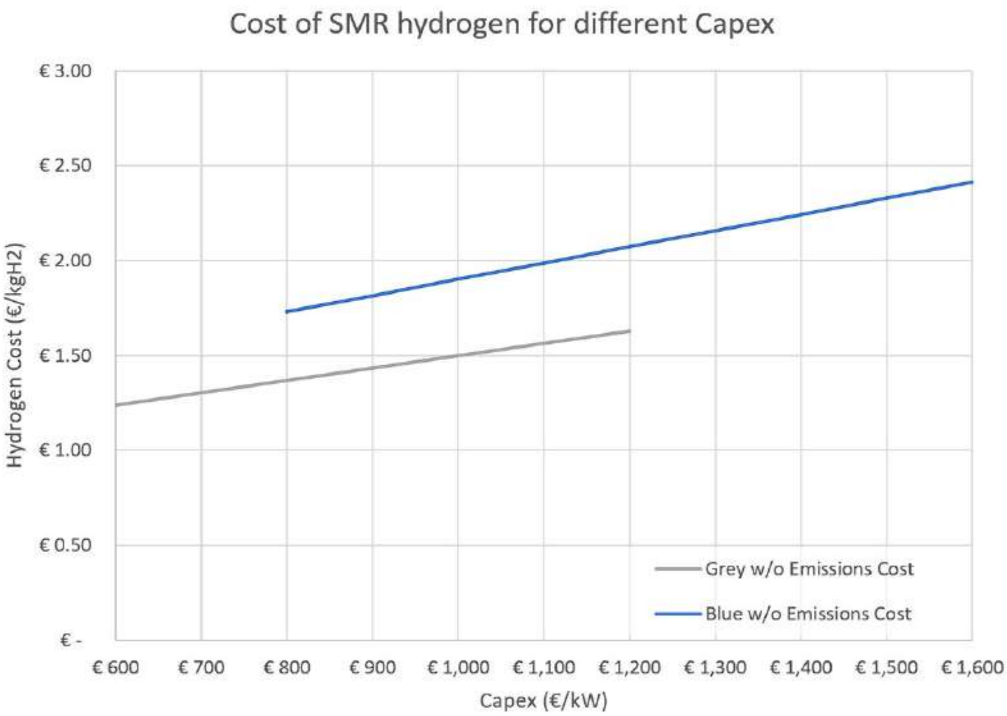

Figure 36 - Cost of SMR hydrogen for different CAPEX

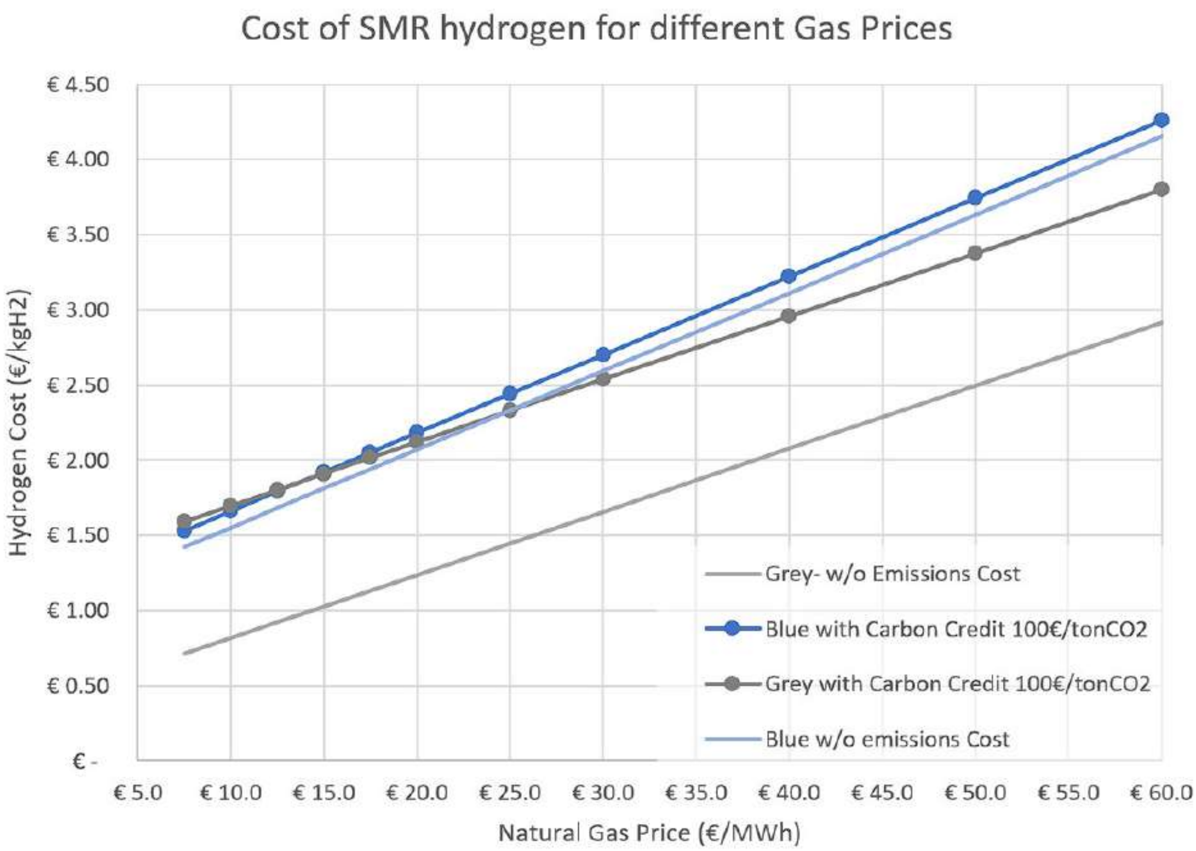

Figure 37 - Cost of SMR hydrogen for different Gas Prices

As can be seen in Figure 36, CAPEX strongly influences the final cost of hydrogen. The CAPEX of grey hydrogen is not expected to decrease much in the future and may even increase due to regulations, but it may vary between regions. The CAPEX of blue hydrogen may vary a lot, as CCS techniques are still under development.

As the bibliography indicates, it is noticeable in Figure 37 that the cost of fuel is the most influential parameter in the cost of hydrogen. Currently, in Europe, values between 40 and 50 €/MWh in the last year are being considered, both for natural gas from pipelines and for LNG imports. However, values as low as 7.5 €/MWh are shown because there are regions in the world where this is the cost for gas, while the historical value in Europe is around 20 €/MWh.

It is noticeable that when incorporating the current cost of emissions, both technologies present much more competitive values, although all other things being equal, the cost of grey hydrogen is still slightly lower.

Pink Hydrogen Analysis

The cost of the pink hydrogen shown in the general calculation (4.82 €/kgH_2) is far from the cost of green, grey and blue hydrogen. It has been calculated with mean parameters that are expected for this technology in the next few years, but no big plants are already operating with this combination of nuclear generation and SOEC electrolysers. The following analysis shows the different costs of pink hydrogen in different scenarios.

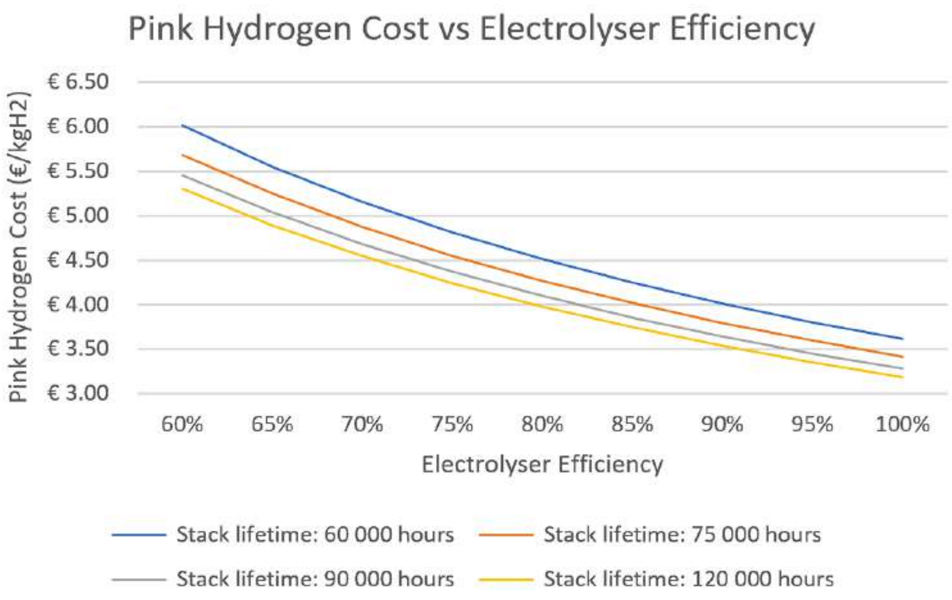

Figure 38 - Pink hydrogen cost VS electrolyser efficiency

In Figure 38, it is visible how technological improvements in the electrolyser can lead to much lower costs than those presented above. The values used for the overall analysis are those that have been achieved for this type of electrolyser, but it is expected that they will improve in the coming decades. In fact, this type of electrolyser is the only one that can reach, technically speaking, close to 100% efficiency, although it is projected that by 2050, they will reach 90% efficiency.

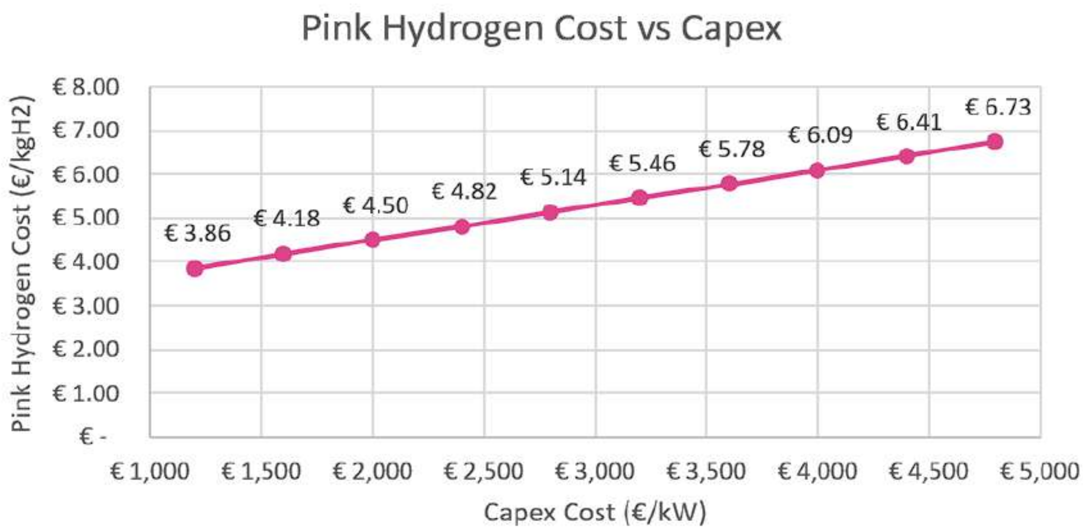

Figure 39 - Pink hydrogen cost VS CAPEX

As can be seen in Figure 39, CAPEX is another of the most influential factors in the final cost. For various reasons, the CAPEX value is much more variable than in other cases. In the absence of a database of industrial projects carried out, it is necessary to present a greater dispersion in the values that CAPEX can take in this case. Nevertheless, the final cost depends on parameters related to safety, legislation and insurance, which can vary greatly from region to region.

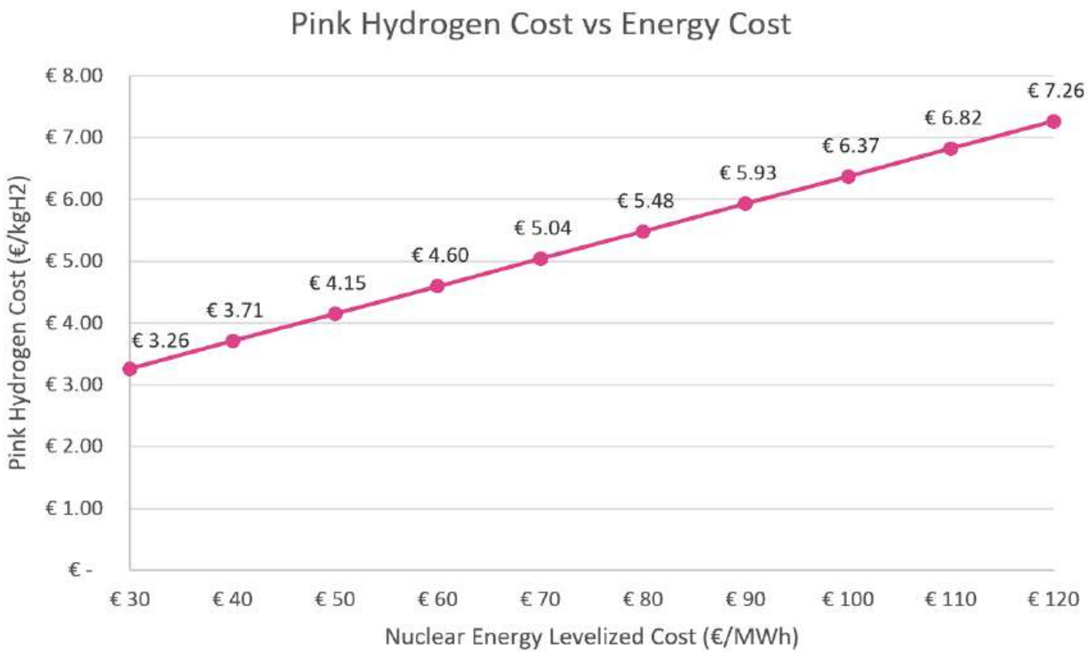

Figure 40 - Pink hydrogen cost VS levelized cost of Nuclear Energy

As in all other cases, the cost of energy is the most influential factor in the final cost of hydrogen (see Figure 40). In this case, it can vary significantly between regions and even within the same country. France manages to generate electricity from nuclear power in several of its projects with production costs below €40/MWh, and the consultancy Lazard (LCOE-V15 2021) indicates that refurbishing mothballed reactors to operate in these projects, rather than decommissioning them (which carries a higher cost), would result in nuclear power generation with levelized costs of €30/MWh. However, there are also many existing projects which, when adapted to new safety regulations, reach values of 120 €/MWh in the generation of nuclear power.

One advantage is that production is continuous and not dependent on stochastic factors of nature. It leads to better planning and energy security for nations, which is very important nowadays. Also, there are countries that do not have the natural conditions for an optimal generation with renewable energies, so this is a viable alternative for producing no-emissions hydrogen.

There is one particular scenario in which this technology has even greater potential. As explained earlier, electricity demand is not constant throughout the day (it has peaks of consumption at certain times) and is also affected by seasonal factors. Countries plan their electricity generation system with a combination of technologies to ensure a base for constant consumption while other plants are brought into peak operation at times when demand increases.

Nuclear power plants operate continuously and belong to the load-based generation group. Plants in this group do not usually exceed 30% of a country's energy matrix, as flexibility is needed in the system.

The implementation of pink hydrogen generation opens up a new possibility:

- When electricity demand is low, nuclear plants can be used for pink hydrogen generation, using it precisely as an energy reserve.

- At times of high electricity demand, the energy produced by the nuclear plant is fed into the grid instead of being used to produce hydrogen. The stored hydrogen is, in turn, used at these times to produce electricity as well, which can be done in various ways. One alternative is to replace some of the natural gas used in currently operating turbines, or to use turbines designed to operate on hydrogen. The other option is to use hydrogen in fuel cells to generate electricity.

This option is even more attractive in the case of SOEC electrolysers as they can be operated in reverse, meaning that the same equipment that produces hydrogen at times of low demand can be used at times of high demand to produce the reverse reaction, consuming hydrogen and obtaining electrical energy as a result.

Whichever method is used to obtain electricity at times of high demand, there are two major advantages of implementing this system. Firstly, it brings greater flexibility to the electricity generation system and allows the base generation to be increased. Secondly, it decarbonises the country's electricity generation matrix, as fossil fuel generation is replaced by this system, which today brings an additional economic benefit to producers who would otherwise have to pay the cost of emissions explained earlier. One particular example of the replacement of natural gas in currently operating turbines is shown in the next section to clarify how it would work.

Hydrogen as replacement of natural gas in turbines

One of the most promising near-term uses of hydrogen is the partial replacement of natural gas in power generation. One option is to generate electricity directly with turbines that run directly on hydrogen, such as Siemens' SGT-A35 model or General Electric's B-Class, E-Class and F-Class models. Another option is that existing gas turbine power plants can partially replace the fossil fuel they use as fuel with a mixture of natural gas and hydrogen.

It has been demonstrated analytically and empirically that blends of up to 20% by volume of hydrogen can be used as fuel in turbines that originally operated only on natural gas without having to invest large sums in retrofitting the current systems on which they operate (Nima Simon, 2022).

The following is a simplified economic analysis of the last alternative, using green hydrogen, and taking into account the reduction in emissions costs that this would mean, considering the current carbon credit value of 100 €/tonCO_2.

Under normal pressure and temperature conditions, one kg of hydrogen has an energy of 120 MJ while one kilogramme of natural gas (mostly methane) stores an energy of 56 MJ per kilogram, so to generate the same thermal energy inside the combustion chamber of the turbine, each kg of natural gas must be replaced by approximately half a kilogram of hydrogen. In other words, each kilogram of green (or pink) hydrogen used to produce the same thermal energy replaces the emissions associated with the combustion of two kilograms of natural gas.

According to the International Energy Agency (IEA 2019), the emission factor for natural gas is 3 kgCO_2 for every kg of fuel burned (depending on the exact composition of the natural gas). Therefore, each kilogram of hydrogen used in generation avoids the emission of 6 kg of CO_2, decreasing its environmental impact and the associated emission costs to be paid by the company. Considering the current price of 0.1 €/kgCO_2 (2023), this is reflected as a decrease in the cost of 0.6 € for each kilogram of hydrogen used instead of natural gas, which can be directly computed as a decrease in the cost of hydrogen.

Considering the cost of green hydrogen calculated preciously of 2.59 €/kgH_2, each kg used would mean a saving of 0.6 € by avoiding emissions, so it would be equivalent to buying hydrogen at 1.99 €/kgH_2, or its equivalent value of 59.7 €/MWh, considering the hydrogen's low heating value in the conversion: 33.3 kWh/kg.

The aim of this example is to show how the use of emission-free hydrogen can mean an extra economic advantage due to the reduction of emissions in the process in which it is used, and this reduction of emissions can be seen as a reduction of the cost of hydrogen, which makes this alternative even more competitive in specific cases.

5. Results and Conclusions

This last section condenses the most important results of this work and its conclusions.

The parameters used for each part of the analysis are duly detailed and justified, focusing on current values representative of Europe. However, the calculation tool created as part of this project has the added value of allowing the cost of hydrogen production to be quickly recalculated with parameters specific to another region or to be recalculated in the future, in order to adapt the results to the fluctuating parameters of the energy market. It is remarkable how reports from previous years show hydrogen costs that differ greatly from those calculated considering the current context. This demonstrates the need to systematically assess costs in order to have an accurate picture of the current situation, and the importance of having an adaptable calculation tool, such as the one designed.

From the economic analysis, it can be concluded that black hydrogen (from coal) is not cost-effective at present when considering the cost of the associated emissions, as is the case today in the European economic area, but may be a possibility for production in other regions of the world, although international policies seek to discourage it as much as possible due to the high level of emissions involved in this method.

Pink hydrogen (from nuclear energy) is also far from being price competitive in Europe (4.8 €/kgH_2), mainly due to the rising cost of nuclear energy because of the many safety regulations. Despite this, there are several reasons why it can be an emission-free hydrogen production alternative in several cases, such as its capacity for continuous production and its independence from natural factors.

Without considering emissions, and considering the average price of natural gas in Europe over the last decades (20 €/MWh), the cost of grey hydrogen is 1.24 €/kgH_2, while blue hydrogen cost is 2.07 €/kgH_2. When the current cost of emissions is added, the costs are respectively 2.12 €/kgH_2 and 2.18 €/kgH_2. It is thus evident that the current cost of carbon permits makes the blue hydrogen option very competitive, leading to a 90% reduction in emissions.

However, considering the current high price of natural gas in Europe (approximately 40 €/MWh in 2023) and the cost of emissions, the cost of blue hydrogen is 3.22 €/kgH_2. In this context, green hydrogen becomes a highly viable solution, presenting a cost of €2.59/kgH_2. These values catalyse the creation of new green hydrogen production projects and accelerate the transformation towards a more sustainable economy. In fact, countries such as Germany and France are expected to integrate clean hydrogen into their systems in the short term.

As a final conclusion it must be noted that, because of the technological advances that lead to cost reduction, the changes in the global market and the increased awareness regarding energy security, the demand for zero- or low-emission hydrogen is increasing <u>even more</u> than predicted in previous works.

Appendix

Example of Levelized Cost of Hydrogen calculation

This sheet contains the analysis for GREEN hydrogen production

Quick View and control		Units	Value
Real LCOH		Eur/kgH2	€ 2.59
Parameters			
Tax Rate			35%
Green energy cost		Eur/MWh	40
Carbon permit cost		Eur/tonCO2eq	0
Capex cost		Eur/kW	600
Project lifetime		years	20
Electrolysis Efficiency		%	70%
Load Factor		%	50%
Stack Lifetime		Hours	90000

Economic Parameters		Units	Value
Inflation rate	inf		2.17%
Tax Rate	tr		35%
Cost of Equity	Ce		10%
Cost of Debt	Cd		7%
Proportion of Equity	Pe	%	40%
Proportion of Debt	Pd	%	60%
Cost of Capital (WACC)	WACC		6.73%
Real WACC (adjusted by inf)			4.46%

Electrolyser Technical and Economic Parameters			
Project life	t	years	20
Capacity		kW	100000
Load Factor		%	50%
Electrolyser efficiency		%	70%
Electrolyser efficiency		kWh/kgH2	47.6
Tax Life		years	10.0
Variable Declining factor		factor	1.0
Tax shield			24.89%

Outcome		
Operating hours	hours	4383
Hydrogen Production	kgH2	9205221
Hydrogen Production	tonH2	9205
Oxygen Production	ton O2	73642
CO2 emissions factor	ton CO2eq/GWh	4
Emissions	ton CO2eq	1753.2
CO2 emissions factor	tonCO2eq/kgH2	0.00019

Demand		
Electrycity	KWh	438300000
Electrycity	GWh	438.3
Water Demand	kgH2O/kgH2	17.38041667
Water Demand	tonH2O/year	159991

Capital Expenditures		
Capex	Eur/kW	600
Total capex	Eur	60000000
Total capex	MEur	60
Stack Lifetime	Hours	90000
Stack Replacement year	Year	21
Stack Replacement cost	%of capex	30%
Stack Replacement cost	Eur/kW	180
Total Stack Replacement cost	Eur	18000000
Total Stack Replacement cost	MEur	18
Number of Stack Replacements		0
Stack replacement at present value cost	Eur	0
Stack replacement at present value cost	MEur	0.0
Total Capex considering Stack replacement	Eur	60000000.0
Total Capex considering Stack replacement	MEur	60.0
Nominal Capex Recovery	Eur/kgH2	0.696
Real Capex Recovery	Eur/kgH3	0.577
Oparating costs		
Cost of Energy	Eur/MWh	40
Total cost of Energy	Eur	17532000
Total cost of Energy	Meur	17.5
O&M (% of CapEx)		1.50%
O&M Anual cost	Eur	900000
O&M Anual cost	Meur	0.9
Water cost	Eur/tonH2O	0.8
Total Water cost	Eur	127992
Cost of Carbon Permit	Eur/tonCO2eq	0
Total cost of emissions	Eur	0
Total anual Operating Cost	Eur	18559992
O&M Cost per Unit	Eur/kgH2	2.02
Nominal Opex per unit	Eur/kgH2	2.43
Real Opex per unit	Eur/kgH2	2.02
LCOH		
Real LCOH	Eur/kgH2	2.59

Bibliography

ACER. (2023). Spot LNG price assessment for EU. *European Union Agency for the Cooperation of Energy Regulators.* https://aegis.acer.europa.eu/terminal/price_assessments

Bilicic, G. & Scroggins, Samuel. (2021). Levelized cost of energy V15. *Lazard Ltd.* https://www.lazard.com/media/sptlfats/lazards-levelized-cost-of-energy-version-150-vf.pdf

Bilicic, G. & Scroggins, Samuel. (2021). Levelized cost of hydrogen analysis v2. *Lazard Ltd.* https://www.lazard.com/media/erzb5rkv/lazards-levelized-cost-of-hydrogen-analysis-version-20-vf.pdf

Birol, F., et al. (2022). Breakthrough Report. Accelerating Sector Transitions Through Stronger International Collaboration. *International Energy Agency & International Renewable Energy Agency.* https://www.iea.org/reports/breakthrough-agenda-report-2022

Bloomberg. (2020). Hydrogen Project Evaluation https://www.bloomberg. com/news/articles/2020-04-01/the-eu-s-carbon-market-is-about-to-enter-its-turbulent-20s.

Chen, G., Tu, X., Homm, G. et al. (2022) Plasma pyrolysis for a sustainable hydrogen economy. *Nat Rev Mater 7, 333–334.* https://doi.org/10.1038/s41578-022-00439-8

EDF. (2023). Nuclear Electricity Cost in France. *French multinational electric utility company.* https://www.edf.fr/en/the-edf-group

European Energy Agency. (2016). Air quality in Europe. https://www.eea.europa.eu/publications/air-quality-in-europe-2016

Fraunhofer (2020). Fuels for the Future. *Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT, Oberhausen.* https://www.umsicht.fraunhofer.de/content/dam/umsicht/en/documents/publications/2020/position-paper-fuels-of-the-future.pdf

Golden. (2020). Tech&Ec Potential H2 USA. *National Renewable Energy Laboratory.* https://www.nrel.gov/docs/fy21osti/77610.pdf

Gül, T., Turk, D., et al. (2019). The Future of Hydrogen, Seizing today's opportunities. *Report prepared by the International Energy Agency for the G20, Japan.* https://www.iea.org/reports/the-future-of-hydrogen

Hydrogen Council. (2020). Path to hydrogen competitiveness. A cost perspective. https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

Hydrogen Council. (2021). Hydrogen Insights A perspective on hydrogen investment, market development and cost competitiveness. https://hydrogencouncil.com/en/hydrogen-insights-2021

Hydrogen Council. (2022). Global Hydrogen Flows. https://hydrogencouncil.com/en/global-hydrogen-flows/

International Energy Agency. (2020). Global Hydrogen Review. https://www.iea.org/fuels-and-technologies/hydrogen

International Energy Agency. (2021). Global Hydrogen Review. https://www.iea.org/fuels-and-technologies/hydrogen

International Renewable Energy Agency. (2021). Power Generation Costs. https://www.irena.org/Publications

Ismail, A. & Bahnemann, D. (2014). Photochemical splitting of water for hydrogen production by photocatalysis: A review. Solar Energy Materials and Solar Cells. https://doi.org/10.1016/j.solmat.2014.04.037

Jasi, Amanda. (2021) Shell starts up Europe’s largest PEM ‘green’ hydrogen electrolyser. https://www.thechemicalengineer.com/news

Jens, J., Gräf, D., Schimmel, M. (2021). Market state and trends in renewable and low-carbon gases in Europe. *Guidehouse*. https://www.europeanbiogas.eu/wp-content/uploads/2021/12/Gas-for-Climate-Market-State-and-Trends-report-2021.pdf

Jolly, W. Lee. (2023). Hydrogen Properties. *Encyclopedia Britannica.* https://www.britannica.com/science/hydrogen

Leiblein, J., Bär, K., Graf, F., Hotz, C., Mörs, F. (2021). Techno-Economic Analysis of Green Hydrogen Production from Solar Energy in MENA and Transport to Central Europe. *DVGW Research Center at Engler-Bunte-Institut of Karlsruhe Institut of Technology, Karlsruhe (Germany)* https://doi.org/10.18086/swc.2021.01.01

Lucchese, P. et al. (2021). Annual Report. *Hydrogen Technology Collaboration Programme.* https://www.ieahydrogen.org/annual-reports/

Lux, B. & Pfluger, B. (2020). A supply curve of electricity-based hydrogen in a decarbonized European energy system in 2050. *Fraunhofer Research Institution for Energy Infrastructures and Geothermal Systems IEG.* doi.org/10.1016/j.apenergy.2020.115041

Lux, B., Gegenheimer, J., Franke, K., Sensfuß, F., Pfluger, B. (2021) Supply curves of electricity-based gaseous fuels in the MENA region. *Fraunhofer Research Institution for Energy Infrastructures and Geothermal Systems IEG.* https://doi.org/10.1016/j.cie.2021.107677.

N. Norouzi (2021). Assessment of Technological Path of Hydrogen Energy Industry Development: A Review. *Iranian (Iranica) Journal of Energy and Environment, 12(4), pp. 1-12.* https://doi.org/10.5829/ijee.2021.12.04.01

Nima Simon (2022). Retrofitting gas turbine facilities for hydrogen blending. *ICF.* https://www.icf.com/insights/energy/retrofitting-gas-turbines-hydrogen-blending

Riemer, M., Zheng, L., Pieton, N.,Eckstein, J., Kunze, R., Wietschel, M. (2022) Future hydrogen demand: A cross-sectoral, multiregional meta-analysis. *HYPAT Working Paper 04/2022. Karlsruhe: Fraunhofer ISI (ed.).* https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2022/HYPAT%20WP_04_2022_Future%20hydrogen%20demand_V02.pdf

Rik van Rossum, Jaro Jens, Gemma La Guardia, Anthony Wang, Luis Kühnen, Martijn Overgaag (2022). European Hydrogen Backbone. *Guidehouse.* https://guidehouse.com/insights/energy/2022/european-hydrogen-backbone-energy-independence

Shiva Kumar, S. & Himabindu, V. (2019). Hydrogen production by PEM water electrolysis – A review. *Materials Science for Energy Technologies V2, Issue 3, Dec 2019, p 442-454* https://doi.org/10.1016/j.mset.2019.03.002

Shripad T. Revankar (2019). Nuclear Hydrogen Production. *School of Nuclear Engineering, Purdue University, West Lafayette, IN, United States.* https://doi.org/10.1016/B978-0-12-813975-2.00004-1

Trattner, A., Höglinger, M., Macherhammer, M. & Sartory, M. (2021). Renewable Hydrogen: Modular Concepts from Production over Storage to the Consumer. *Chemie Ingenieur Technik.* https://doi.org/10.1002/cite.202000197

Wang, A., Jens, J., Mavins, D., Moultak, M., Schimmel, M., Van der Leun, K., Peters, D. & Buseman, M. (2021). Analysing future demand, supply, and transport of hydrogen. *Guidehouse.* https://gasforclimate2050.eu/wp-content/uploads/2021/06/EHB_Analysing-the-future-demand-supply-and-transport-of-hydrogen_June-2021.pdf

Wang, A., Van der Leun, K., Peters, D., Buseman, B. (2020). European Hydrogen Backbone. *Guidehouse.* https://ehb.eu/files/downloads/ehb-report-220428-17h00-interactive-1.pdf

Yukesh Kannah, R., Kavitha,S., Preethi, Parthiba Karthikeyan, Gopalakrishnan & Banu, R. (2021). Techno-economic assessment of various hydrogen production methods – A review. *Bioresource Technology, Volume 319, ISSN 0960-8524,* doi.org/10.1016/j.biortech.2020.124175

List of Figures

List of Tables