MSc Program
Environmental Technology & International Affairs

Green Hydrogen for the Steelmaking Industry

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
Univ.-Prof. Dr. Günther Brauner

Émile Rieger, BSc

01630355

Vienna, 29.05.2023

ACADEMY FOR
CONTINUING
EDUCATION

diplomatische
akademie wien
Vienna School of International Studies
École des Hautes Études Internationales de Vienne

Affidavit

I, **ÉMILE RIEGER, BSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "GREEN HYDROGEN FOR THE STEELMAKING INDUSTRY", 77 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

Vienna, 29.05.2023

Signature

Abstract

This work studies the production of green hydrogen for the steelmaking industry using offshore wind energy. It reviews the main existing and developing technology for the production, storage, transport and use of green hydrogen. It also examines the history and current state of policy making on green hydrogen. It the proposes a possible configuration for the green hydrogen value chain from its production to its end-use in the steelmaking industry. Finally, it defines the main challenges observed in such a configuration and makes recommendations for future policy making.

Table of contents

List of abbreviations

AC	Alternating Current
CCS	Carbon Capture and Storage
Cp	Specific heat capacity
Cv	Specific heat capacity at constant volume
DB	Deutsche Bahn
DC	Direct Current
DR	Direct Reduction
DRI	Direct Reduced Iron
EC	European Commission
EU	European Union
FCH-JU	European Commission’s Fuel Cells and Hydrogen Joint Undertaking
FLH	Full Load Hour
GHG	Greenhouse Gas
HFP	Hydrogen and Fuel Cell Technology platform
HLG	High-Level Group
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
MW	Mega Watt
PEM	Proton Exchange Membrane
PP	Pelletizer Plant
RFNBO	Renewable Fuel of Non-Biological Origin

1. Introduction

Hydrogen has been a topic of discussions in European policy making for decencies now. But the recent years have been marked by a growing interest following the greenhouse gas emission targets and the energy transition pursued by the European Union. In this context, green hydrogen, which is hydrogen produced using a renewable energy source, has often been mentioned as a key technology to achieve those goals. Furthermore, certain industries have specifically been targeted due to their high emission values and overall environmental impact. The European steelmaking industry is one of those industries. The dominant steelmaking processes either use huge amounts of fossil fuels or are very energy demanding. Green hydrogen is however seen as a technology which could help reduce the use of conventional fossil fuels by the steelmaking industry.

Current literature does present the different technologies existing or in development for hydrogen production, hydrogen storage, hydrogen storage, hydrogen production with offshore wind energy or the uses of green hydrogen in the steelmaking industry. However, an overview on the whole value chain, from the production to the final use is still lacking. Furthermore, policy making is often omitted from the literature. Finally, studying the configuration of the hydrogen value chain from its production using offshore wind energy to its end-use in the steelmaking industry allows to identify challenges and limitations which would have been omitted in a targeted study.

The objectives are therefore to first review each key technology in the hydrogen value chain for its production, storage, transport and end-use. Then, it will be to summarize the key policies an strategies pursued on (green) hydrogen in Europe. Following this, a potential value chain configuration will be drawn taking into account the most relevant technologies in each case. Finally, the main challenges and limitations will be summarized, and recommendations shall be made.

1.1.Research question

In light of the above, an attempt will be made to answer the research question: “What are the main challenges of producing green hydrogen for the steelmaking industry using offshore wind energy?”. Furthermore, updates on the current states of technology developments and policy making will be provided. Finally, this opens the door the different value chain configurations which are characterized by their own complications.

1.2.Methodology

In an attempt to answer the above-described research question, the following methodology shall be used:

First the different existing technologies for green hydrogen production will be reviewed and their main advantages, disadvantages and applications will be pointed out. The different types of offshore wind turbine structures as well as the different ways in which they can be configurated for green hydrogen production shall be discussed. The different methods for storage and transport of green hydrogen will have to be compared as well. Finally, the potential uses of green hydrogen in the steelmaking industry will be studied and their impact on the steel production processes evaluated.

Second, the past and current policies, strategies and treaties on (green) hydrogen in Europe will be summarized and their key target areas pointed out.

Third, one possible configuration of the green hydrogen value chain for the steelmaking industry using offshore wind energy will be presented in an attempt the propose an overview from the production to the end-use of green hydrogen.

Fourth and last, the main challenges to such a configuration will be defined and recommendations on policy making in the green hydrogen domain will be made.

2. Green hydrogen production, storage, transport and uses

2.1.General introduction to hydrogen

In a context of continuous economic growth and despite the climate related pressures to reduce our overall consumption, energy demand has been increasing and will be increasing for the years to come (IEA 2022b). The decarbonization of our energy supply is therefore a priority as the use of fossil fuels and emission of greenhouse gases are the main cause of global warming. To achieve this goal of decarbonization, renewable energy sources are playing an important role. However, shifting to an exclusively renewable energy supply system brings up many new issues which need to be taken care of. For instance, renewable energy sources are mostly only available by intermittence, meaning they are not available at any time or can only be used under certain conditions. Photovoltaic parcs can only be operated during the day and rely on a clear sky to be efficient. The same way, wind turbines require a minimum amount of Full Load Hours (FLH) to be productive enough. Even electricity produced from hydropower depends on the water content in the reservoirs in the case of dams. This can be negatively affected in the case of droughts which are predicted to become more and more recurrent as well as more intensive as a consequence of climate change (IPCC 2023). Those limitations therefore imply a need for smart solutions or additional technologies to have a resilient and reliable sustainable energy supply. Design solutions can help to solve some of those issues. Offshore wind energy plants are for instance much more stable than onshore wind energy plants, FLH expected to be above 3000h on average and even more than 4000h in some cases (Morthorst and Kitzing 2016). I will discuss offshore wind plants more in depth in the next chapters as they are also a promising solution in the case of green hydrogen production. The storage of renewable energy is also a major issue. There are some solutions which propose to combine wind and solar energy to hydropower and use the reservoirs of water dams as a huge battery (Hauer 2013). However, those are not sufficient and therefore other technologies are necessary.

In this context, hydrogen offers and elegant solution as a clean energy storing technology. It can be produced carbon-free, stored, and even transported. Hydrogen also has the highest energy density (MJ/kg) of all known substances at around 120 MJ/kg (Dutta 2014). The table below compares the energy density (MJ/kg) of hydrogen to other known fuels. It is over two time as high as liquified natural gas and almost three times as high as automotive gasoline. The main disadvantage, however, is that it has also a relatively low energy density (MJ/L) at around 5.6 MJ/L when compressed at 700bar compared to 32 MJ/L for gasoline. This makes the efficient storage and transport of hydrogen more complicated. This will be further discussed in the next chapters. Literature however also mentions the possibility of a "hydrogen economy" (Boudellal 2018). There are several ways on which can be produced whereas it is using fossil fuels, renewable energies, energy recovery or even nuclear energy (Dincer 2012). As explained in an article of the international journal of hydrogen energy, "*The renewable hydrogen creates the link between renewable energy resources and the modernization of energy supply, transport, industry and renewable energy export. A hydrogen-based energy system is not less* *resilient than the conventional fossil fuel based system as hydrogen can be used as direct fuel (pure H2 or fuel admixture) or converted to other liquid/gas fuels*" (Dawood, Anda, and Shafiullah 2020).

Table 1 Energy contents of different fuels. Retrieved from (Dutta 2014)

Fuel	**Energy content (MJ/kg)**
Hydrogen	120
Liquefied natural gas	54.4
Propane	49.6
Aviation gasoline	46.8
Automotive gasoline	46.4
Automotive diesel	45.6
Ethanol	29.6
Methanol	19.7
Coke	27
Wood (dry)	16.2
Bagasse	9.6

Hydrogen is the most abundant element in the universe. On our planet, it is mostly found in water and organic compounds. As the simplest and lightest element, it is a colorless, odorless, combustible gas made up of just one proton and one electron (H_2 has two protons and electrons). Compared to hydrocarbons such as fossil fuels, hydrogen has rather good energy density in terms of weight. However, when it comes to energy density in terms of volume, hydrogen is worse off by a factor of 4 making its storage more complicated and requiring larger storage tanks (Dawood, Anda, and Shafiullah 2020). It is also very flammable due to its low ignition temperature requirements. The general proprieties of hydrogen can be found in the table below:

Table 2 Properties of Hydrogen (Dawood, Anda, and Shafiullah 2020)

Properties	**SI Units**
Discovery date/by/Chemical formula	1766/Henry Cavendish/H_2
Isotopes	^{1}H (99.98%), ^{2}H, ^{3}H, (^{4}H-^{7}H Unstable)

Equivalences; Hydrogen solid, liquid and Gas at Pressure = 981 mbar and Temperature = 20 ○C	1 kg = 14,104 l = 12,126 m^3
Molecular weight	1.00794
Vapor pressure at (—252.8 °C)	101.283 kPa
Density of the gas at boiling point and 1 atm	1.331 kg/m^3
Specific gravity of the gas at 0 °C and 1 atm (air = 1)	0.0696
Specific volume of the gas at 21.1 °C and 1 atm	11.99 m^3/kg
Specific gravity of the liquid at boiling point and 1 atm	0.0710
Density of the liquid at boiling point and 1 atm	67.76 kg/m^3
Boiling point at (101.283 kPa)	-252.8 °C
Freezing/Melting point at (101.283 kPa)	-259.2 °C
Critical temperature	-239.9 °C
Critical pressure	1296.212 kPa, abs
Critical density	30.12 kg/m3
Triple point	-259.3 °C at 7.042 kPa, abs
Latent heat of fusion at the triple point	58.09 kJ/kg
Latent heat of vaporization at boiling point	445.6 kJ/kg
Solubility in water vol/vol at 15.6 °C	0.019
Dilute gas viscosity at 26 °C (299 K)	9x10^{-6} Pas
Molecular diffusivity in air	6.1x10^{-5} m^2/s
Cp	14.34 kJ/(kg) (°C)
Cv	10.12 kJ/(kg) (°C)
Ratio of specific heats (Cp/Cv)	1.42
Lower heating value, weight basis	120 MJ/kg
Higher heating value, weight basis	141.8 MJ/kg
Lower heating value, volume basis at 1 atm	11 MJ/m^3
Higher heating value, volume basis at 1 atm	13 MJ/m^3
Stoichiometric air-to-fuel ratio at 27 °C and 1 atm	34.2 kg/kg
Flammable limits in air	4% - 75%
Explosive (detonability) limits	18.2 to 58.9 vol% in air

Maximum combustion rate in air	2.7/3.46 (m s-1)
Maximum flame temperature	1526.85 °C
Autoignition temperature/in air	400 °C/571 °C

2.2.Hydrogen Cleanness and Hydrogen Production Pathways

Hydrogen Production Pathways

When it comes to classifying the different ways of producing hydrogen, there are three main factors to take into account (Dawood, Anda, and Shafiullah 2020).

(1) The material containing hydrogen: There we further distinguish between hydrocarbons and non-hydrocarbons. In the category of hydrocarbons can be found Biomass, Coal, Methane, or Fuels (natural gas)(Silveira 2017). In the category of non-hydrocarbons can be found mostly Water.

(2) The energy source: The energy source is usually electricity when electrolysis is used which in turn can either be obtain from renewable or non-renewable sources. It can however also be heat in the case of Thermolysis when using fuels as material containing hydrogen. Finally, other energies sources can also be used in rarer occasions such as chemical reactions or bioenergy.

(3) The catalyst material: This is also an important factor for the efficiency of the hydrogen production process and therefore an active field of research. Most commonly used materials are usually Platinum, Nickel or Palladium(Silveira 2017).

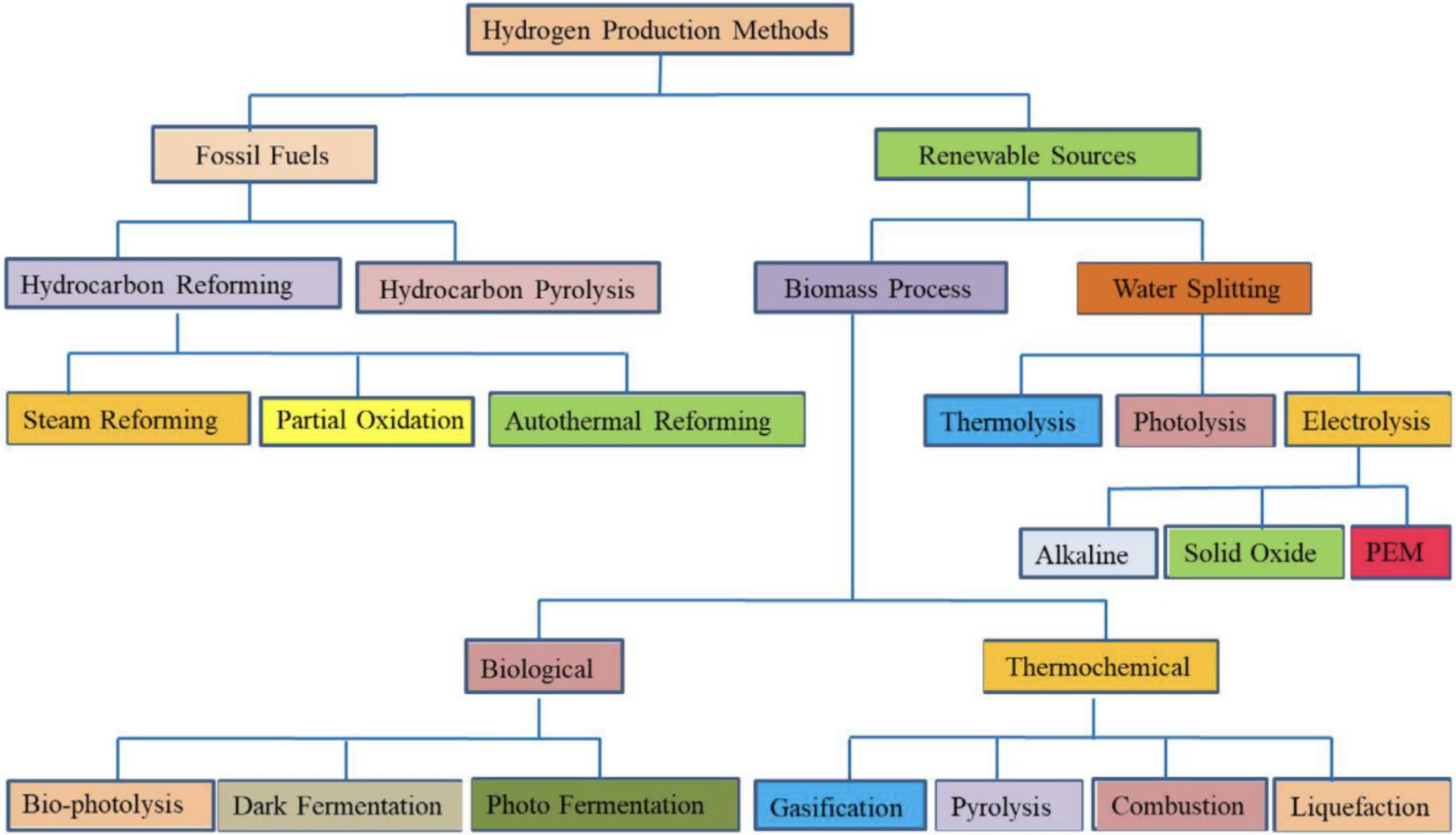

Figure 1 Various Hydrogen Production Methods. Retrieved from(Shiva Kumar and Himabindu 2019)

The figure above depicts the different methods for hydrogen production. As we can see, a first distinction is made between fossil fuels and renewable sources. The production methods using fossil fuels mentioned are Hydrocarbon Reforming and Hydrocarbon Pyrolysis. Some of these processes are shortly mentioned in the chapters below. In the category of renewable sources are distinguished Biomass Process and Water Splitting. Water Splitting has further sub-categories with Thermolysis, Photolysis and Electrolysis. In the chapters below, only Water Splitting by Electrolysis is covered. Furthermore, the three key technologies, Alkaline, Solid Oxide and Proton Exchange Membrane (PEM) are described in detail.

Hydrogen Cleanness

While hydrogen in itself can often be considered a carbon-neutral energy source, it might very well not be the case for the whole production process in itself. Indeed, depending on the Hydrogen Production Pathway chosen, more or less greenhouse gases can be emitted. It is therefore important to take into account the origin of the hydrogen before considering it as a "clean" energy source.

The cleanness of the produced hydrogen can therefore vary a lot depending on the material used containing hydrogen, the energy source or even the technology used. In order to gain an easier overview of the cleanness of the different production processes, a classification system has been developed. It is a color code where hydrogen is assigned a color based on its cleanness and production process. The article of Michel Noussan reports the following categories (Noussan et al. 2021):

"Hydrogen generation technologies are increasingly being codified by referring to a scheme based on different colors. The main colors that are being considered are the following:

- ***grey*** *(or brown/black) hydrogen, produced by fossil fuels (mostly natural gas and coal), and causing the emission of carbon dioxide in the process;*
- ***blue*** *hydrogen, through the combination of grey hydrogen and carbon capture and storage (CCS), to avoid most of the GHG emissions of the process;*
- ***turquoise*** *hydrogen, via the pyrolysis of a fossil fuel, where the by-product is solid carbon;*

- ***green*** *hydrogen, when produced by electrolyzers supplied by renewable electricity (and in some cases through other pathways based on bioenergy, such as biomethane reforming or solid biomass gasification);*
- ***yellow*** *(or purple) hydrogen, when produced by electrolyzers supplied by electricity from nuclear power plants.(Noussan et al. 2021)"*

Furthermore, the author mentions that "*In addition to these colours, different nomenclatures are often in use when referring to groups of hydrogen pathways, including "clean hydrogen", "low-carbon hydrogen", "renewable hydrogen". These definitions may sometimes be confusing, since there is no unique standard to provide a common reference."*(Noussan et al. 2021).

However, only three of the above-mentioned colors are usually commonly used: Grey hydrogen, blue hydrogen and green hydrogen. The figure below gives an overview on those three categories.

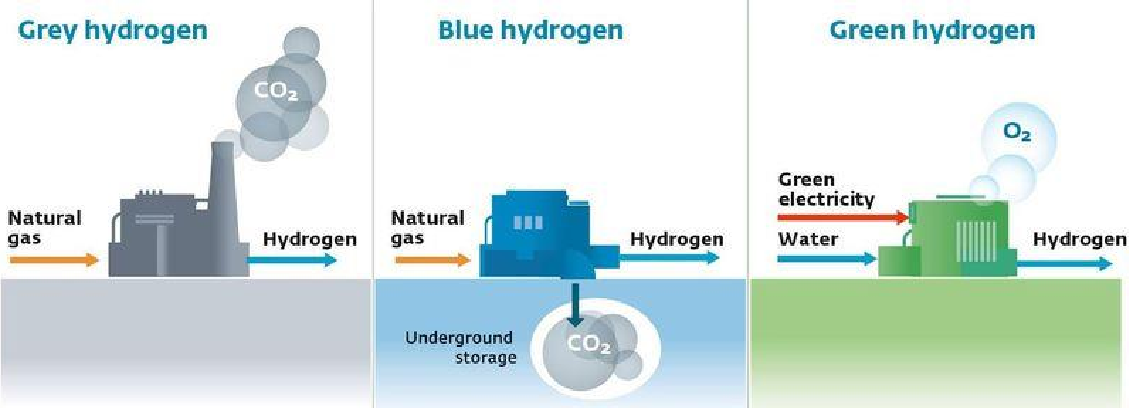

Figure 2 Depiction of grey, blue and green hydrogen production (University of Calgary n.d.)

In this thesis, I will only be considering green hydrogen and go more in depth regarding its production process via electrolysis in the following chapter. Green hydrogen can be considered as the cleanest hydrogen since it only uses electricity produced from renewable energy sources. Furthermore, while I will focus on green hydrogen by electrolysis when it comes to the production processes, all categories of hydrogen have to be considered regarding its utilization. However, it is important to mention at this stage that while all different processes do produce hydrogen, the purity of the hydrogen produced can vary which is in turn relevant for the utilization made.

2.3.The Hydrogen Value Chain

As we saw in the previous chapter, hydrogen can be produced using different pathways which also show different levels of cleanness. The latter is important for the color classification of the hydrogen produced (Grey, Blue or Green). In our case we will focus on Green Hydrogen, meaning hydrogen produced by electrolysis using renewable energy sources. Depending on the scale of the production, it can either take place close to the end-user or decentralized (Vidas and Castro 2021). Once the hydrogen is produced, it has to be transported to the end-user and often also needs to be stored. In this stage, different methods are used to suit the different scenarios and situations the best. Regarding the transport, this could take place either by road transport, ships, hydrogen gas pipelines or even by blending hydrogen with natural gas to use the existing infrastructure. Depending on the mode of transport used, the hydrogen could be moved either in liquid or gaseous state. Finally, it is also necessary to distinguish between the different types of end-uses which can be made out of the hydrogen. Whereas it is to be used in the general gas network, used for mobility, used for the industry or used as a power source in fuel cells.

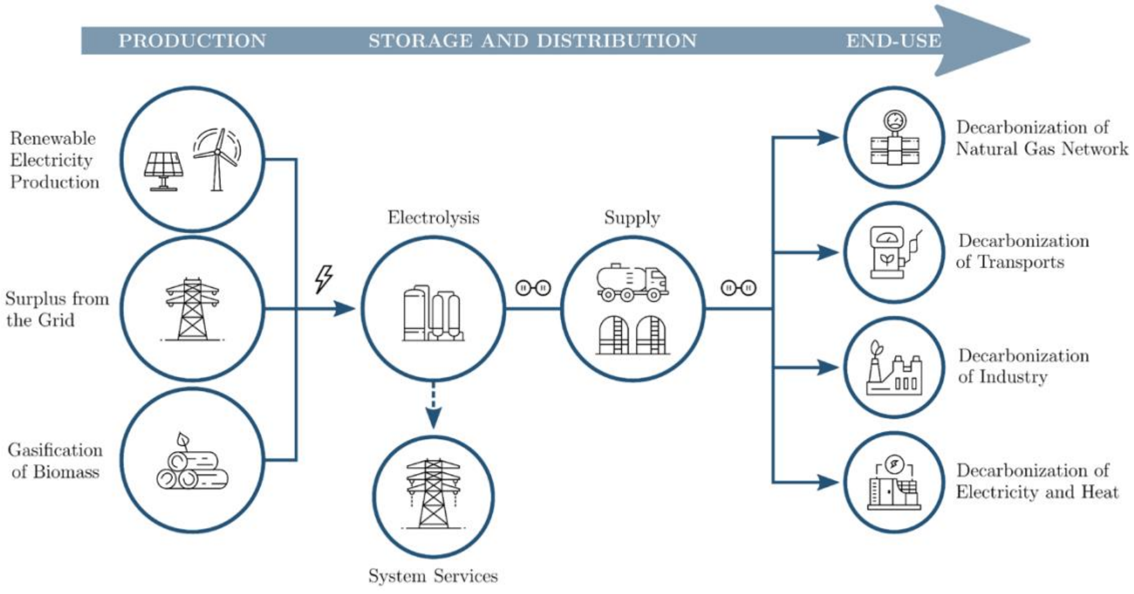

Figure 3 Green Hydrogen Value Chain. Retrieved from (Vidas and Castro 2021)

In the following chapters, I will primarily focus on offshore wind turbines for the production of the hydrogen and on the steelmaking industry for the end-use. The objective will be to point out the main technologies which can be used in the value chain for the production, storage and transport of the green hydrogen. Then, I will define the challenges and limitations to such a configuration review the current trends in policy making in the field and make recommendations. The main reasons behind this approach are the following:

I. Offshore Wind Parcs are an important field of development in Europe with many already in operation and having a big potential in most coastal areas.
II. The steelmaking industry is an important emitter of greenhouse gases but green hydrogen could be a solution in decarbonizing parts of the industry's processes.
III. Focusing on one possible value chain configuration restricts the scope of the study while also pointing out the main challenges.
IV. It gives us an overview on the whole value chain of green hydrogen from the energy source until the use of green hydrogen.
V. It takes into account the policy trends and bridges the gap between scientific facts and policy making

2.3.1. Production

2.3.1.1.Electrolysis

So far, the most commonly ways in which hydrogen is produced have been unthoughtful of the environment and linked with the release of greenhouse gases such as Carbon Di-Oxide or Carbon Monoxide. While it is possible to capture those off gases, this is not always the case and even when it is, this requires additional infrastructure and carbon capture technologies. Three of the main processes are described in an article published in the Journal Applied Science (Vidas and Castro 2021):

"*Steam Methane Reforming*

This is a process in which methane is heated, with steam (usually also with a catalyst), to produce a mixture of carbon monoxide and hydrogen. Methane, coming from natural gas, reacts with steam under a pressure up to 25 bar, splitting into carbon monoxide (later removed) and hydrogen molecules—as shown in the Equation. Because this is an endothermic reaction, heat must be supplied to the process for it to occur:

$$CH_4+H_2O\rightarrow+Heat\rightarrow CO+3H_2$$

Oil and Naphtha Reforming

Also known as catalytic reforming, this is a complex chemical process used to convert petroleum refinery naphthas (distilled from crude oil) into high-octane liquid reformates, which are stocks for gasoline. The process converts linear hydrocarbons into branched alkanes and cyclic naphthenes, which are then partially dehydrogenated to produce high-octane aromatic hydrocarbons—and also significant amounts of hydrogen gas, as a byproduct.

Coal Gasification

Coal is a chemically complex and highly variable substance, which can be converted into a variety of products. The gasification process of coal is one method to produce power, liquid fuels, chemicals, and hydrogen.

Specifically, hydrogen is produced by first reacting coal with oxygen and steam—under high pressures and temperatures—to form synthesis gas (a mixture consisting primarily of carbon monoxide and hydrogen), like is shown in the Equation.

$$2CH+O_2+H_2O\rightarrow+Heat+Pressure\rightarrow CO+4H_2+CO_2$$

After removing impurities from the synthesis gas, the carbon monoxide present in the gas mixture reacts again with steam to produce additional hydrogen and carbon dioxide, following the reaction of the Equation.

$$CO+H_2\,O\longrightarrow H_2+CO_2\ CO+H_2O\longrightarrow H_2+CO_2$$

Hydrogen is removed in a separation system, and the highly concentrated carbon dioxide stream is subsequently captured and stored. (Vidas and Castro 2021)"

There are however "green" ways to produce hydrogen using renewable sources. One is using biomass which will not be covered in the study. The other one requires water splitting, usually by electrolysis.

The electrolysis of water for hydrogen production has been known for many years. It also comes with the important characteristic that it produces an extremely pure hydrogen (Zeng and Zhang 2010). It can generally be summarized as connecting a DC electricity source to two electrodes place in water. By doing so, it breaks the water molecules into its constituting elements being hydrogen and oxygen. The whole process can also be made more efficient by using electrolytes to the solution or using a catalyst (Dincer 2012). While hydrogen production with fossil fuels remains more popular due to its higher efficiency, hydrogen production via water electrolysis technologies have the advantage of producing a more pure hydrogen and without releasing greenhouse gases into the atmosphere (Holladay et al. 2009). Water electrolysis are therefore in the center of attention and many efforts are currently being made to develop more efficient production methods and technologies. Overall, the electrolysis reaction can be described as in the equation below:

$$H_2O \rightarrow +\text{Electricity and Heat} \rightarrow H_2 + 1/2\ O_2$$

As we can see, and as the name indicates it, electrolysis requires the use of electricity. Therefore, to ensure the whole process is “green” and does not emit any greenhouse gases it is important that the energy source used is a renewable source. I discussed already the different possibilities in the chapter above and also focused on offshore wind energy as it is a very promising source of energy. Nevertheless, this whole process comes with high electricity consumption. Therefore, it is also important to keep in mind that the costs of electricity, especially if produced from renewable sources, need to be taken into account in other to have a clear overview on the profitability of hydrogen production by water electrolysis (Ball and Wietschel 2009).

The electricity and the heat generated affecting the water molecules is called the oxidation-reduction process. It dissociates the water molecules into their constituting elements being oxygen and hydrogen. It is also possible to distinguish this process into three further categories based on the “*operating conditions, the electrolyte and the electrolyzer used, and the ionic agent present (*OH^-,H^+,O^{2-}*“)* (Vidas and Castro 2021). I will describe the three categories below as they represent the most recent developments and technologies for water electrolysis.

Alkaline Water Electrolysis

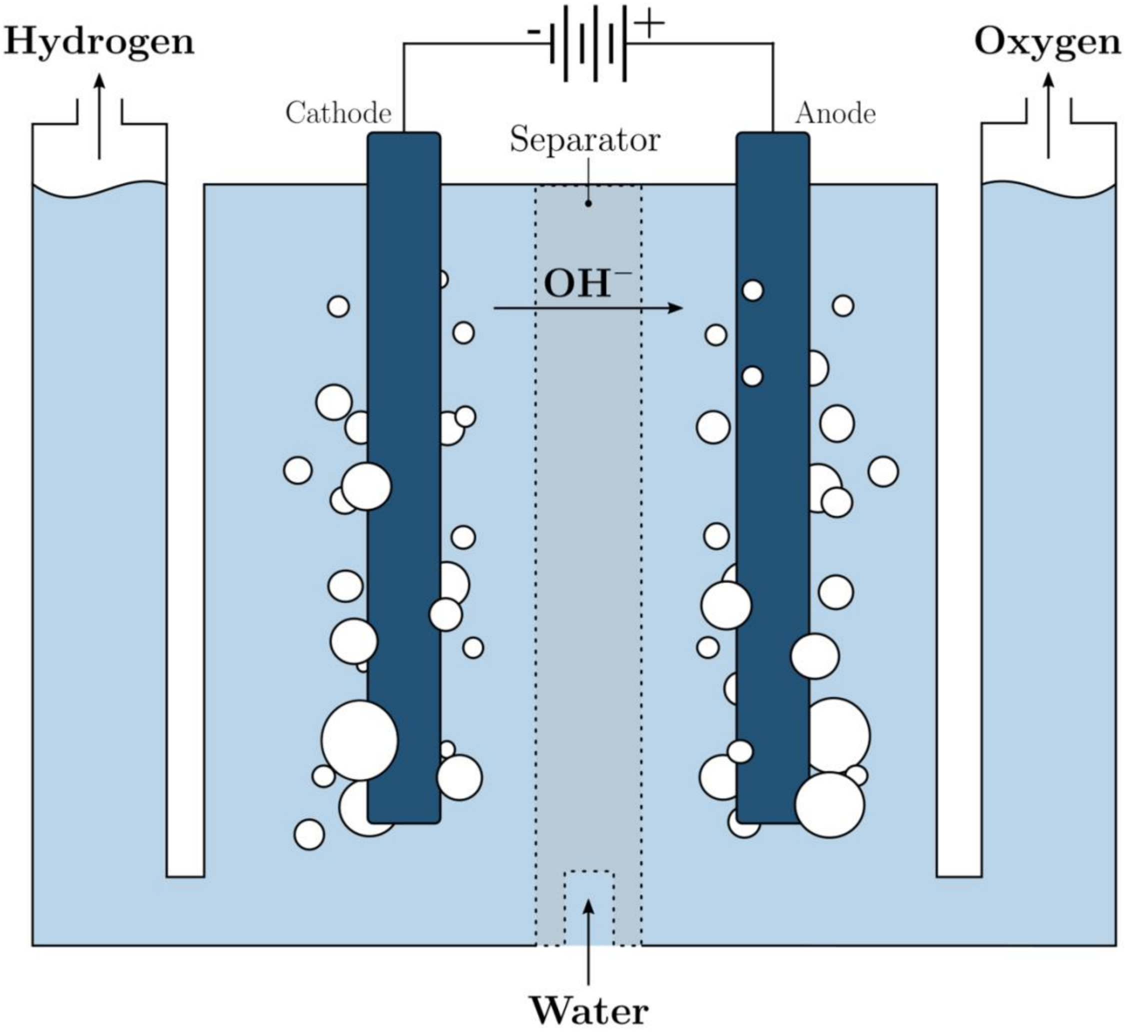

Figure 4 Schematic illustration of an alkaline water electrolyzer. Retrived from (Vidas and Castro 2021)

This process has the particularity to operate in an alkaline electrolyte solution as its name indicates it. This can be a solution with potassium or sodium hydroxide. Two electrodes, anode and cathode are submerged in the solution and separated by a diaphragm where the hydroxide ions are being transported from the on electrode to the other (Holladay et al. 2009). On the cathode side, the alkaline water solution is reduced to produce a molecule of hydrogen. In the process, hydroxyl ions are also produced and are moved through the diaphragm to the anode. The hydrogen molecules form together as a gas and are collected on the cathode side. There, the water molecules are being oxidized to produced oxygen.

The whole process takes place at relatively low temperatures in an alkaline electrolyte solution (Vermeiren et al. 1998). However, there are some important disadvantages of this process to be mentioned. First, the materials used for the diaphragm and electrodes are usually respectively asbestos and nickel. Asbestos has now for many years been recognized as a dangerous material for human health. While human beings may not be directly exposed to the asbestos in the diaphragm, it is important to consider the exposition of humans during the construction of the electrolyzer and during the production of the asbestos itself (Gualtieri et al. 2022). Furthermore, the low energy efficiency of the whole process is also a major draw back of alkaline electrolysis. It is also limited to a certain current density and low operating pressures (Zeng and Zhang 2010). This is an important factor to mention when considering using renewable energy sources which are usually characterized by dynamic and variable electricity outputs.

Proton Exchange Membrane Electrolysis

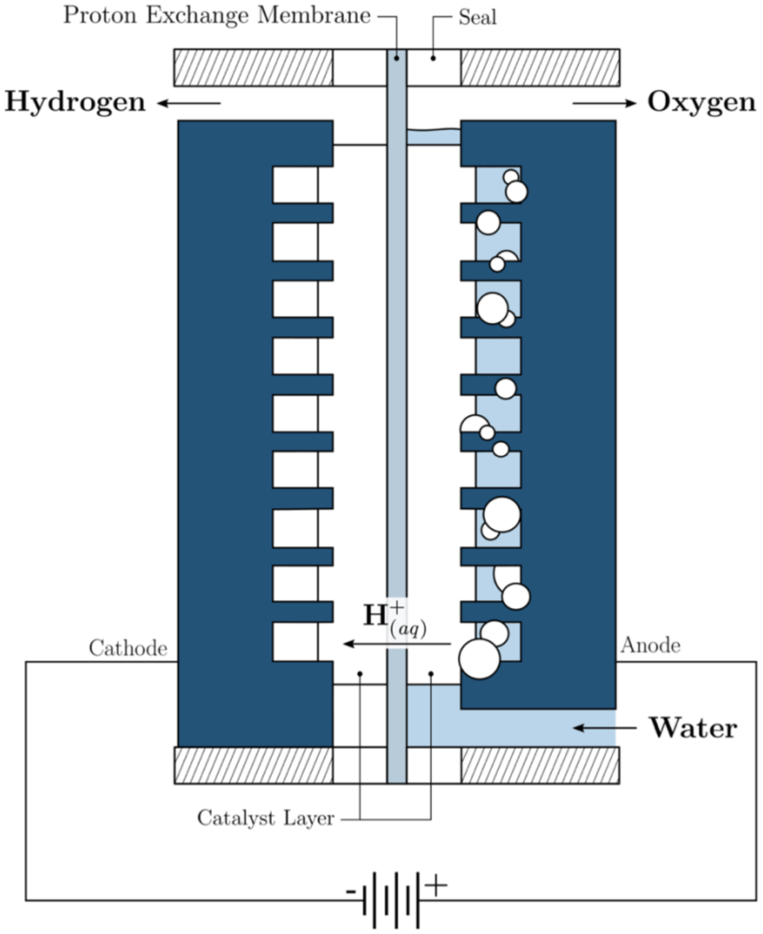

Figure 5 Schematic illustration of a proton-exchange membrane water electrolyzer. Retrieved from(Vidas and Castro 2021)

The Proton Exchange Membrane Electrolysis can be shortly described as the reverse process of a hydrogen fuel cell. The article ” Hydrogen production by PEM water electrolysis – A review" (Shiva Kumar and Himabindu 2019) published in the journal "Material Science for Energy Technologies describes the whole process as following:

"In PEM water electrolysis, water is electrochemically split into hydrogen and oxygen at their respective electrodes such as hydrogen at the cathode and oxygen at the anode. PEM water electrolysis is accrued by pumping of water to the anode where it is spilt into oxygen (O_2), protons (H+) and electrons (e-). These protons are traveled via proton conducting membrane to the cathode side. The electrons exit from the anode through the external power circuit, which provides the driving force (cell voltage) for the reaction. At the cathode side the protons and electrons re-combine to produce the hydrogen (Shiva Kumar and Himabindu 2019)."

It also solves some of the main issues encountered with Alkaline Water Electrolysis as it is operational under higher pressures and currents and is more energy efficient. It also produces a high purity hydrogen, and its design is relatively compact. There are however currently more expensive to produce than Alkaline Water Electrolysis as many of the required materials for production are noble metals (Shiva Kumar and Himabindu 2019). However, it is a very active field of research in the domain of electrolysis technologies and commercialization of PEM technologies is set to take place soon.

More importantly, Proton Exchange Membrane Electrolysis show a relatively simple design which could potentially be a huge advantage in being used for offshore wind parks (Vidas and Castro 2021). The main obstacle to its wider use and commercialization remain therefore the costs of the materials required for the production. Currently, capital expenditures for Alkaline Water Electrolysis range from around EUR 1250/kW_{el} to around EUR 700/kW_{el}. Capital Expenditures for Proton Exchange Membrane Electrolysis are currently (2020) estimated at around EUR 2000/kW_{el} but are foreseen to sink to EUR 900/kW_{el} by 2030(Zeng and Zhang 2010). Alkaline Water Electrolysis is therefore still relatively cheaper to produce in terms of investment costs. However, taking into account the simplicity of the technology and the higher efficiency, Proton Exchange Membrane Electrolysis could very well be favored by specific industries and in certain conditions such as offshore wind parks.

Solid Oxide Electrolysis

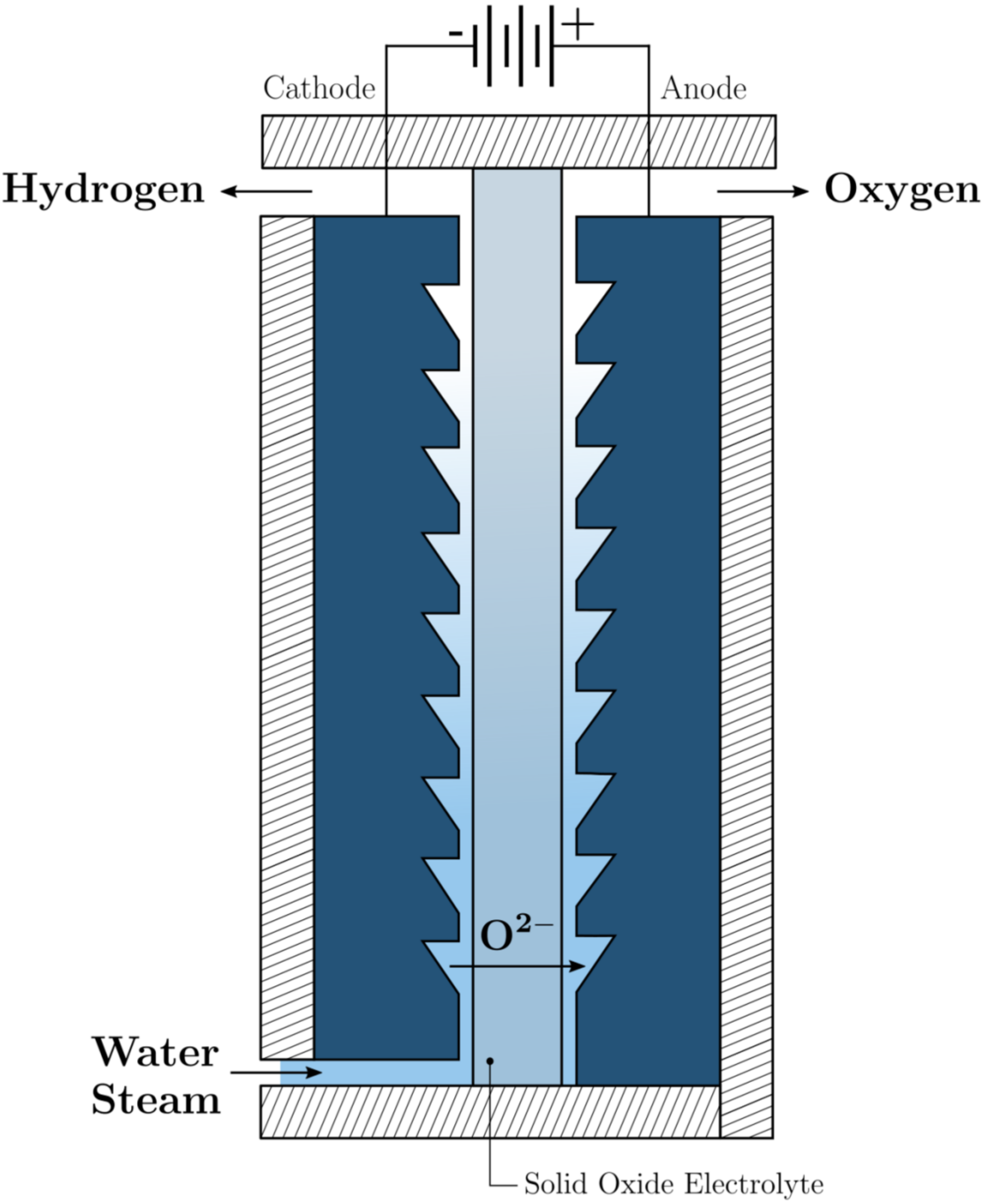

Figure 6 Schematic illustration of a Solid Oxide Water Electrolysis. Retrieved from (Vidas and Castro 2021)

The main characteristic of Solid Oxide Electrolysis is that it uses water steam rather than liquid water. It therefore operates at higher pressures and temperatures. Alkaline Water Electrolysis and Proton Exchange Membrane Electrolysis operate at around 30–80 °C and 20–80 °C respectively. Solid Oxide Electrolysis operates at around 500-850 °C (Shiva Kumar and Himabindu 2019). It is the most similar to Alkaline Water Electrolysis. One of the functioning principles, is that it converts electrical energy into chemical energy and produces a very pure hydrogen. "*Solid oxide electrolysis process conventionally uses the* O^{2-} *conductors which are mostly from nickel/yttria stabilized zirconi* (Shiva Kumar and Himabindu 2019). Solid oxide fuel cells have been developed and researched using certain ceramic materials that conduct protons. Recently, there has been growing interest in using these ceramic materials for the process of solid oxide electrolysis due to their high efficiency and superior ionic conductivity compared to O2 conductors, especially at temperatures between 500-700°C (Pandiyan et al. 2019). Those lower temperatures come with the benefits of lower heat losses, better heat efficiency, more material can be used and lower capital costs.

Nevertheless, it remains a relatively unstable technology where high degradation rates are observed. The high temperatures and pressures also imply certain adaptations in terms of design(Pandiyan et al. 2019). It also makes it a less favored technology for green hydrogen production from renewable energy sources as it requires a constant energy supply with low variations. In some cases, it could make sense to use it with nuclear energy (Vidas and Castro 2021). All of the above implies that Solid Oxide Electrolysis is still a technology under development and far from commercialization. However, while the capital costs are currently (2020(estimated at around EUR 3000/kW_{el} , they are forecasted to drop significantly over the next 10 years and reach around EUR 750/kW_{el} by 2030 (Vidas and Castro 2021).

Overview

Overall, water electrolysis can be considered as a key process for hydrogen production in the years to come. The different electrolysis technologies, Alkaline Water Electrolysis, PEM Electrolysis and Solid Oxide Electrolysis all show different advantages and disadvantages. High hopes can be placed in PEM Electrolysis especially due to its high efficiency, relatively low energy consumption and simple design. It could be a key technology in green hydrogen production from offshore wind parks and other energy generations off the grid. Generally, it should play an important role in green hydrogen production from renewable energy sources. The purity of the hydrogen produced via electrolysis also widens to possibilities for its use. Water electrolysis also comes with the obvious but highly important advantage that it doesn't emit greenhouse gases during the production process. A summary of the main advantages and disadvantages of the different electrolysis technologies is given in the table below.

Table 3 Overview of the advantages and disadvantages of the different electrolysis technologies. Some information retrieved from (Vidas and Castro 2021) and (Shiva Kumar and Himabindu 2019)

Electrolysis Process	**Advantages**	**Disadvantages**
Alkaline Water Electrolysis	– Well developed and researched process – High existing technological development – Relatively high durability – A transition technology for further electrolysis technologies – Non-noble material for electro catalysts – Relatively low capital cost technology – Energy efficiency (70–80%) Commercialized	– Low current densities – Relatively low purity of gases – Corrosive system – Low operational pressure (3–30 bar) – Low dynamic operation and versatility – More complex design – Hazardous materials required – High energy consumption
PEM Electrolysis	– High current densities – Compact system design and Quick Response – Greater hydrogen production rate with High purity of gases (99.99%) – High energy efficiency (80–90%)	– Relatively new process and lack of development so far – High cost of components due to noble metals – Acidic environment – Low durability – Commercialization is still on the way

	– High dynamic operation	
Solid Oxide Electrolysis	– Higher efficiency (90–100%) – Non-noble electro catalysts – Low energy consumption	– Laboratory stage – Large system design – Low durability – High temperatures

2.3.1.2.Energy Source: Offshore Wind Turbines

So far, I discussed how green hydrogen could very well play an important role in the energy transition and decarbonization of the European economy. Hydrogen has a high energy density (MJ/kg). It can also be produced “cleanly” while achieving a highly pure hydrogen thanks to water electrolysis. Furthermore, it can be used to store excess energy and can also be relatively easily transported. The storage and transport will be discussed in the next chapter. Nevertheless, to be considered as “green” when produced via electrolysis, the electricity used in the process must originate from a renewable energy source.

Renewable energies are a fast-growing sector in Europe. From 2021 to 2022, renewable energies have been forecasted to increase capacity by 35% in Europe (IEA 2022a). Globally, they are foreseen to represent 38.1% of all energy sources compared to 28% in 2021 (IEA 2022a). This rise is mostly driven by solar and wind energy.

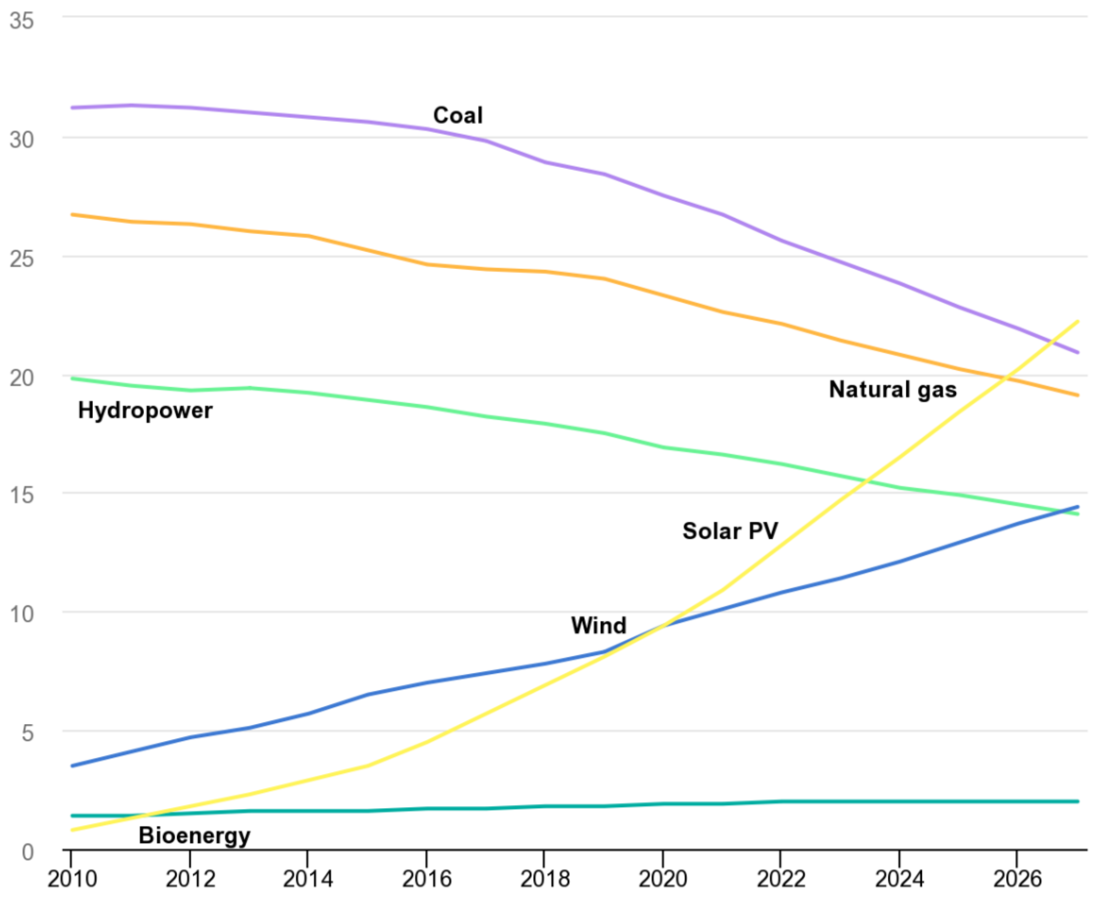

Figure 7 Share of cumulative power capacity by technology 2010 - 2027. Retrieved from (IEA 2022a)

Solar and wind energy are also the main two renewable energy sources to be considered to produce green hydrogen by electrolysis (Hassan et al. 2023). In the following paragraphs, I will only focus on wind energy, specifically offshore wind energy for the production of green hydrogen.

General Information

Offshore wind energy has caught a growing interest as a renewable energy source in addition to onshore wind energy. So much, that out of the 20 billion Euros to be invested by the EU into wind energy, 60% of which would be targeted towards offshore wind energy (Wu et al. 2019). Moreover, offshore wind turbines are being built further into the sea, meaning also on deeper waters. The majority are situated about 10 km away from the coast (Wu et al. 2019). This also led to the development of floating wind turbines opposed to conventional fixed wind turbines. While onshore wind turbines remain cheaper and easier to build and maintain, there are plenty of advantages about offshore wind parks

(Nikitas, Bhattacharya, and Vimalan 2020). Offshore wind turbines remain still about 50% more expensive per megawatt than onshore wind turbines (Wu et al. 2019).

Two main advantages of offshore wind parks in opposition to onshore wind parks can be pointed out. First, the average wind speed is higher on the seas than on the lands (Nikitas, Bhattacharya, and Vimalan 2020). This implies higher efficiency. Furthermore, the Full Load Hours (FLH) are on average between 2000 – and 2300 h per year for onshore wind turbines. The FLE of offshore wind turbines averages 3000 h and can sometimes even reach 4000 h (Morthorst and Kitzing 2016). Full Load Hours are the number of hours per year in which a wind turbine or other renewable energy source produces electricity at full capacity.

A second important comparative advantage is that there is more space available for wind parks offshore than onshore. Onshore wind parks need to go through many complex procedures such as environmental impact assessments, stakeholder participations etc. and are more likely to be a source of disturbance than offshore. That doesn't mean that there are no environmental impacts to be considered for offshore wind turbines. The construction process itself can be an important source of pollution on marine waters and floors (Thomsen 2014). The waste produced offshore must also be taken care off and not simply thrown in the seas. The decommissioning of the wind turbines is also a costly and complex process which needs to be done properly to avoid any damages on the ecosystem. Finally, the location of the wind parks can be the fishing area of local coastal civilizations. This was for instance the exact case during the construction and now operation of the offshore wind park near the coastal city of Saint-Nazaire in France where fishermen complained about the installations ("Les parcs éoliens en mer ravivent la colère des pêcheurs" 2022). Nevertheless, building wind parks offshore allows the construction of bigger wind turbines than onshore, the biggest planned to reach 260 m of diameter (https://newatlas.com/author/loz-blain 2023).

Types of offshore wind turbines

Generally, it is distinguished between two main categories of offshore wind turbines: bottom fixed wind turbines and floating wind turbines. The first ones are used in water not exceeding 60 m of depth (Nikitas, Bhattacharya, and Vimalan 2020). The later are used on deep seas, further away from the coast. Site conditions, such as geotechnical conditions, are also an important factor when considering the type of foundation to be used. Finally, the size of the wind turbine to be installed is also an important factor. So far, most of offshore wind turbines are bottom fixed. However, with wind parks being constructed further off the coasts, floating wind turbines will become more and more relevant (X. Wang et al. 2018).

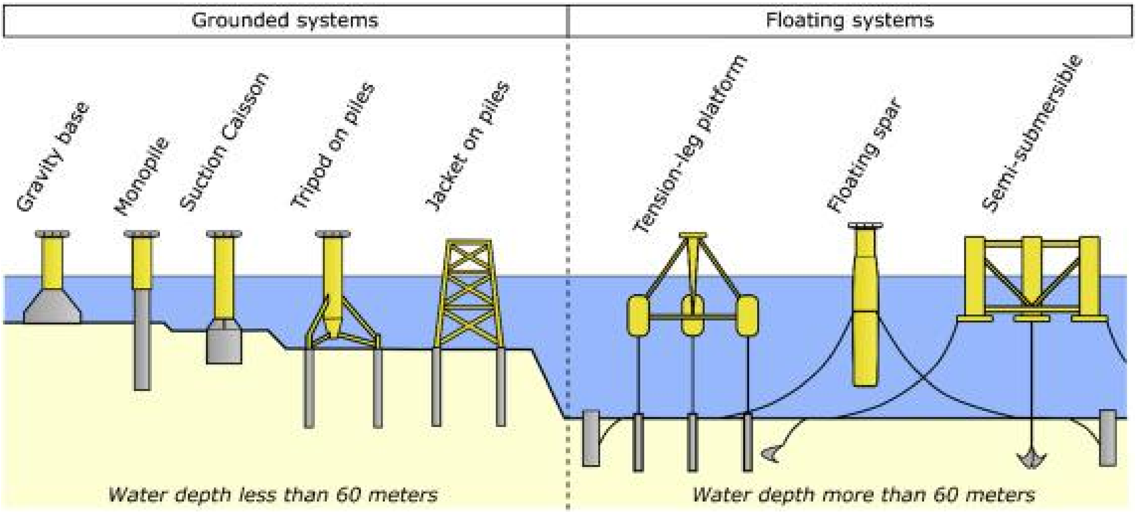

Figure 8 Common types of foundations to support offshore wind turbines. Retrieved from(Nikitas, Bhattacharya, and Vimalan 2020)

Monopile foundations are the most common type of foundations for offshore wind turbines. It is also the simplest hence its popularity. It is constituted of a long steel hollow cylinder, close to half of which is embedded in the ground. The main advantage is that it can be constructed onshore and directly installed on the sea floor without preparation works (X. Wang et al. 2018). It therefore also has the advantage to have relatively low construction costs. There installation are however limited to about 30m water depth (Nikitas, Bhattacharya, and Vimalan 2020).

Figure 9 Monopile foundation for offshore wind turbine. Retrieved from ("Offshore Wind Turbine Foundations: Leveling and Fixation with Hydraulic Cylinders" 2022)

Gravity base foundations are, as their name indicates it, foundations which use their own weight to stabilize on the sea floor. The weight must be heavy enough in order to compensate extreme winds and currents to avoid the turbine to tip over (Wu et al. 2019). The structure is usually made out of concrete and the advantage is that it does not require any drilling on the seabed. Some preparation of the sea ground is however required to have a clean and place surface (X. Wang et al. 2018). They are a simple solution, which however cannot be used in depth greater than 10 meters of water.

Figure 10 Gravity based foundation for offshore wind turbine. Retrieved from (Lewis 2022)

Tripod foundation for offshore wind turbines consist of three steel cylinders disposed in a triangular shape. They provide therefore more stability than monopile foundations and can be placed in deeper waters, up to 50 meters depth (Nikitas, Bhattacharya, and Vimalan 2020). However, since they consist of three additional cylinders in addition to a central one, they are also heavier. This in turn increases the costs of production and makes the installation more difficult (X. Wang et al. 2018).

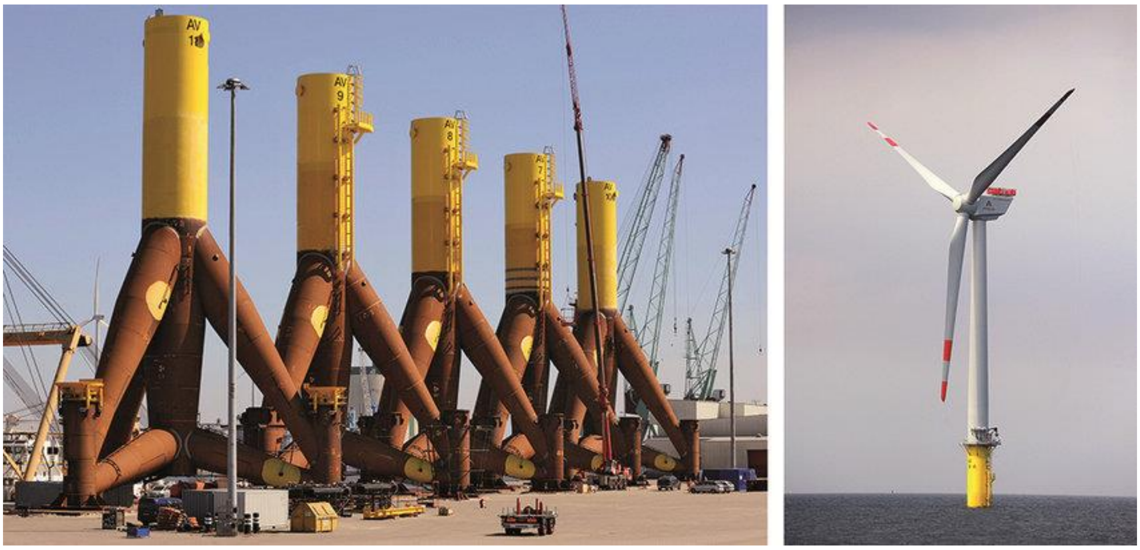

Figure 11 Tripod foundation for offshore wind turbine. Retrieved from(Stahlmann and Schlurmann 2012)

Jacket foundations for offshore wind turbines consist of several smaller pieces which can be assembled to fit the requirements and constraints of the sea floor easily (Taylor 2019).

Each component is usually fabricated on land before being assembled together on site. They can carry heavier turbines and larger facilities. They are also better suited for deeper waters up to 80 meters (X. Wang et al. 2018). Due to the on-site installation, they are also more costly to set up and require more complex logistics.

Figure 12 Jacket foundations for offshore wind turbine. Retrieved from (CORPORATIVA n.d.)

Floating wind turbines are an alternative to bottom fixed foundations for wind turbines on deeper seas, usually over 60 meters depth. They are anchored on the sea bed and a floating structure provides buoyancy force to support the whole turbine (Wu et al. 2019). The floating structure must be stable enough to maintain movements of the wind turbine inside a certain range. The fact that they are not drilled into the seabed means that they can also me more flexibly placed to the best suited location. However, waves and wind can still lead to important movements during operations. The main types of floating wind turbines are semi-submersible platforms, spar platforms and tension leg platforms as shown on the figure below.

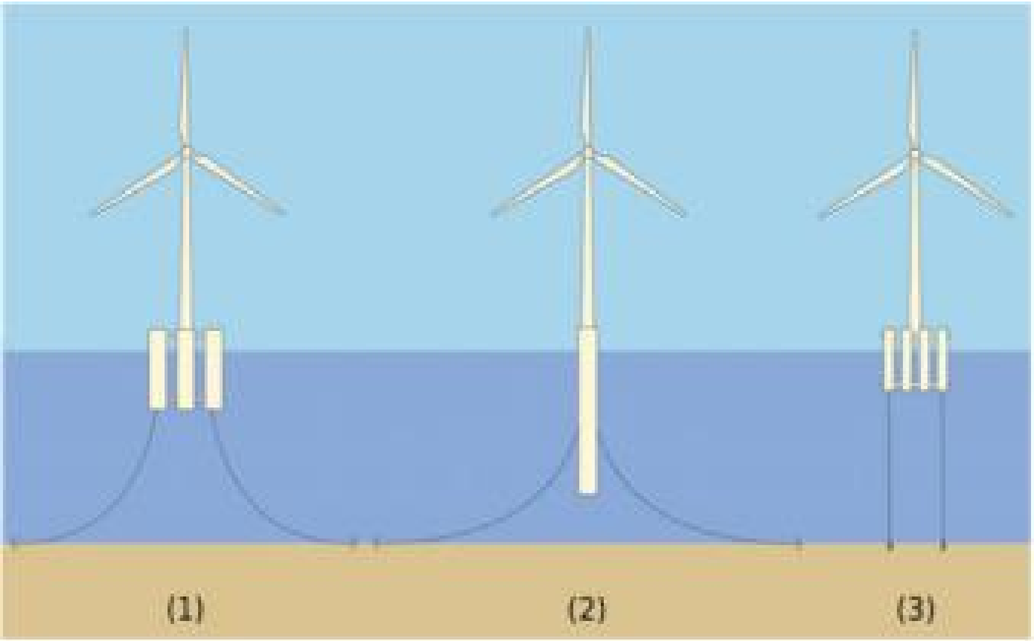

Figure 13 Floating wind turbine concepts: (1) semi-submersible platform (2) spar (3) tension leg platform. Retrieved from (Wu et al. 2019)

The main advantage and disadvantage of each type of structure are presented the table below as summarized by Wang in "A review on recent advancements of substructures for offshore wind turbines" (X. Wang et al. 2018):

Table 4 Advantages and limitations of structures for offshore wind turbines. Retrieved from (X. Wang et al. 2018)

Foundation	**Advantages**	**Limitations**
Monopile	Simplest technical solution; low cost; industrialization	Limitation of water depth; scour effect
Gravity	Simple technical solution; used at locations where piles cannot be driven	Limitation of water depth; seabed preparation is necessary
Tripod	Larger bearing capacity; adapt to larger water depth (up to 50 m)	Higher cost; more difficult installation
Jacket	Adaptable to larger water depth (up to 80 m)	Higher cost in construction and installation
Floating	Largest adaptable water depth; flexibility	Large movement during operation

Different configurations for hydrogen production

Green hydrogen produced by water electrolysis via renewable energy sources can relatively easily be achieved onshore. Onshore wind parks or photovoltaic parks are a viable option and will most probably be involved to produce green hydrogen. However, as mentioned above, offshore wind energy has a great potential as well. Offshore wind parks show many comparative advantages opposed to onshore wind parks. But producing green hydrogen from offshore wind energy raises new challenges. The simple fact of building and conducting any type of activity on water makes everything more complex and therefore also costly. The main question is therefore, do the advantages of offshore wind energy overcome the challenges imposed by producing green hydrogen from it? In the following paragraphs, I will discuss this question and review the different configurations possible for producing green hydrogen from offshore wind energy and define the main difficulties arising.

Generally, the main debate concerns whereas the electrolysis should take place onshore or offshore. In the first case, electrolysis takes place in a facility on the coast and in the second case, electrolysis takes place either on a centralized facility on an offshore platform or the electrolysis system is directly installed for each wind turbine (Jang et al. 2022). The three different configurations are presented in the figure below:

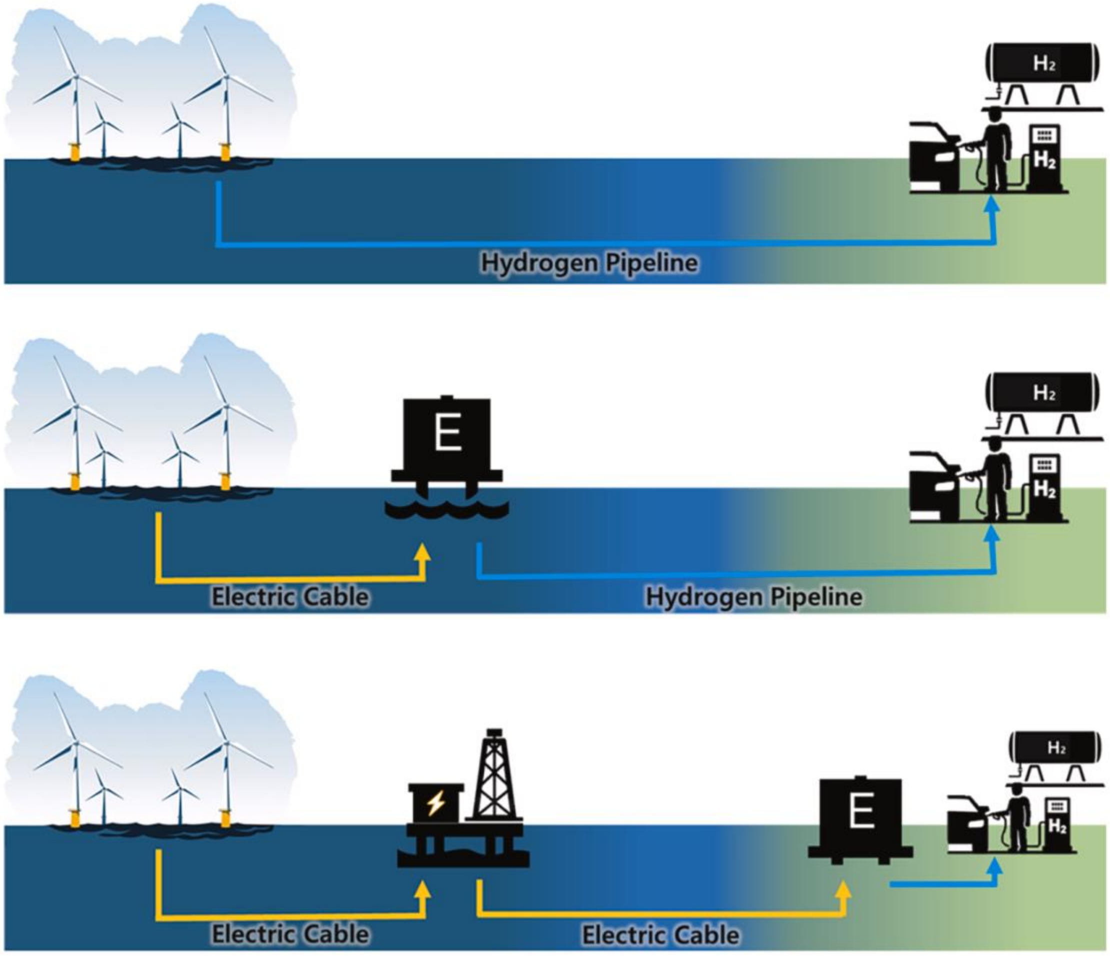

Figure 14 Three different configurations for producing green hydrogen from offshore wind energy, from top to bottom: Individual Offshore electrolysis, Centralized Offshore electrolysis, Onshore electrolysis. Retrieved from(Jang et al. 2022)

Offshore Electrolysis

The main argument for producing the green hydrogen offshore is that the losses during the transport of hydrogen to shore are much lower than the losses during the transport of electricity to shore. This is formidably explained by Calado and Castro in their article “Hydrogen Production from Offshore Wind Parks-Current Situation and Future Perspectives” (Calado and Castro 2021):

“*Considering a High Voltage Alternating Current (HVAC) transmission system, losses are around 1% farms with nominal power from 500 to 1000 MW and located 50–100 km from shore. For a HVDC system, losses range from 2% to 4%, depending on nominal power and distance. However, hydrogen travelling through a pipeline has considerably lower losses, under 0.1%, along with reduced initial costs for an underwater pipeline compared* *to underwater electrical cables and the power electronics needed (Calado and Castro 2021).*"

Regarding the choice of electrolysis technology, PEM electrolysis seems to be the most favored technology due to its simple and compact design, in addition to its easy maintenance. All those three factors are essential for offshore hydrogen production since place and accessibility are limited (Calado and Castro 2021). Another advantage of PEM electrolysis in the case of offshore hydrogen production is that it uses pure water opposed to an alkaline solution in the case of alkaline water electrolysis. Finally, it can also function with more important currents and is more reactive to variable electricity supply which is characteristic of renewable energy sources (Jang et al. 2022). In addition to the electrolysis, which is the main process, the produced electricity from the wind turbines can also be used to purify the sea water and pressurize the produced hydrogen to be transported with pipelines to the shore. The design and size of the pipeline is also important as depending on the pressure and distance to the shore, different diameters of pipes should be use to minimize the losses and maintain a stable flow. While all technologies can operate on the electricity produced from the wind turbines, a backup power source needs to be provided for the short periods of shutdowns which may occur (Calado and Castro 2021).

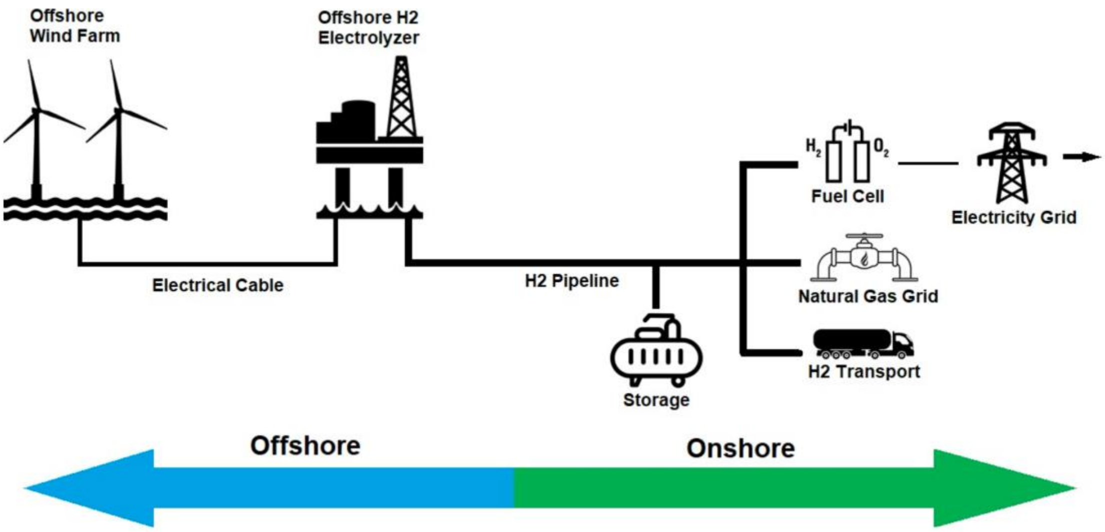

Figure 15 Offshore electrolyzer system. Retrieved from (Calado and Castro 2021)

Remains the question, whereas a centralized electrolyzer system or individual electrolyzers for each wind turbine should be used. The two configurations are described below.

A centralized electrolysis systems doesn't change much the usual disposition of the wind park. Each individual wind turbines transmit electrical power in AC to the centralized platform where the hydrogen is produced. While some of the electrical power can be directly used to operate the water purifiers and hydrogen pressurizers, the rest needs to be transformed to DC to be used during the electrolysis. DC power is also used to operate the backup power source and supporting facilities (Calado and Castro 2021). Once produced, the hydrogen needs to be pressurized before being transported onshore via an underwater pipeline.

Individual electrolysis system functions similarly to the centralized electrolysis, with the only difference that the hydrogen is directly produced on the wind turbine and not on a centralized platform. While this requires therefore as many PEM electrolysers as there are wind turbines, it avoids having to build a central platform to host one larger electrolyser. Furthermore, as I already mentioned, the losses from transporting electrical power are much larger than the ones from transporting hydrogen. In addition, underwater hydrogen pipelines are cheaper than underwater electricity cables. Hence, in an individual electrolysis system, the losses due to the underwater transport of electrical power is further minimalized. Small diameter hydrogen pipeline transport the produced hydrogen from each wind turbine to a larger pipeline connected via a subsea collection manifold and is then transported to the shore with a single pipeline (Calado and Castro 2021).

Onshore Electrolysis

Onshore electrolysis systems differ to offshore electrolysis systems by transporting the electrical power to shore before producing the hydrogen instead of producing the hydrogen offshore and then transporting it onshore. One advantage is that the electricity produced can also be directly sold on the grid in addition to being used for hydrogen production. This offers more flexibility as it can be decided either to produce more hydrogen or to sell the electricity to the grid depending in the market price of electricity. However, the main disadvantage are the losses during the transport of electrical power in underwater cables. Furthermore, having all equipment relating to the hydrogen production onshore facilitates the logistics of construction and maintenance. The facilities are also better protected from the natural elements on the seas and the corrosive sea salt. Since more place is available, it can also be possible to use an alkaline water electrolysis system instead of a PEM system.

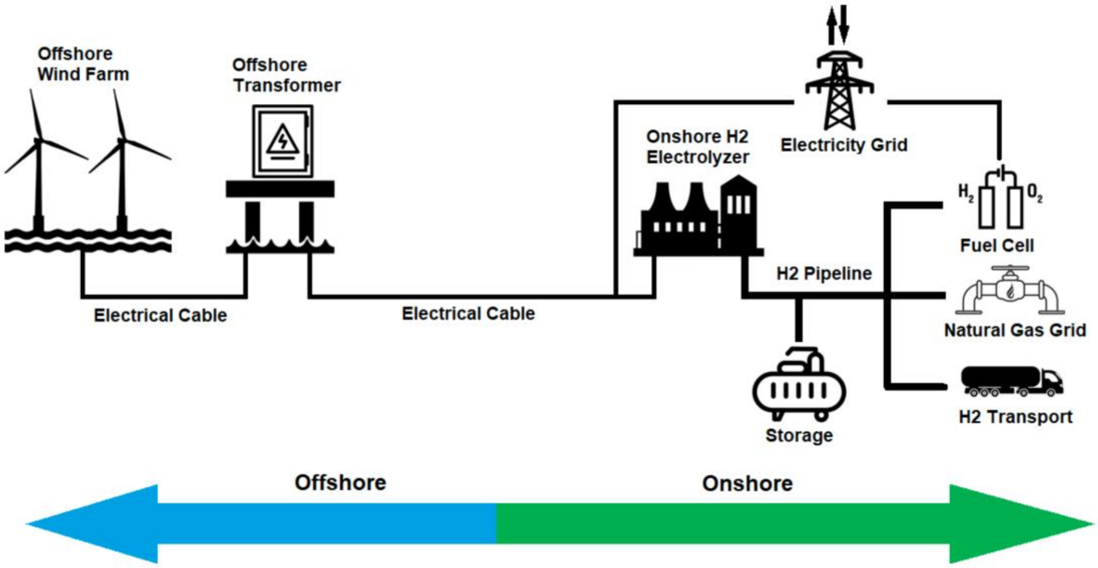

Figure 16 Onshore electrolyser system. Retrieved from (Calado and Castro 2021)

Regarding the type of current to be transmitted, whereas it is HVDV or HVAC, it really depends on the distance to the shore of the wind turbine park. Losses in HVDC are significantly lower than the ones for HVAC. Therefore, at a distance from the shore above 50km, it can be preferable the convert the HVAC produced from the wind turbines into HVDC on an offshore transformer (Calado and Castro 2021). Finally, the water used for electrolysis can either be sourced from the existing freshwater supply onshore or can be pumped from the sea and then desalinated. The first option, while being simpler, can however be an issue in dry locations where fresh water is scarce or where water supply facilities do not exist.

Comparison between all three configurations

Overall, each of the three configurations can be considered depending on what factor is considered the most important. If a flexible installation is wished, which can alternate between producing green hydrogen and sell electricity directly to the power grid, then onshore electrolysis systems are best suited. If, however, a more efficient system is wished, which also minimizes the losses is preferred, then offshore electrolysis is probably the best option. Whereas individual electrolysis or centralized electrolysis is the be used depends on the size of the wind turbine park. A study has been conducted to determine which of the three alternatives is the most cost efficient. The results show that offshore individual electrolysis systems are most likely the be the most cost effective configuration (Jang et al. 2022). Offshore centralized electrolysis systems are not too far off and could be justified for smaller wind turbine parks. Finally, onshore electrolysis systems are the least cost efficient due to the high losses during the transport of electricity in underwater cables. However, the higher flexibility makes them still an option worth considering.

2.3.2. Storage and transport

One of the reasons why hydrogen is in the center of attention when it comes to the future of the energy sector is because it has the particularity that it can be stored. This is an essential characteristic when considering an energy sector based fully on renewable energy sources which are often characterized by an unregular output and the incapacity to be stored. By finding a way to store this renewable energy, it allows us to control and monitor supply and demand of energy (Møller et al. 2017). Using renewable energies to produce hydrogen which can then be used in different ways, is therefore a promising way to bring stability, reliability and control to renewable energy-based economy. There may be alternative ways in which renewable energies can be stored with each advantages and disadvantages. For instance, "*potential mechanical energy as pumped-hydro and compressed air energy storage… …however, the latter largely depends on the geographical conditions e.g. lakes in mountain areas or under- ground salt caverns*." (Møller et al. 2017).

Hydrogen also has the main propriety to have the highest energy density per kg of all known elements. This is an immense advantage as it means higher energy efficiency per kg of fuel. However, it also has a much lower energy density per volume than other common fuels. This makes the storage and transport of hydrogen much more complicated and requires bigger fuel tanks etc. It is also mentioned in literature, that due to its small size, it also has the ability to exit and escape its container should it not be perfectly permeable. In addition, "*its destructive capability (hydrogen embrittlement) can lead to mechanical degradation and failure to the point of leakage in certain materials*" (Dawood, Anda, and Shafiullah 2020). Taking into account that hydrogen is a very flammable element which requires very low ignition temperatures, this creates an additional risk factor to be taken into account (Dawood, Anda, and Shafiullah 2020).

There are therefore several different ways in which hydrogen can be stored. Here I will distinguish between storage by compression, storage by liquefaction and storage by chemical processes. Each has its advantages and disadvantages and could be better suited than another depending on the purpose and end use of the hydrogen.

2.3.2.1.Storage

Storage by compression

Storage by compression requires much less energy than storage by liquefaction. It however also comes with the disadvantage that it requires much more storing place which can be crucial in certain appliances. For comparison, compressed hydrogen "*requires over two times the volume that of natural gas with the same energy output*" (Vidas and Castro 2021).

It remains however the most popular storing system for hydrogen so far. Its simplicity also brings the advantage that it is therefore less costly than other storage facilities. Other often mentioned advantages are rapid discharge, operations at more variable scope of heat, release at room temperature possible and minimal energy requirements (ZHANG et al. 2015). The fact that it can be operated at such a wide range of temperatures makes it a very resilient option for storage for diverse geographic locations with different climates.

Nevertheless, safety concerns are also part of the factors to be considered in the storage method to be used. Compressed hydrogen also leads to higher risks of gas leakages, especially as I already mentioned, hydrogen has to particularity to be a relatively small sized compound making it even more difficult to contain in an impermeable tank. This would be less of an issue if hydrogen wasn't as explosive as it is. Also, when considering pressurized tanks, the faster weakening of the structure is also to be taken into account compared to normal storage tanks.

Still, considering all the above-mentioned advantages, storage by compression remains the preferred storage method and is thus also a well-developed technology (ZHANG et al. 2015). Furthermore, compressed storage tanks can be used in a wide range of applications such as large stationary infrastructure, on large transport vehicles and even for ship transportation.

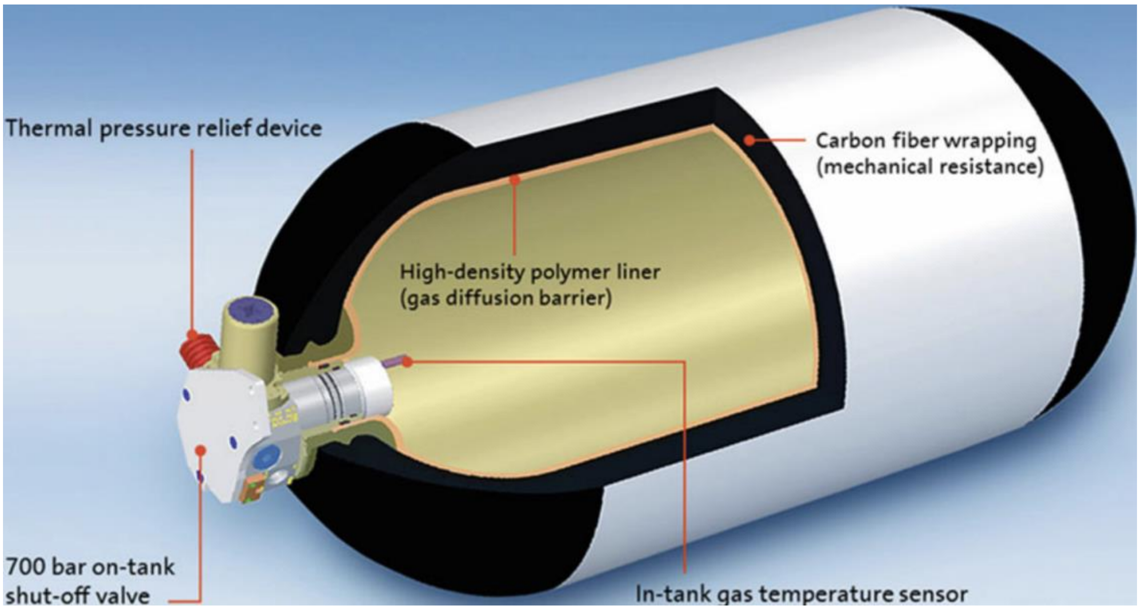

Figure 17 Compressed hydrogen storage tank. Retrieved from (Helmolt and Eberle 2014)

Storage by liquefaction

Storage by liquefaction has been developed with the aim the resolve the issues imposed by the large volumes required for gaseous hydrogen storage. To liquefy the hydrogen, it is first compressed before being transformed into cryogenic temperatures which means at below -252,15 °C (ZHANG et al. 2015). Hydrogen freezing/melting points and boiling points are respectively -259.2 °C and -252.8°C (Dawood, Anda, and Shafiullah 2020).

The liquid hydrogen is afterwards stored in a specific container which has to be isolated from external heat and also be remained vacuumed. This is a perfect method to store hydrogen without having to use a lot of space. However, the main drawback of this method is that it requires important amounts of energy liquefy the hydrogen. Zhang mentions that "*30 % of the total hydrogen energy in practical engineering application*" is used during liquefaction (ZHANG et al. 2015). The thermal insulation is also not that easy to achieve and further imposes additional constraints on the possible uses of liquified hydrogen thanks.

There are therefore many challenges which need to be addressed in order to fully commercialize liquified hydrogen storage tanks and to see them used for a variety of purposes. They are for instance being considered for long haul flights as shown in the figure below. Their smaller size could indeed become very practical in specific cases such as air and road transport.

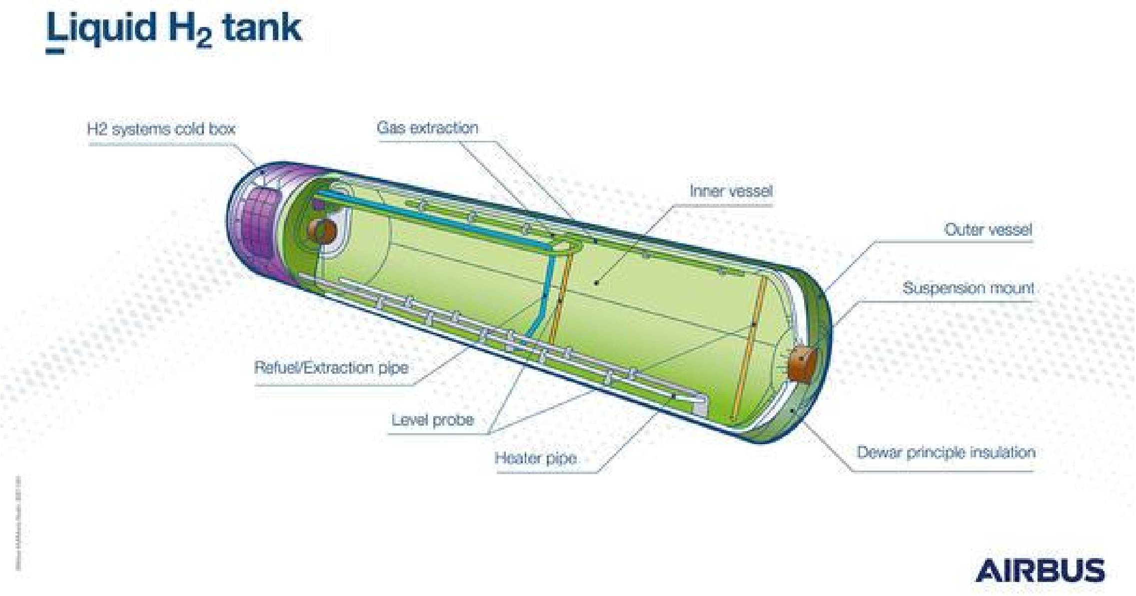

Figure 18 Liquid hydrogen storage tank designed for zero emission flights. Retrieved from (Airbus 2021)

Storage by chemical processes

When it comes to storage by chemical processes, we must distinguish between two processes: metal hydride systems and storage in Ammonia.

The first one, metal hydride systems refer to storing hydrogen in a solid state by bonding hydrogen molecularly to a metal. This has the advantage to be much more efficient tin terms of volume used than compression storage or liquified storage systems (Vidas and Castro 2021). It is however still in the development phase but shows encouraging results so far. At some point, it could even become a serious alternative to battery storage. The main drawback of this technology so far is that it requires relatively high ambient temperatures for “discharging” it (Langmi et al. 2022). Metal hydride systems can be further distinguished into three categories: intermetallic hydrides, binary hydrides, and complex metal hydrides. Each sub-category shows different proprieties and complexities. Those are well described in (Langmi et al. 2022).

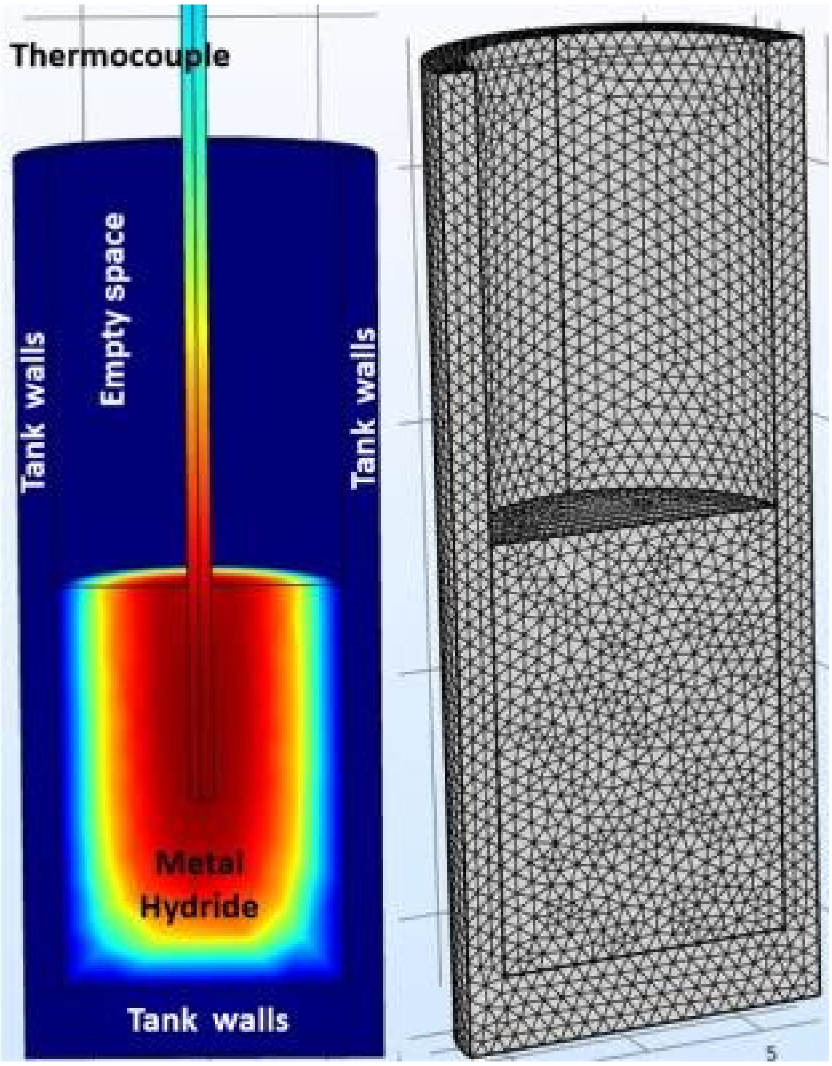

Figure 19 Schematic of a cylindrical metal hydride storage tank. Retrieved from(Gkanas 2018)

The second storage system by chemical processes is Ammonia. Hydrogen can indeed be stored in ammonia, which is an already well-known compound used as fuel for a variety of purposes. This also means that the concerned industries are already familiar with the associated technologies. As it is described by Langmi et al., (Langmi et al. 2022):

"*The process of ammonia synthesis (the Haber–Bosch process) has been applied since the early 1900s. Later that century, it led to a significant increase in global crop production, with ammonia acting as agricultural fertilizer. In 2019, the global annual ammonia production rate was estimated at ~170 million metric tons. Although ammonia is a carbon-free molecule, the hydrogen necessary for its synthesis comes with significant carbon emissions due to the reforming of natural gas and the gasification of coal—*

processes still applied today for hydrogen production. The ammonia synthesis process can, however, be decarbonized, with the implementation of electrolytic hydrogen production, using renewable energy sources"

Ammonia can be stored over a long period of time, is relatively stable and can also be more easily transported. It contains a high hydrogen density such as that ammonia storage methods can sometimes store higher volumes of hydrogen than other hydrogen storage methods such as liquified hydrogen (Vidas and Castro 2021). Furthermore, it can be stored at standard temperature and pressures (25°C and 1 bar). It is however therefore heavier than pure hydrogen which could be an issue for transportation. Furthermore, releasing hydrogen from ammonia is a very energy intensive process, especially if hydrogen high in purity is required. However, ammonia can also be used for power generation whereas it is internal combustion engines, fuel cells or gas turbines(Langmi et al. 2022).

Figure 20 Ammonia storage tank. Retrieved from ("Ammonia Storage Tanks - Sagebrush" 2020)

2.3.2.2.Transport

Once produced, the question remains how the hydrogen is to be transported to its end-user. This of course will depend on a variety of factors such as who is the end-user, where is the hydrogen being produced, how is the hydrogen being stored etc. Typically, it would be more economical, efficient and sustainable to transport the energy as electricity to the end-user. Then, the renewably produced energy can be used to produce green hydrogen (Gerboni 2016).

However, this is logistically not possible over long distances. This is the case when the original energy source, whereas it a renewable source or a fossil fuel source, is located remotely or even overseas. In this case the transport of the original energy source can be too costly, e.g., for coal or simply impossible in the case of renewable energy sources e.g., wind or solar energy. In this case, the storing propriety of hydrogen is again an important advantage. It would then make sense to produce the hydrogen on the site of the energy source before transporting it directly to the end-user.

Furthermore, when considering renewable energy sources to produce electricity, those are usually directly integrated to the power grid. However, this is where the main disadvantage of renewable energies strikes again being that they are relatively unpredictable in time, vary in their intensity, usually only operate at a certain time of the day and most importantly cannot be stored. This is already a proven source of issues in the balance of the power grid (Gerboni 2016). Furthermore, this also makes the electricity pricing more unpredictable. In this case, producing hydrogen with the excess electricity from renewable energies could be an elegant solution. It can then either be re-transformed into electricity or even be transport to its end-user directly.

Transporting energy as hydrogen could even allow to exploit renewable energy sources situated in other continents such as Africa ("New Study Confirms € 1 Trillion Africa's Extraordinary Green Hydrogen Potential" n.d.). This however would create also a whole new range of risks and challenges. Depending on any energy source produced in another country, moreover sometimes also a relatively unstable country, is the kind of vulnerability states would tend to avoid.

Overall, the transport of hydrogen is an important field of development which will grow in attention over the next years. Depending on the type of storage, the origin of the energy source or the end-user, different methods of transportation could be preferred. The main categories of transport are the following: Road / train transport, transport by ship, pipelines. The different categories are described below.

Transport by road and train

Whereas it is for gaseous or liquid hydrogen, transport by road or rail is a key method of transportation to be considered. Indeed, the main advantage is that the infrastructure, being roads or railways, already exist. The hydrogen tanks can be filled near the production site, before being loaded on the carrier, train or truck, for shipping. Once the transport arrives at destination, the full hydrogen tanks can simply be exchange with empty ones. This is the same system as it is used for instance for households using gas, but which are not connected to the gas supply network.

Logically, this mean of transportation relies on existing infrastructure and is less likely to be possible over longer distances. Furthermore, it is simply not possible for hydrogen produced overseas. Nevertheless, it remains one of the main means of transportations of hydrogen for medium/long distances. Some European national railway companies are already preparing for this kind of transport in the near future. As can be read on the DB website, "*The hydrogen future is coming. Since there are no special pipelines for transporting hydrogen yet, DB Cargo is bridging this technology gap with an alternative solution and aims to transport the urgently needed fuel by freight train in the future*." ("Hydrogen by Rail" n.d.).

When it comes to transportation by truck, further safety conditions need to be taken into account as national road regulations may consider hydrogen as a dangerous substance due to its highly flammable nature (Gerboni 2016). Another factor to be accounted for are the losses occurring during each transfer from one vessel to another. It is therefore important to minimize such losses whereas it is by design or technological solutions.

Transport by ship

The main advantage of transport by ship is obviously that it allows to achieve long distances and cross seas and oceans. In the case of transporting hydrogen, it is first important to understand why it would be relevant to produce hydrogen far away from where it is needed. As I mentioned previously, the main reason is that certain resources are only available or more easily available in remote locations. For instance, Namibia has the characteristic to have one of the biggest potential in terms of solar and wind energy ("Namibia" n.d.). Directly transporting this energy in the form of electricity to Europe requires an immense power grid system which would have to cross many countries and even seas. However, transforming this energy in hydrogen on site before transporting it by ship to Europe seems much more feasible.

Most of the studies conducted so far on transport of hydrogen by ship, favored liquid hydrogen to gaseous hydrogen (Gerboni 2016). Furthermore, some even considered the possibility to re-use the boiloff of hydrogen during the transport as a source of fuel for the ship itself (Pekic 2022).

Figure 21 Suiso Frontier LH2 Carrier. Retrieved from (Pekic 2022)

Transport by pipeline

The transportation of hydrogen via pipeline is likely to play an important role in the case of the development towards an hydrogen economy (Gondal 2016). The technology used can be derived from the existing natural gas pipeline networks. Furthermore, hydrogen can be mixed to natural gas so that it can be transported in the existing natural gas pipeline networks (Gerboni 2016). Also, pipelines come with the great advantage that they can be buried underground, reducing the issues encountered when building for instance infrastructure road or railway infrastructures.

There are already long distance pipelines for hydrogen existing, mainly in western Europe and more are planned to be built (Steen 2016). However, the costs for building a natural gas pipeline are minimum US $ 200,000.00 per kilometer and increase a lot depending on the diameter of the pipeline. Furthermore, the costs of building an hydrogen pipeline are currently about 10 % above the costs of building a natural gas pipeline (Gondal 2016). Nevertheless, pipeline also show a longer longevity, meaning while they may require high initial investment costs, they can usually also be used over a long period of time.

Pipelines are also much safer than transporting hydrogen by truck, train or ship. There are still some technological challenges to be overcome for a wider use of hydrogen pipelines. Other emerging issues are safety concerns since gas pipelines are spreading over large distances and areas which makes it difficult to monitor and surveil them. Current materials used for natural gas also are not adequate for pressurized hydrogen transport since hydrogen is a very small compound and thus existing materials can be too porous and lead to leakages. Finally, the low volumetry energy density of hydrogen means that higher volumes need to be transported to obtain similar energy equivalents. Hydrogen pipeline would therefore have to be either of larger diameter or stronger pressurizers would have to be used than for natural gas (Gondal 2016).

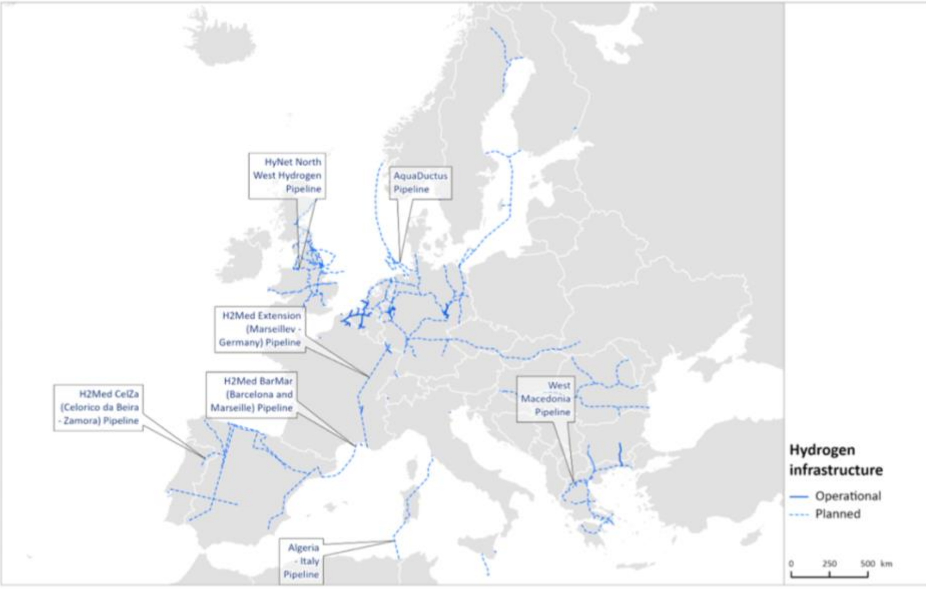

Figure 22 Existing and planned hydrogen pipelines in Europe. Retrieved from (Steen 2016).

Summary

Whereas it is by road, train, ship or pipeline, the transport of green hydrogen will be crucial to secure the success of a sustainable hydrogen economy. Each alternatives have its advantages and limitations. Road and rail transportation can count on already existing infrastructure but are not well suited for long distance transport. Transport by ship is a promising domain, especially when it comes to long distances from one continent to another. Progress still needs to be made in terms of technological development, but the first attempts seem promising. Finally, pipeline transportation is probably the most ideal alternatives but will require many years until it is fully constructed and operational. Therefore, road and railway transportation will play an important role on the short term until pipeline and ship transportation fully develop and become operational.

2.3.3. Uses of (Green) Hydrogen and focus on the steelmaking industry

2.3.3.1.Main uses

So far, the different technologies of water electrolysis, the production of hydrogen using offshore wind energy, the storage and transport of green hydrogen have been discussed stating their main advantages and limitations. Now I shall present the main uses of hydrogen currently existing. First, hydrogen to produce electricity, then hydrogen for the natural gas grid, and finally hydrogen as feedstock.

Hydrogen to produce electricity

The main advantage of hydrogen is that it can be used as an energy carrier. Once produced, it can be stored and transported before serving as a source of energy to produce electricity via fuel cells. Fuel cells are a kind of electric battery continuously recharging, given they are being supplied with hydrogen and air (Edwards et al. 2008). Fuel cells produce electricity via the electrochemical reaction of hydrogen and air. While fuel cells can function with any kind of fuel containing hydrogen, fuels from hydrocarbon will emit greenhouse gases such as CO2. However, electrolysis allows us to produce a very rich hydrogen fuel which therefore does not emit greenhouse gases when used in a fuel cell to produce electricity.

$$2H_2 + O_2 \rightarrow 2H_2O + \text{energy}$$

Fuel cells therefore allow us to produce energy in the form of electricity while only emitting water as a by-product. Fuel cells can convert fuel into electricity in a much more efficient way than classic combustion engines (Edwards et al. 2008).

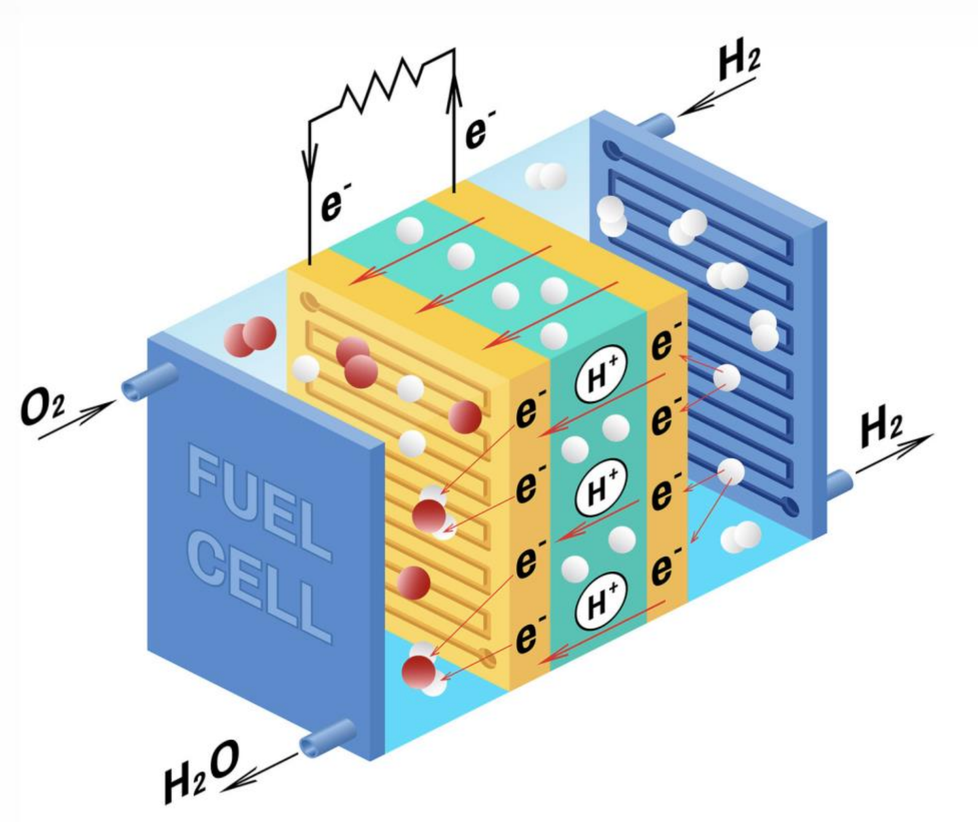

Figure 23 Hydrogen fuel cell. Retrieved from (https://www.facebook.com/airbus 2021)

A major application of fuel cells resides in the mobility sector. The aviation, railway and heavy automotive sectors could benefit from hydrogen fuel cells to decarbonize their activities. The main advantage compared to classical electric vehicles is that it can quickly be charged for a long distance range (Calado and Castro 2021).

Another application of hydrogen fuel cells is in the electrical power supply. Excess electricity produced during low demand peaks, especially from renewable energies, can be stored by producing hydrogen via electrolysis. This stored energy could later be reconverted into electricity during high demand peaks using fuel cells (Mekhilef, Saidur, and Safari 2012). Hydrogen fuel cells could also replace small diesel generators which are for example highly used on small islands (Yousefzadeh et al. 2020). While fuel cell technology hasn’t yet reach commercialization, it is a promising technology which will certainly play an important role in the energy transition.

Hydrogen for the natural gas grid

Hydrogen has a very high energy density per weight. This makes it therefore a very flammable gas. It is possible to mix the hydrogen with natural gas into the grid without having to change the infrastructure. Up to a ratio of about 30%, hydrogen can be mixed with natural gas without altering the combustion conditions (Capurso et al. 2022).

Hydrogen as feedstock

Hydrogen is already used in several industries such as refineries and ammonia production (Calado and Castro 2021). To be more precise, “*currently, over 90% of hydrogen produced in Europe is used as a feedstock in oil refining, ammonia and methanol production, which represent about the 41% of the EU’s industrial emissions. Moreover, about 55% of the global hydrogen demand is for ammonia synthesis, 25% in refineries, 10% for methanol production, and 10% for others*.” (Capurso et al. 2022). However, most of the hydrogen used originates from natural gas (grey hydrogen) using steam methane reforming. Transitioning to green hydrogen would therefore contribute in decarbonizing the industry. In the steelmaking industry, hydrogen can be used as a reducing agent to decarbonize the Direct Reduced Iron production. Green hydrogen could “*lead to 740 Mt of atmospheric carbon dioxide reduction per year by 2050 when accounting for the growth of the steel industry*” (Oliveira, Beswick, and Yan 2021). The potential uses in the steelmaking industry will be discussed in the next chapter.

Efficiency

At this stage, it is relevant to mention the overall energy efficiency of producing green hydrogen by electrolysis to later use it as a power source. First of all, water electrolysis itself is characterized by a 70 % energy efficiency (Younas et al. 2022). Meaning from 100% energy produced from a renewable energy source, only 70 % are converted into hydrogen. In addition, the conversion from chemical energy into electrical energy by hydrogen powered fuel cells is about 60 % according to the US department of energy (“Fuel Cells” n.d.). Combining those two factors gives us an overall efficiency of about 42 %. This is ignoring energy losses due to compression, storage and transport of the hydrogen. Those losses can vary depending on the method of transport or storage but could lower the overall efficiency to around 30 % (Lu et al. 2022). As comparison, classical diesel combustion engines have an energy efficiency of around 40 % (Xin and Pinzon 2014). However, electric engines show a much higher energy efficiency from the grid to the power generation at around 77 % ("All-Electric Vehicles" n.d.).

2.3.3.2. Uses in the steelmaking industry

The steelmaking industry is an essential industry in Europe. Indeed, the European Union is the second largest steel producer in the world after China ("Steel" n.d.). The steel making process requires however high quantities of energy, natural resources and uses fossil fuels in the form of natural gas, coke, etc. The industry is therefore an important challenge when it comes to the decarbonization ambitions of the European Union. While steel is a material which can be recycled, its production remains one of the most polluting activities in the world. Steelmaking activities are estimated to represent around 5.5–6% of the total annual greenhouse gas emissions (Mapelli et al. 2022). In addition to CO_2 emissions, steelmaking is also very demanding in terms of energy requirements, water use and land use.

Steelmaking can be decomposed into two main steps. First the reduction of the iron ore, second the conversion into crude steel:

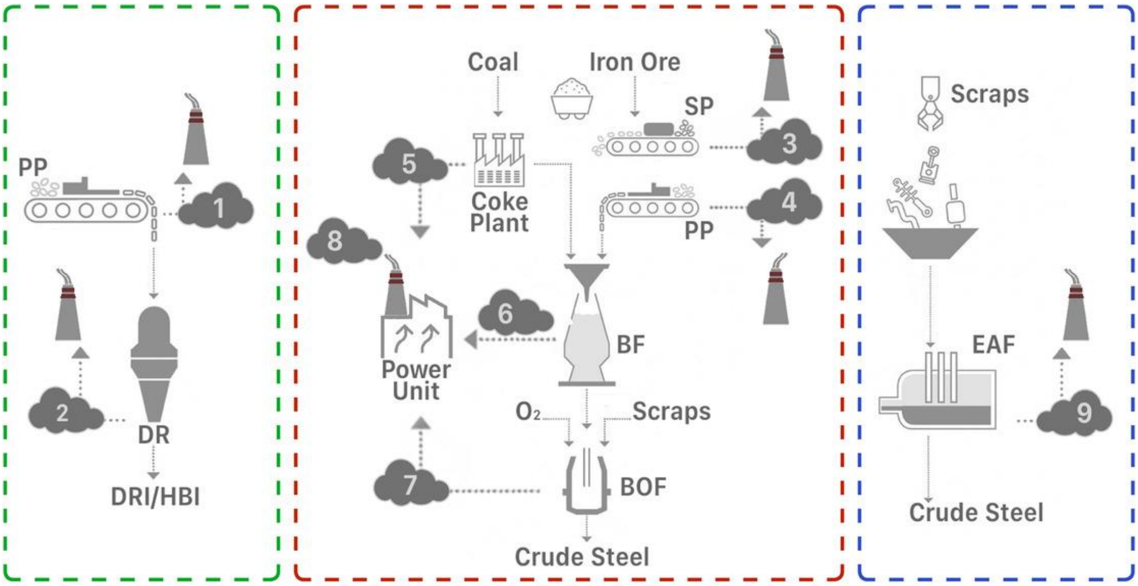

Figure 24 Steelmaking processes. From left to right: Direct Reduction, Integrated Cycle, Electric Arc Furnace. Retrieved from (Mapelli et al. 2022)

The reduction of the iron ore can be achieved through two main processes. The first one is Direct Reduction. During Direct Reduction, iron ore pellets, produced in the pelletizer plant (PP), are used to produce Direct Reduced Iron (DRI). In this case, CO and H_2 are the reducing agents (R. R. Wang et al. 2021). The second is reduction in a Blast Furnace. Here, pellets or sintering of iron ore are reduced using coke and limestone as reducing agents.

The conversion into crude steel can also be achieved In two different ways. The first one requires a Basic Oxygen Furnace. This process is usually directly following the blast furnace reduction and together they form a so-called integrated cycle. In addition to the charge material from the Blast furnace, Direct Reduced Iron obtained through Direct Reduction can also be added into the Basic Oxygen Furnace to produce the crude steel. Direct Reduced Iron can however also be used in the second method for crude steel production, the Electric Arc Furnace. The particularity of this process is that it is also used to recycle scrap metal. This process uses electricity. Assuming the electricity used originates from a renewable source, this process greatly reduces greenhouse gas emissions compared to a Basic Oxygen Furnace (Mapelli et al. 2022). However, natural gas and carbon are usually also used in the process to speed up the process and lower the electricity consumption.

In the following paragraphs, I will explain in which processes, green hydrogen can be involved. The first is using directly green hydrogen instead of hydrogen from natural gas in the Direct Reduction process. The second is the role of green hydrogen as mean to store and produce electricity when needed, electricity which demand increases when an Electric Arc Furnace is used.

Direct Reduction of iron ore

The process of transforming iron ore into iron is called reduction. So far, the most popular method for reducing iron ore has been through the use of a blast furnace to melt the iron (Battle et al. 2014). During Direct Reduction (DR), the iron ore is transformed into quality metallic iron while remaining in the solid state (Battle et al. 2014). In this case, reducing agent are used. The reductants are hydrogen and certain forms of carbon (R. R. Wang et al. 2021). Currently, most direct reduction plants use natural gas to derive the two reducing agents. While this method avoids the use of coke and does not require high energy from fossil fuels to heat up the blast furnace, it still uses natural gas which is a mixture of hydrocarbons. But it is also possible to directly use hydrogen as reductant. It has been described how green hydrogen can be produced using renewable energies and without releasing greenhouse gases in the process. This therefore represents a good alternative, providing that green hydrogen is available at competitive costs.

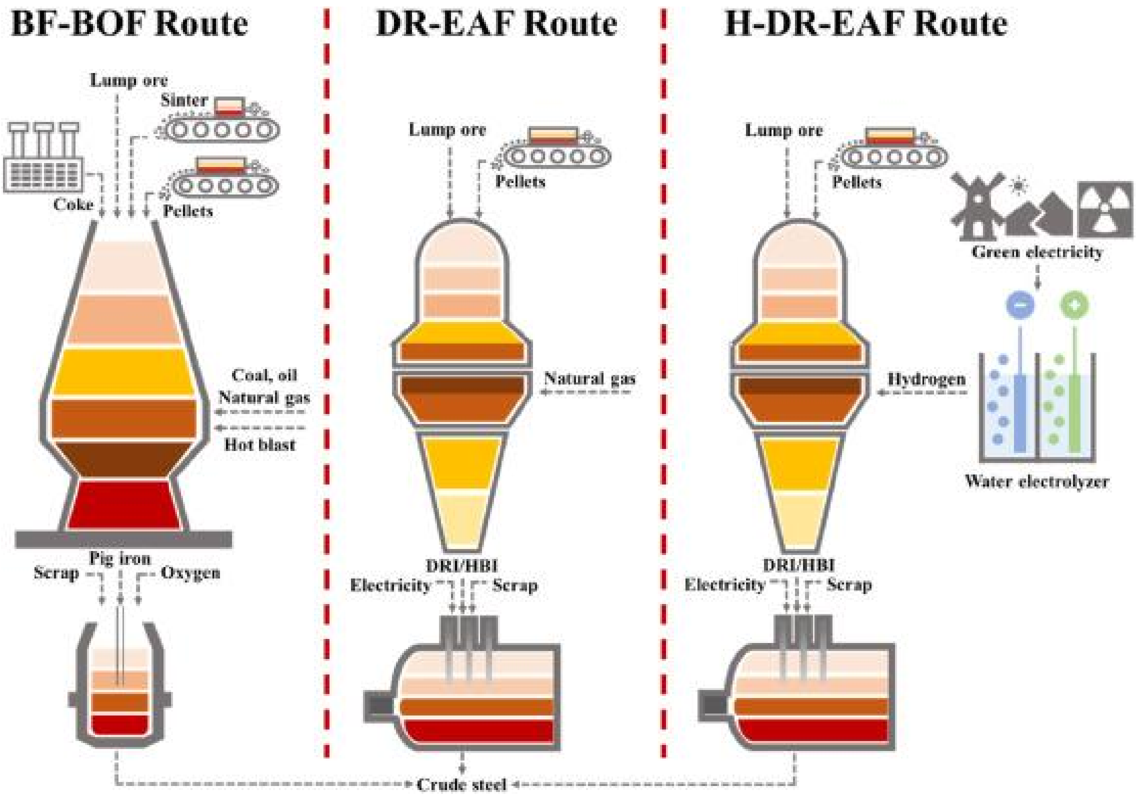

Figure 25 Methods for steelmaking from iron ore. Blast furnace, direct reduction with natural gas and direct reduction with hydrogen. Retrieved from (R. R. Wang et al. 2021)

It is important to mention that since the reactions take place at much lower temperatures in this process, impurities are more likely to end up in the direct reduced iron product compared to a blast furnace process (Battle et al. 2014). Furthermore, direct reduction only works when using iron pellets and not with iron sinters which can be used in a blast furnace. While it is possible to reduce iron ore with only H_2, this also reduces the efficiency of the whole process and affects the quality of the metallic iron (Mapelli et al. 2022). Moreover, the environmental impact of the pelletizer plant producing the iron ore pellets is also to be considered. Overall, direct reduction of iron ore is a competitive alternative to the blast furnace method. However, to fully decarbonize the process, green hydrogen needs to be easily available and at a competitive price since not using carbonates reduces the overall efficiency.

As a power source

Hydrogen as a power source and its efficiency compared to other power sources has been covered in the previous chapter. To sum up, it is possible to used stored hydrogen to produce electricity using fuel cells. This method is however much less efficient than directly using the electricity. But the main reason why there is an incentive to still consider hydrogen as a power source for the steelmaking industry is its storage capacity. Indeed, green hydrogen is already required in the DR process. Therefore, the supply and storage is already existing and it would make sense to also use the hydrogen as a clean power source. Big steelmaking industries cannot only rely on the power grid for their electricity supply. Furthermore, the electric arc furnaces in development for the transformation of iron into steel require important amounts of electricity. It is therefore essential for a steelmaking plant to dispose of their own power source. However, the decarbonization of the industry means that conventional power sources using fossil fuels are to be avoided. Green hydrogen could therefore represent a clean, reliable and resilient power source for the industry. In times where electricity from the grid is expensive, the stored hydrogen could be used to produce electricity using fuel cells in addition to its use for the direct reduction of iron ore. In times where the electricity from the grid is cheaper, the excess hydrogen can be stored to minimize the exposition to price fluctuations of electricity. Green hydrogen should therefore not be seen as a primary power source but rather as a technology allowing for more resilience while avoiding greenhouse gas emissions.

3. Review of the current state of European policies and strategies on (Green) Hydrogen

The objective of this chapter is to propose a clear and understandable overview on the several policies, legislations and regulations which have been published and agreed on over the past 20 years in Europe. Indeed, hydrogen and green hydrogen have been the topic of many discussions in the European institutions and among member states. Sometimes, it can be heard that this technology will play a central role in the energy transition or in the decarbonization of certain industries. Some other times, the opposite is being defended stating that the contribution of green hydrogen is vaguely overestimated (Steen 2016). This chapter therefore is therefore a key to this master thesis as it drafts a clear picture on what role (green) hydrogen is planned to take by policy and law makers in Europe.

I will begin by shortly recapping the main elements of the history of the key milestones when it comes to hydrogen in political debates and legislations. The purpose of this is to be able to situate temporally the evolution of hydrogen as a relevant topic in policy making and to observe which were the points of focus. Then, I will discuss in depth the ten main policy statements, legislations or regulations published by European institutions and which are building the core of the political agenda on (green) hydrogen in Europe. During this, I will point out the principal elements that can be found in those texts to oversee as clearly as possible what are their main targets and objectives. The texts in question are, amongst other, the European Hydrogen Strategy published in 2020, the European Union's Renewable Energy Directive which sets the energy targets for 2030 and in which hydrogen also plays a role, and other statements from European institutions such as the European Investment Bank. Finally, I will present the main take-aways from this review in order to forecast the European ambitions on green hydrogen and undertake the core of this master's thesis which is the comparison and gap analysis with the current state of technology and applications. It is important to mention, that as is was presented in the overall presentation of hydrogen, I will focus mostly on green hydrogen, the means of production and its uses for the steelmaking industry.

3.1.History

In the "European Green Deal", the European has made public its admissions to be the very first continent to be climate neutral by 2050 ("A European Green Deal" 2021). This implies, stepping away from fossil fuels and developing massively renewable energies and adjacent technologies. Green hydrogen, meaning hydrogen produced using renewable energies, is one of those technologies and has since then been in the center of attention and of hopes in order to achieve the 2050 target. However, green hydrogen and hydrogen in general has already been acknowledge as a useful resource in policies and official statements long before the European Green Deal. Already back in the beginning of the millennium, discussions on hydrogen were taking place:

"*The most important regional policy initiative is that of the European Union (EU) and European Commission (EC). A major report and action plan were issued by the EU/EC in 2003 that outline the hydrogen vision. The report is a significant indication of the EC's commitment to a long-term conversion to a hydrogen economy—the first major political* *body to do so beyond Iceland and Japan. A High-Level Group (HLG) was put together to examine the potential contribution that hydrogen and fuel cells can play in the long run to achieving viable, sustainable energy systems for Western Europe. The HLG was created in 2002 by the Vice President of the EC responsible for energy and transport, and the Research Commissioner. It consists of representatives from some of Europe's leading energy, automobile, and research institutions, i.e., "stakeholders." The report suggests that traditional fossil fuels and nuclear power can be used to produce hydrogen energy, along with renewable energy sources, though with carbon sequestration in the case of the former feedstocks."* (Solomon and Banerjee 2006).

As we can read, already back in June 2003, the European Commission was having a close look at hydrogen as a new important technology for the future of our energy systems. Hydrogen was already described in the EC Report 2003 (EC (European Commission), 2003) as a strategically important choice for the next 20-30 years. This report was the result of a conference which took place in Brussels on the 16th and 17th of June 2003 and had as objective to put hydrogen at the top of the EU agenda. While it also acknowledges the fact that at this time, the technology was still under development and quite expensive, it also states that development and further investments in the field are essential. The High-Level Group (HLG) mentioned above prepared a report specifically for the conference of Brussels.

The final report of the Brussels conference (EC (European Commission), 2003) also mentions the creation of a "European Hydrogen and Fuel Cell Technology Partnership" which as I will describe later was indeed formed and operated. Furthermore, it is important to notice that while the report mentions renewable energies to produce hydrogen, it is presented as an auxiliary source of energy for production behind fossil fuels and nuclear energy. Green hydrogen as we understand it today wasn't therefore as important back then. Barry Solomon points out this issue clearly by mentioning that "*The draft EC report suggested that fuel cells are intrinsically cleaner and more efficient that conventional energy converters. The main problem with this is the focus on the cleanliness of the energy carrier instead of the cleanliness of the fuel used to make that carrier.*" (Solomon and Banerjee 2006).

As mentioned above, the Brussels conference organized by the European Commission in 2003 on hydrogen and fuel cell technology also set the way for the creation of the Hydrogen and Fuel Cell Technology platform (HFP) the role of which would be to allow different stakeholders from the hydrogen and fuel cell industry and supply chain to meet and exchange on the most up to date developments. The HFP would later, in 2007/2008, evolve in the European Commission's Fuel Cells and Hydrogen Joint Undertaking (FCH JU), (Clean Hydrogen Partnership 2023). The aim of this partnership was to mobilize and activate all available resources and knowledge in order to simulate the development of hydrogen and fuel cells technologies. The ultimate objective was to make fuel cell and hydrogen technologies commercially viable since the costs for development were high and not profitable yet. Members of it were universities, private and public companies, institutes, non-profit organizations, and of course international organizations and the EC. The FCH JU would make financial resources available and lead the way for cooperation in this field. As described by Bert De Colvenaer and Claire Castel,

"*It is felt that market forces alone will not deliver the required technological breakthroughs, due mainly to the high risks and high levels of investment that are necessary, without sufficient profitability in the short term. A partnership between the public and private sectors is therefore the only realistic route to take, in order to achieve the objective of commercial hydrogen/fuel cell application in the next decade.*"(De Colvenaer and Castel 2012).

The commercial application and profitability Is an essential element and Important factor when it comes to renewable energy technologies. Seeing that this aspect is being taking into account by the European instances reflects positively on their initiatives when it comes to the development of the hydrogen industry. I will later review more in depth which type of projects and which sectors of development the FCH JU has been focusing on.

The European Green Deal was a key milestone when it comes to Europe's environmental commitment and ambitions. The European Union members and the European Union itself had by 2019 already adopted several policies and regulations to reduce greenhouse gas emissions, and other kinds of environmental impacts. Furthermore, they had also taken part in important international treaties and commitments such as the Paris Agreements

(United Nations 2015). However, those were mostly targeted initiatives which firstly did not convince in achieving the said targets, and secondly also omitted some very relevant sectors. Therefore, a broader and more collective approach and agreement was necessary for all EU members. This unprecedented initiative lead to the European Green New Deal which's main objective is to achieve climate neutrality for Europe by 2050 (Claeys 2019).

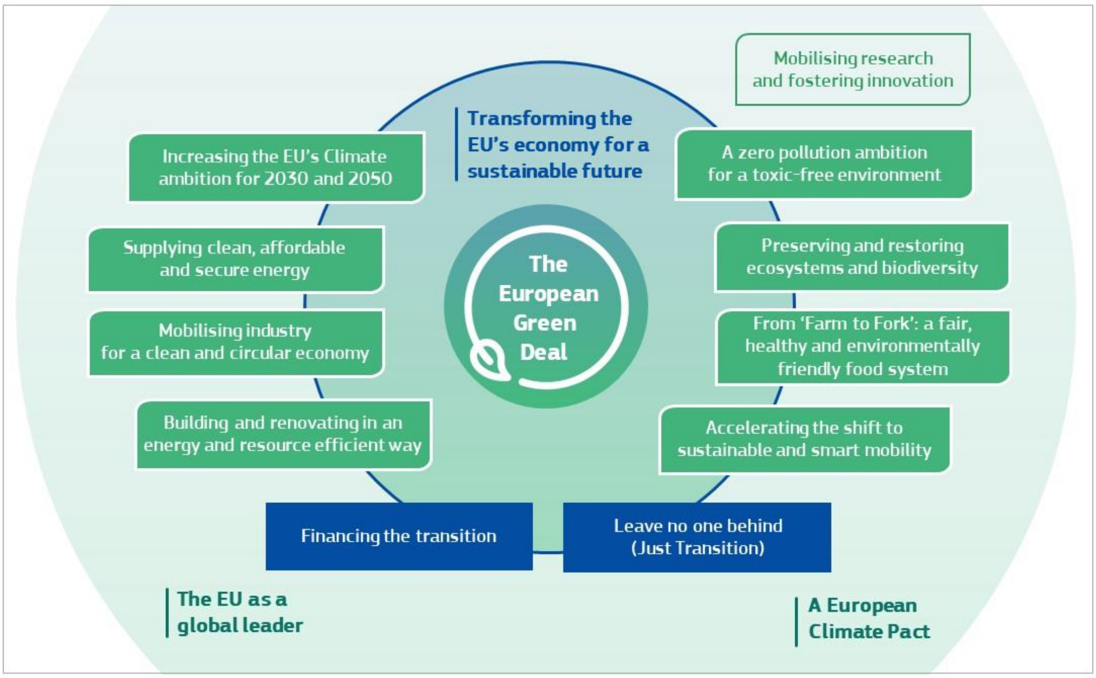

Figure 26 The European Green Deal (European Comission 2019)

Amongst the introduction of a carbon tax or a European Union emission trading system, it also addresses the issue of a clean affordable and secure energy. In this context, "*This framework should foster the deployment of innovative technologies and infrastructure, such as smart grids, hydrogen networks or carbon capture, storage and Decarbonization, energy storage, also enabling sector integration. Some existing infrastructure and assets will require upgrading to remain fit for purpose and climate resilient.*" (European Comission 2019). Further down can be read that "*EU industry needs 'climate and resource frontrunners' to develop the first commercial applications of breakthrough technologies in key industrial sectors by 2030. Priority areas include clean hydrogen, fuel cells and other alternative fuels, energy storage, and carbon capture, storage and decarbonization.*" (European Comission 2019). In the next chapter I shall review more in detail what exactly the extent of the European Green Deal is. At this point, it is however important to mention that the agreement only drafter the policies which member states should follow and did not explore more in depth which concrete commitments should be taken specifically in the case of green hydrogen. Nevertheless, the European Green Deal still marks an important milestone and opened the way to more concrete initiatives on hydrogen.

Following the European Green Deal and in a context of rapid growth in the renewable energy sector, it became clear that a more detailed strategy on hydrogen and its related technologies was necessary. Furthermore, the recent efforts on the development of the hydrogen industry, the declining costs of the production and the related growing interest of investors meant that it became even more important to channel this development. Article 3.1. of the EU hydrogen strategy 2020 mentions that

"*The European Green Deal, which aims to achieve climate neutrality in Europe by 2050, needs tangible policies to become reality. The European Union is also currently facing a dual health and economic emergency triggered by the COVID-19 pandemic. The European Union and the Member States must therefore coordinate their responses to these crises, so that economic recovery can be a springboard for a clean and resilient future. For that future to become reality, the EU's economic sovereignty must be bolstered, partly by developing renewable energy and the relevant storage capacity."* (European Commission 2020).

Taking all of the above into account, the EU Hydrogen strategy 2020 was drafted to frame the developments in the field while focusing on three main pillars: Production, distribution and storage, and end-use (European Commission 2020). The EU hydrogen strategy 2020 was a very important step for the development and future role of hydrogen in Europe. It also confirms that the European Union members are now placing high expectations on the hydrogen industry, and it is one of the priority sectors of focus to achieve the 2050 climate neutrality objective set in the European Green Deal.

The most recent publication giving out indications about the EU's ambitions on hydrogen was a press release by the European Commission on the rules for renewable hydrogen. The aims of the rules are to define renewable hydrogen and are part of a broader regulatory framework on hydrogen concerning also infrastructure, transport, and a set of targets. Most importantly, the first act in the press release clarifies that hydrogen produced by electrolysis has to be produced using renewable energies to be considered a Renewable Fuel of Non-Biological Origin (RFNBO). This is hugely important as it clearly sets apart green hydrogen from hydrogen produced from other energy sources or retrieved from other sources than renewable energies. Furthermore, it also considers the pressures which building new hydrogen electroliers could have on the renewable energy power grits. As it can be read in the press release,

"*The Act clarifies the principle of "additionality" for hydrogen set out in the EU's Renewable Energy Directive. Electrolysers to produce hydrogen will have to be connected to new renewable electricity production. This principle aims to ensure that the generation of renewable hydrogen comes with an increase in the volume of renewable energy available to the grid compared to what exists already. In this way, hydrogen production will be supporting decarbonization and complementing electrification efforts, while avoiding pressure on power generation*." (European Commission 2023).

Here we can observe some concrete and reflected measures taking using a systemic approach. The press release also mentions some concrete targets in terms of RFNBO which are set to account for 14% of the total EU Electricity consumption by 2030 (European Commission 2023).

To summarize, hydrogen has been part of the discussions on the EU policy making level for over 20 years now. However, it merely started as a side topic to the broader energy question and what would the future of the energy sector look like. In 2003, during a conference in Brussels, the vision of the role of hydrogen for the future of the European Union was expressed. This marked for the first time the concept of hydrogen as a key technology for the future of the EU energy sector. A symbol was the creation of the Hydrogen and Fuel Cell Technology platform (HFP). The HFP would later evolve into the European Commission's Fuel Cells and Hydrogen Joint Undertaking (FCH JU) making even more resources available to that field and committing the EU countries to developing their hydrogen industries. While the European Green Deal remained rather shallow on the topic of hydrogen, its content and the extant of the commitments expressed in it such as the climate neutrality by 2050 raised the topic of hydrogen to another level. Thanks to the prior efforts and research made in that field, hydrogen quickly became a domain of focus and high hopes were placed in the technology. Following the European Green Deal, the EU Hydrogen Strategy transformed the vision expressed during the 2003 Brussels conference into concrete actions. Key areas of development were defined, objectives were defined, and tools and resources were made available to the stakeholders. Finally, the recent publications and press releases of the European Commission are going much more in depth regarding the feasibility of such ambitions and foresee the necessary regulations to make those changes possible.

3.2.Main texts

The European Green Deal

The European Green Deal drafts the pathway of the European Union member states shall take to achieve a sustainable economy by 2050. Released in 2019, it englobes a variety of sectors and key industries to a green growth such as the energy, transport or steel industries. Central goals of the European Green Deal is the achievement of a carbon free economy and the decoupling of economic growth from resource use. A hydrogen network is mentioned in the European green deal as a key infrastructure to be developed. Furthermore, clean hydrogen to which belongs green hydrogen is a priority technology area to be developed according to the European green deal. It is cited as a fuel but also energy storage technology and its role in fuel cells. More importantly, it is specifically mentioned as a technology for the decarbonization of the steelmaking sector. Overall, while the European Green Deal remains rather vague regarding which specific green hydrogen technologies should play a role in the decarbonization of the European economy. However, particular attention is given to its uses in the steelmaking industry.

European Hydrogen Strategy

Adopted in July 2020, the European Hydrogen Strategy is a road map for the development of hydrogen related technologies in Europe. This strategy is part of the broader decarbonization plan set in the European Green Deal. Twenty key actions of the European Hydrogen Strategy have been defined. Those key action are for instance the increase of investments, create incentives to boost the hydrogen demand in a variety of sectors, the development of all transboundary infrastructures as well as the international cooperation on hydrogen. The fact that a whole strategy has been developed and is being implemented on hydrogen shows how committed the European community is to this technology.

Furthermore, green hydrogen is central to this strategy as it will help achieve the decarbonization targets of the EU. Furthermore, concrete actions in the form of legislative proposals have already been taken. Those actions include for instead measures to increase the share of green hydrogen and low carbon gases and decrease the share of fossil natural gas. This extent of engagement in hydrogen is unprecedented and clearly shows how serious and ambitious the expectations on (green) hydrogen technologies are. The main question remaining is whereas technological improvement will yes, or no be enough to meet those expectations?

3.3.Where do we stand

To summarize, hydrogen has been a topic of discussions for many years in Europe. However, it was at first only mentioned during broader discussions on energy related issues. Research programs were launched but those were clearly not a priority on the agenda. Furthermore, it is important to notice that while using renewable energies to produce hydrogen was mentioned even back in the early 2000's, it was presented as an auxiliary energy source for its production behind fossil fuels and nuclear energy. However, the recent commitments from the European Member countries on climate related targets greatly enhanced the discussions on the role that hydrogen could play in Europe's future economy. The European Green Deal was an important milestone in that aspect as it set a fix target for decarbonization of the European economy. While until then, research on hydrogen was not a priority, it still was enough to later identify the key technologies to achieve the objectives set in the European Green Deal. So much, that hydrogen and green hydrogen even became an integral part of the European energy transition with the European Hydrogen Strategy. There, hydrogen is clearly defined as a key technology which is essential to the decarbonization of certain industries. The steelmaking industry is one of them. However, while hydrogen related technologies for some have been known for many years such as alkaline water electrolysis, other have only been under development for a few years, especially when it comes to the storage and use of the hydrogen. Furthermore, the European ambitions for hydrogen are system wide meaning the changes in terms of technology, infrastructure and consumption are huge making a full transition very long and difficult.

4. Green Hydrogen value chain from production to end-use – Main challenges

To sum up the previous chapters, the whole hydrogen value chain, from the origin of the power source used to produce it, to the different end-uses which can be made of it, is a very complex and not yet fully operational system. Further developments and research are still needed in certain key areas in order to make green hydrogen a commercially viable technology. Nevertheless, considerable progress has been made in certain fields has been achieved. Important infrastructure and flagship projects are under way and investments are exploding. Policy making has also witnessed a rapid growth in the sector, pushed by the decarbonization and clean energy ambitions from the European Union. We can already imagine what a green hydrogen and renewable energies-based economy could potentially look like. In the next two chapters, I will attempt to present one possible value chain of hydrogen, with offshore wind energy as a power source and the steelmaking industry as the end-user. The, I shall point out the main challenges and limitations of such a configuration to make recommendations for future policies.

4.1. The green hydrogen value chain from production with offshore wind energy to end use in the steelmaking industry

In the next paragraphs I will present how the value chain of green hydrogen produced using offshore wind energy for the steelmaking industry could potentially look like. I will first select the best suited configuration for offshore hydrogen production. This could be either offshore centralized production, individual offshore production, or onshore production. Then, depending on which configuration is preferred, I will determine what electrolysis technology is to be used. This could be either alkaline water electrolysis system, Proton Exchange Membrane electrolysis system, or solid oxide electrolysis system. Then I shall discuss how the hydrogen is to be stored, therefore either in pressurized tanks or as liquefied hydrogen. Then the mean of transportation of the green hydrogen to the end-user will be decided. Finally, the uses of green hydrogen in the steelmaking industry will be once again presented.

Configuration for offshore hydrogen production

All three different configurations, offshore centralized production, individual offshore production or onshore production are worth to be considered and the final decision really depends on external factors. However, while onshore hydrogen production offers more flexibility, it would be missing out on the opportunity to cut on the losses due to the transport of electricity using underwater cables. Therefore, offshore production is to be used. Furthermore, considering the high future demand for green hydrogen and the important developments of floating platforms for wind turbines, it is very likely that the offshore wind turbine parks will grow in size and distance from the shore. Therefore, individual offshore production is to be preferred for those large-scale wind parks and to further minimize the energy losses.

Electrolysis technology

When it comes to the electrolysis system, at the moment only alkaline water electrolysis and PEM electrolysis are valuable options on the short term. Alkaline water electrolysis could have been a good choice in the case of onshore hydrogen production since it is an already well-established technology. However, for individual offshore production, PEM electrolysis is better suited, mostly due to its more compact design and easy maintenance.

Storage and transport

To capitalized on the advantage of offshore hydrogen production, transport to shore is most likely to take place via underwater hydrogen pipelines. This also reduces the number of transfers from one hydrogen container to another which is often the source of losses. However, regarding the onshore transport to the end-user, other factors have to be considered. Ideally, this would take place using long range hydrogen pipeline which would deliver the hydrogen ready to be used to the end-user. However, such infrastructure is costly and likely to take several years if not decencies to be fully operational. In the meantime, transport by road and rail which would use the existing infrastructures are a good transition solution. Transport in pressurized tanks is better in this case since liquified hydrogen storage is more likely to be used for fuel tanks for the means of transport themselves.

Final uses in the steelmaking industry

The main argument for using green hydrogen in the steelmaking industry is to decarbonize some of the production processes. While a full decarbonization without carbon capture is quite unlikely du to nature of the activity itself, green hydrogen could have an important impact on the Direct Reduction of iron ore. Furthermore, hydrogen's propriety as a energy storing technology can also be quite useful. Hydrogen could be used in a way to provide "green "electricity in situations of peak demand and bring more flexibility while reducing dependence on the power grid. This is even more important since electric arc furnaces, which are gaining in interest due to their relatively low carbon emissions, require however huge amounts of electricity.

Overview on the value chain

The complete potential value chain of green hydrogen, from the production using offshore wind energy to the end-use in the steelmaking industry can be presented as in the figure below. First, the hydrogen would be produced on offshore wind parks using an individual offshore production configuration. PEM electrolysis systems would be used in this case due to their compact design. The hydrogen would then be transported to shore by underwater pipelines. Then, in the long term, it would directly be provided to the end users using a wide hydrogen pipeline network. In the short term, trucks and railways can be used for the transition. Finally, it can be used for the direct reduction of the iron ore in the steelmaking process as well as a mean to store "green" energy for the energy intensive industry.

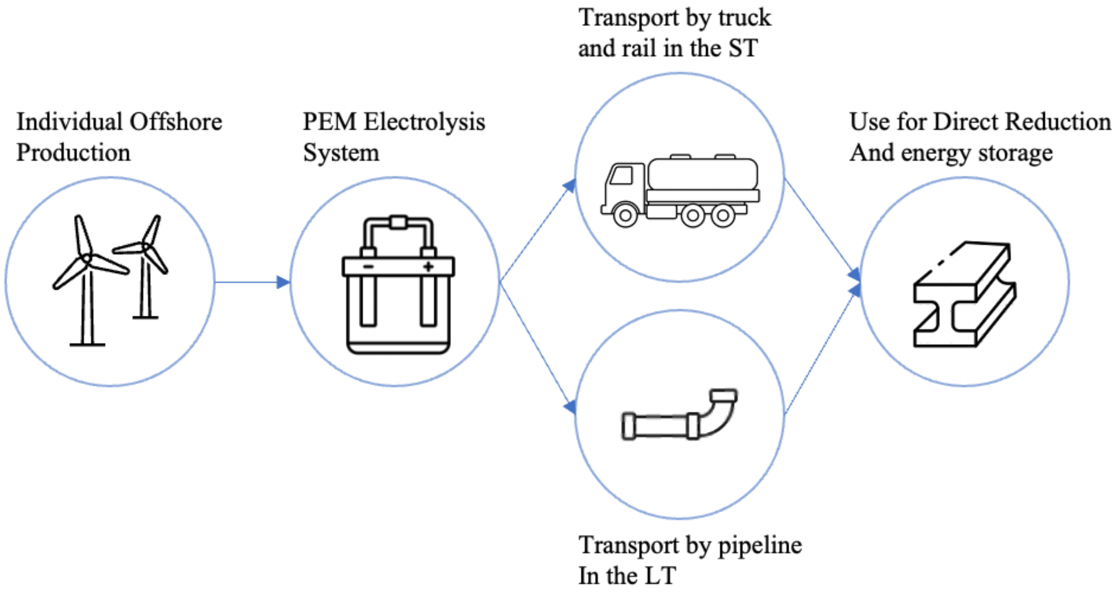

Figure 27 Overview on the green hydrogen value chain produced with offshore wind energy for the steelmaking industry

4.2.Determining the main challenges and points of focus for policy makers

Current policies and strategies place high hopes in hydrogen related technologies. With the decarbonization commitments the EU member states made, unprecedented attention is placed on green hydrogen. However, the relevant technologies are for some still in development or haven't been in use on a larger scale. Furthermore, the decarbonization ambitions require a system wide approach from the production of the hydrogen using renewable energies to its use in a variety of sectors and industries. In the previous chapter, a possible value chain of green hydrogen produced using offshore wind energy for the steelmaking industry has been presented. Each step in the value chain comes with its own challenges and limitations. Furthermore, this approach allows to observe issues only related to a certain configuration of the value chain.

It has been discussed that an offshore hydrogen production where electrolysis using PEM on each wind turbine was the most efficient in terms of losses limitation. In this case, floating wind turbines could also be used to produce hydrogen further off the coast accessing better and more reliable winds. However, constructing offshore wind parks further off the coast make both the construction and operation of the wind turbines more difficult and costly. Therefore, before considering the construction of wind parks far away from the coast, it is essential that hydrogen-producing wind parks close to the shore have been well developed and operated for a certain period of time to imitate reliability issues which could be devastating if occurring far off the coast.

Offshore wind parks also come with their own environmental and social issues. First of all, assuming that constructing a wind turbine on seas has no impact on the ecosystem is simply wrong. Furthermore, its decommissioning, can be very costly if any long-term effect on the environments is to be eliminated. This is especially the case for grounded structure systems. Finally, local inhabitants and stakeholders can be affected by such wide wind parks, especially for fishing activities. It is therefore highly recommended to consult those local stakeholders to understand how they could be affected, but also because they can provide insightful information about the area.

The transport of hydrogen by pipeline is the most efficient and safe method to be used. However, such a complex network is very costly and will take many years to be fully operational. Therefore, transport by road and rail will have to play a role on the short term. However, this brings up additional challenges. First of all, the transfer of hydrogen from one container to another is always the source of losses. Smart design and minimization of transfers are to be prioritized until then. Transport by road is also debatable as hydrogen is a very flammable gas which can be a risk for road transport. It is therefore necessary that the EU member state discuss those issues and attempt to homogenize road transport regulations. Transport by rail is to be preferred.

The direct reduction of iron ore is often mentioned as a method which can decarbonize part of the steelmaking process when only green hydrogen is used. The reality is that today, direct reduction with only hydrogen reduces the quality of the iron produced and makes the process less efficient. It is therefore important not to see in hydrogen this unique solution to decarbonize the steelmaking industry but also to consider other technologies such as carbon capture technologies since carbon compounds will most likely still have to be used in the production process for a while.

The table below gives an overview of the above-described challenges and also mentions some additional challenges.

Table 5 Main challenges and recommendations for green hydrogen production for the steelmaking industry for the steelmaking industry

Challenge	**Recommendation**
Floating offshore wind turbines still under development but necessary for enabling hydrogen production on deeper seas further away of the coast.	It is essential to wait for offshore hydrogen production near the coast to be fully developed before considering production further away from the coast as it makes the construction and operation more difficult.
Constructing offshore wind turbines is more complex than onshore.	Until economies of scale reduce the production costs, financial aid and subsidies should be made available.
Offshore wind parks have their own specific social and environmental impacts and decommissioning is more difficult.	Stakeholders near the wind parks should be included during the planification of the projects as they can provide new insights and their interest can be taken into account.
Alkaline Water Electrolysis operates with relatively low energy efficiency and PEM	Whereas Alkaline Water Electrolysis or PEM Electrolysis should be used is to be decided depending on the configuration

Electrolysis, which is more efficient, requires costly materials.	of hydrogen production. Alkaline Water Electrolysis can be better for onshore production of hydrogen whereas PEM Electrolysis for offshore hydrogen production. R&D is already aiming at making PEM Electrolysis with cheaper materials.
Operation and maintenance of offshore wind turbines is more complex and costly than onshore.	O&M should be accounted for during feasibility studies. Existing monitoring technologies for onshore wind parks such as drones can be adapted for offshore parks.
Losses during the transfer of hydrogen from one container to another are often omitted. But depending on the configuration of the value chain they can accumulate and have a significant impact.	Prioritize transport by pipeline. Until the infrastructure and pipeline network is in place, smart design and supply chain should be used and take into account losses during hydrogen transfer.
Transport by road brings up additional risks and reglementary issues as hydrogen is a very flammable gas.	Consultations and discussions should take place between EU member states to homogenize road transport regulations. If road transport is judged too risky or complicated, transport by rail should be focused on until a pipeline network is operational.
Long distance transport is difficult for train and road transport.	Long distance transport by ship is essential to develop hydrogen production overseas.
Direct Reduction of iron ore with only hydrogen reduces the quality of the iron produced and makes the process less efficient.	Hydrogen should not be considered as the unique solution for decarbonizing the steelmaking industry. Other technologies should be considered as well complementary to hydrogen.

Electric Arc Furnaces represent a promising alternative to Basic Oxygen Furnaces. However, they also require important amounts of electricity.	Renewable energy supply should account for the increased electricity demand. Green hydrogen can be used to store excess energy production during low demand phases.

5. Conclusion

To conclude, producing green hydrogen is an important technology to be developed for the decarbonization of the steelmaking industry. Furthermore, producing green hydrogen with offshore wind energy is very promising and offers advantages which cannot be matched by onshore renewable energy sources. A possible value chain configuration has been developed and discussed. Individual offshore hydrogen production is to be preferred as it minimizes the losses during electricity transport in underwater cables. PEM electrolysis is better suited for this kind of configuration as it is more compact and requires less maintenance. While transport by pipeline is the most efficient method, transport by road and rail will play an important role in the short term. Green hydrogen can be used during the direct reduction of iron ore, but also can serve for storing energy during low electricity demand and later be used to produce electricity during peak demand phases. Current policies and strategies place high hopes and expectations on hydrogen related technologies. Hydrogen has been part of energy related discussions since the beginning the 2000's in Europe but has really gained on attention only recently with the major European commitments on decarbonization and energy transition. The value chain approached helped to identify a series of challenges and limitations for which recommendations have been made. Some of the challenges include the environmental and social impacts of offshore wind parks, the difficulties imposed by building wind parks further off the coast, the risks and efficiency losses of transporting hydrogen by road and train and the limitations of the decarbonization potential of green hydrogen for the steelmaking process.

References

"A European Green Deal." 2021. July 14, 2021. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

Airbus. 2021. "How to Store Liquid Hydrogen for Zero-Emission Flight." December 9, 2021. https://www.airbus.com/en/newsroom/news/2021-12-how-to-store-liquid-hydrogen-for-zero-emission-flight.

"All-Electric Vehicles." n.d. Accessed May 22, 2023. http://www.fueleconomy.gov/feg/evtech.shtml.

"Ammonia Storage Tanks - Sagebrush." 2020. April 5, 2020. https://sagebrushpl.com/ammonia-storage-tanks/.

Ball, Michael, and Martin Wietschel. 2009. "The Future of Hydrogen – Opportunities and Challenges." *International Journal of Hydrogen Energy* 34, no. 2 (January): 615–27. https://doi.org/10.1016/j.ijhydene.2008.11.014.

Battle, Thomas, Urvashi Srivastava, John Kopfle, Robert Hunter, and James McClelland. 2014. "Chapter 1.2 - The Direct Reduction of Iron." In *Treatise on Process Metallurgy*, edited by Seshadri Seetharaman, 89–176. Boston: Elsevier. https://doi.org/10.1016/B978-0-08-096988-6.00016-X.

Boudellal, Méziane. 2018. *Power-to-Gas*. Renewable Hydrogen Economy for the Energy Transition. De Gruyter. https://doi.org/10.1515/9783110559811.

Calado, Gonçalo, and Rui Castro. 2021. "Hydrogen Production from Offshore Wind Parks: Current Situation and Future Perspectives." *Applied Sciences* 11, no. 12. https://doi.org/10.3390/app11125561.

Capurso, T., M. Stefanizzi, M. Torresi, and S.M. Camporeale. 2022. "Perspective of the Role of Hydrogen in the 21st Century Energy Transition." *Energy Conversion and Management* 251, no. January (January): 114898. https://doi.org/10.1016/j.enconman.2021.114898.

Claeys, Grégory. 2019. *How to Make the European Green Deal Work*. Bruegel. https://www.jstor.org/stable/resrep28626.

Clean Hydrogen Partnership. 2023. "Our Story." 2023. https://www.clean-hydrogen.europa.eu/about-us/our-story_en.

CORPORATIVA, IBERDROLA. n.d. "How Are Offshore Wind Turbines Anchored at Sea?" Iberdrola. Accessed May 18, 2023. https://www.iberdrola.com/sustainability/offshore-wind-turbines-foundations.

Dawood, Furat, Martin Anda, and G.M. Shafiullah. 2020. "Hydrogen Production for Energy: An Overview." *International Journal of Hydrogen Energy* 45, no. 7 (February): 3847–69. https://doi.org/10.1016/j.ijhydene.2019.12.059.

De Colvenaer, Bert, and Claire Castel. 2012. "The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) in Europe." *International Journal of Low-Carbon Technologies* 7, no. 1 (March): 5–9. https://doi.org/10.1093/ijlct/ctr035.

Dincer, Ibrahim. 2012. "Green Methods for Hydrogen Production." *10th International Conference on Clean Energy 2010* 37, no. 2 (January): 1954–71. https://doi.org/10.1016/j.ijhydene.2011.03.173.

Dutta, Suman. 2014. "A Review on Production, Storage of Hydrogen and Its Utilization as an Energy Resource." *Journal of Industrial and Engineering Chemistry* 20, no. 4 (July): 1148–56. https://doi.org/10.1016/j.jiec.2013.07.037.

EC (European Commission),. 2003. "Hydrogen Energy and Fuel Cells: A Vision of Our Future (Summary Report)." Brussels.

Edwards, P.P., V.L. Kuznetsov, W.I.F. David, and N.P. Brandon. 2008. "Hydrogen and Fuel Cells: Towards a Sustainable Energy Future." *Foresight Sustainable Energy*

Management and the Built Environment Project 36, no. 12 (December): 4356–62. https://doi.org/10.1016/j.enpol.2008.09.036.

European Comission. 2019. "The European Green Deal." https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640.

European Commission. 2020. "Opinion of the European Economic and Social Committee on 'Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions — A Hydrogen Strategy for a Climate-Neutral Europe." https://op.europa.eu/en/search-results?p_p_id=eu_europa_publications_portlet_search_executor_SearchExecutorPortlet_INSTANCE_q8EzsBteHybf&p_p_lifecycle=1&p_p_state=normal&queryText=COM%2F2020%2F301&facet.collection=EULex%2CEUPub%2CEUDir%2CEUWebPage%2CEUSummariesOfLegislation&startRow=1&resultsPerPage=10&SEARCH_TYPE=SIMPLE.

European Commission. 2023. "Commission Sets out Rules for Renewable Hydrogen." In . Brussels. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_594.

"Fuel Cells." n.d. Energy.Gov. Accessed May 22, 2023. https://www.energy.gov/eere/fuelcells/fuel-cells.

Gerboni, R. 2016. "11 - Introduction to Hydrogen Transportation." In *Compendium of Hydrogen Energy*, edited by Ram B. Gupta, Angelo Basile, and T. Nejat Veziroğlu, 283–99. Woodhead Publishing. https://doi.org/10.1016/B978-1-78242-362-1.00011-0.

Gkanas, Evangelos I. 2018. "5 - Metal Hydrides: Modeling of Metal Hydrides to Be Operated in a Fuel Cell." In *Portable Hydrogen Energy Systems*, edited by Paloma Ferreira-Aparicio and Antonio M. Chaparro, 67–90. Academic Press. https://doi.org/10.1016/B978-0-12-813128-2.00005-X.

Gondal, I.A. 2016. "12 - Hydrogen Transportation by Pipelines." In *Compendium of Hydrogen Energy*, edited by Ram B. Gupta, Angelo Basile, and T. Nejat Veziroğlu, 301–22. Woodhead Publishing. https://doi.org/10.1016/B978-1-78242-362-1.00012-2.

Gualtieri, Alessandro F., Magdalena Lassinantti Gualtieri, Valentina Scognamiglio, and Dario Di Giuseppe. 2022. "Human Health Hazards Associated with Asbestos in Building Materials." In *Ecological and Health Effects of Building Materials*, edited by Junaid Ahmad Malik and Shriram Marathe, 297–325. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-76073-1_16.

Hassan, Qusay, Ammar M. Abdulateef, Saadoon Abdul Hafedh, Ahmed Al-samari, Jasim Abdulateef, Aws Zuhair Sameen, Hayder M. Salman, Ali Khudhair Al-Jiboory, Szymon Wieteska, and Marek Jaszczur. 2023. "Renewable Energy-to-Green Hydrogen: A Review of Main Resources Routes, Processes and Evaluation." *International Journal of Hydrogen Energy* 48, no. 46 (May): 17383–408. https://doi.org/10.1016/j.ijhydene.2023.01.175.

Hauer, Christoph. 2013. "A Novel Assessment of the Role of Danube Floodplains in Flood Hazard Reduction (FEM Method)." *Natural Hazards*, October (October).

Helmolt, Rittmar, and Ulrich Eberle. 2014. "Compressed and Liquid Hydrogen for Fuel Cell Vehicles." In , 245–53. https://doi.org/10.1007/978-1-4419-6996-5_185.

Holladay, J.D., J. Hu, D.L. King, and Y. Wang. 2009. "An Overview of Hydrogen Production Technologies." *Hydrogen Production - Selected Papers from the Hydrogen Production Symposium at the American Chemical Society 234th National Meeting & Exposition, August 19-23, 2007, Boston, MA, USA* 139, no. 4 (January): 244–60. https://doi.org/10.1016/j.cattod.2008.08.039.

https://newatlas.com/author/loz-blain. 2023. "World's New Largest Wind Turbine Sweeps 10 Football Fields per Spin." New Atlas. January 10, 2023. https://newatlas.com/energy/h260-18mw-biggest-wind-turbine/.

https://www.facebook.com/airbus. 2021. "Hydrogen Fuel Cells, Explained | Airbus." October 28, 2021. https://www.airbus.com/en/newsroom/news/2020-10-hydrogen-fuel-cells-explained.

"Hydrogen by Rail." n.d. Accessed May 18, 2023. https://www.dbcargo.com/rail-de-en/logistics-news/hydrogen-by-rail-8897790.

IEA. 2022a. "Renewables 2022." Paris. https://www.iea.org/reports/renewables-2022.

IEA. 2022b. "World Energy Outlook 2022." https://www.iea.org/reports/world-energy-outlook-2022.

IPCC. 2023. "Summary for Policymakers." https://www.ipcc.ch/report/ar6/syr/.

Jang, Dohyung, Kilwon Kim, Kyong-Hwan Kim, and Sanggyu Kang. 2022. "Techno-Economic Analysis and Monte Carlo Simulation for Green Hydrogen Production Using Offshore Wind Power Plant." *Energy Conversion and Management* 263, no. July (July): 115695. https://doi.org/10.1016/j.enconman.2022.115695.

Langmi, Henrietta W., Nicolaas Engelbrecht, Phillimon M. Modisha, and Dmitri Bessarabov. 2022. "Chapter 13 - Hydrogen Storage." In *Electrochemical Power Sources: Fundamentals, Systems, and Applications*, edited by Tom Smolinka and Jurgen Garche, 455–86. Elsevier. https://doi.org/10.1016/B978-0-12-819424-9.00006-9.

"Les parcs éoliens en mer ravivent la colère des pêcheurs." 2022. Les Echos. November 7, 2022. https://www.lesechos.fr/pme-regions/normandie/les-parcs-eoliens-en-mer-ravivent-la-colere-des-pecheurs-1876562.

Lewis, Michelle. 2022. "Check out This Offshore Wind Farm's Massive Gravity-Based Foundations." Electrek. November 7, 2022. https://electrek.co/2022/11/07/offshore-wind-farm-gravity-based-foundations/.

Lu, Qiang, Bo Zhang, Shichun Yang, and Zhaoxia Peng. 2022. "Life Cycle Assessment on Energy Efficiency of Hydrogen Fuel Cell Vehicle in China." *Energy* 257, no. October (October): 124731. https://doi.org/10.1016/j.energy.2022.124731.

Mapelli, Carlo, Gianluca Dall'Osto, Davide Mombelli, Silvia Barella, and Andrea Gruttadauria. 2022. "Future Scenarios for Reducing Emissions and Consumption in the Italian Steelmaking Industry." *Steel Research International* 93, no. 5 (May): 2100631. https://doi.org/10.1002/srin.202100631.

Mekhilef, S., R. Saidur, and A. Safari. 2012. "Comparative Study of Different Fuel Cell Technologies." *Renewable and Sustainable Energy Reviews* 16, no. 1 (January): 981–89. https://doi.org/10.1016/j.rser.2011.09.020.

Møller, Kasper T., Torben R. Jensen, Etsuo Akiba, and Hai-wen Li. 2017. "Hydrogen - A Sustainable Energy Carrier." *SI-HYDROGEN STORAGE MATERIALS* 27, no. 1 (February): 34–40. https://doi.org/10.1016/j.pnsc.2016.12.014.

Morthorst, P.E., and L. Kitzing. 2016. "Economics of Building and Operating Offshore Wind Farms." In *Offshore Wind Farms*, edited by Chong Ng and Li Ran, 9–27. Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100779-2.00002-7.

"Namibia." n.d. Green Hydrogen Organisation. Accessed May 18, 2023. https://gh2.org/countries/namibia.

"New Study Confirms €1 Trillion Africa's Extraordinary Green Hydrogen Potential." n.d. European Investment Bank. Accessed May 18, 2023. https://www.eib.org/en/press/all/2022-574-new-study-confirms-eur-1-trillion-africa-s-extraordinary-green-hydrogen-potential.

Nikitas, Georgios, Subhamoy Bhattacharya, and Nathan Vimalan. 2020. “16 - Wind Energy.” In *Future Energy (Third Edition)*, edited by Trevor M. Letcher, 331–55. Elsevier. https://doi.org/10.1016/B978-0-08-102886-5.00016-5.

Noussan, Michel, Pier P. Raimondi, Rossana Scita, and Manfred Hafner. 2021. “The Role of Green and Blue Hydrogen in the Energy Transition—A Technological and Geopolitical Perspective.” *Sustainability* 13, no. 1. https://doi.org/10.3390/su13010298.

“Offshore Wind Turbine Foundations: Leveling and Fixation with Hydraulic Cylinders.” 2022. *Enerpac Blog* (blog). February 7, 2022. https://blog.enerpac.com/offshore-wind-turbine-foundations-leveling-and-fixation-with-hydraulic-cylinders/.

Oliveira, Alexandra M, Rebecca R Beswick, and Yushan Yan. 2021. “A Green Hydrogen Economy for a Renewable Energy Society.” *Current Opinion in Chemical Engineering* 33, no. September (September): 100701. https://doi.org/10.1016/j.coche.2021.100701.

Pandiyan, Arunkumar, Aarthi Uthayakumar, Rengaraj Subrayan, Suk-Won Cha, and Suresh Babu Krishna Moorthy. 2019. “Review on Solid Oxide Electrolysis Cell: A Clean Energy Strategy for Hydrogen Generation.” *Nanomaterials and Energy* 8, no. January (January). https://doi.org/10.1680/jnaen.18.00009.

Pekic, Sanja. 2022. “Suiso Frontier Brings World’s 1st LH2 Shipment to Japan.” *Offshore Energy* (blog). February 25, 2022. https://www.offshore-energy.biz/suiso-frontier-brings-worlds-1st-lh2-shipment-to-japan/.

Shiva Kumar, S., and V. Himabindu. 2019. “Hydrogen Production by PEM Water Electrolysis – A Review.” *Materials Science for Energy Technologies* 2, no. 3 (December): 442–54. https://doi.org/10.1016/j.mset.2019.03.002.

Silveira, José. 2017. *Sustainable Hydrogen Prodution Processes*. https://doi.org/10.1007/978-3-319-41616-8.

Solomon, Barry, and Abhijit Banerjee. 2006. “A Global Survey of Hydrogen Energy Research, Development and Policy.” *Energy Policy* 34, no. February (February): 781–92. https://doi.org/10.1016/j.enpol.2004.08.007.

Stahlmann, Arne, and Torsten Schlurmann. 2012. “Investigations on Scour Development at Tripod Foundations for Offshore Wind Turbines: Modeling and Application.” *Coastal Engineering Proceedings* 1, no. December (December). https://doi.org/10.9753/icce.v33.sediment.90.

“Steel.” n.d. Accessed May 20, 2023. https://single-market-economy.ec.europa.eu/sectors/raw-materials/related-industries/metal-industries/steel_en.

Steen, M. 2016. “Building a Hydrogen Infrastructure in the EU.” In *Compendium of Hydrogen Energy*, edited by Michael Ball, Angelo Basile, and T. Nejat Veziroğlu, 267–92. Oxford: Woodhead Publishing. https://doi.org/10.1016/B978-1-78242-364-5.00012-9.

Taylor, Rebekka. 2019. *A Study on Offshore Wind Energy and Grid Integration*. *A Study on Offshore w*. Wien: Wien. https://doi.org/10.34726/hss.2019.66877.

Thomsen, Kurt E. 2014. “Chapter Eighteen - Environmental and Other Issues.” In *Offshore Wind (Second Edition)*, edited by Kurt E. Thomsen, 331–52. Boston: Academic Press. https://doi.org/10.1016/B978-0-12-410422-8.00018-2.

United Nations. 2015. “The Paris Agreement.” https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf.

University of Calgary. n.d. “Types of Hydrogen Fuel - Energy Education.” Accessed May 10, 2023. https://energyeducation.ca/encyclopedia/Types_of_hydrogen_fuel.

Vermeiren, Ph., W. Adriansens, J.P. Moreels, and R. Leysen. 1998. “Evaluation of the Zirfon® Separator for Use in Alkaline Water Electrolysis and Ni-H2 Batteries.” *International Journal of Hydrogen Energy* 23, no. 5 (May): 321–24. https://doi.org/10.1016/S0360-3199(97)00069-4.

Vidas, Leonardo, and Rui Castro. 2021. “Recent Developments on Hydrogen Production Technologies: State-of-the-Art Review with a Focus on Green-Electrolysis.” *Applied Sciences* 11, no. 23. https://doi.org/10.3390/app112311363.

Wang, R.R., Y.Q. Zhao, A. Babich, D. Senk, and X.Y. Fan. 2021. “Hydrogen Direct Reduction (H-DR) in Steel Industry—An Overview of Challenges and Opportunities.” *Journal of Cleaner Production* 329, no. December (December): 129797. https://doi.org/10.1016/j.jclepro.2021.129797.

Wang, Xuefei, Xiangwu Zeng, Jiale Li, Xu Yang, and Haijun Wang. 2018. “A Review on Recent Advancements of Substructures for Offshore Wind Turbines.” *Energy Conversion and Management* 158, no. February (February): 103–19. https://doi.org/10.1016/j.enconman.2017.12.061.

Wu, Xiaoni, Yu Hu, Ye Li, Jian Yang, Lei Duan, Tongguang Wang, Thomas Adcock, et al. 2019. “Foundations of Offshore Wind Turbines: A Review.” *Renewable and Sustainable Energy Reviews* 104, no. April (April): 379–93. https://doi.org/10.1016/j.rser.2019.01.012.

Xin, Q., and C.F. Pinzon. 2014. “9 - Improving the Environmental Performance of Heavy-Duty Vehicles and Engines: Key Issues and System Design Approaches.” In *Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance*, edited by Richard Folkson, 225–78. Woodhead Publishing. https://doi.org/10.1533/9780857097422.2.225.

Younas, Muhammad, Sumeer Shafique, Ainy Hafeez, Fahad Javed, and Fahad Rehman. 2022. “An Overview of Hydrogen Production: Current Status, Potential, and Challenges.” *Fuel* 316, no. May (May): 123317. https://doi.org/10.1016/j.fuel.2022.123317.

Yousefzadeh, Moslem, Manfred Lenzen, Elijah Keenan Tyedmers, and S.M. Hassan Ali. 2020. “An Integrated Combined Power and Cooling Strategy for Small Islands.” *Journal of Cleaner Production* 276, no. December (December): 122840. https://doi.org/10.1016/j.jclepro.2020.122840.

Zeng, Kai, and Dongke Zhang. 2010. “Recent Progress in Alkaline Water Electrolysis for Hydrogen Production and Applications.” *Progress in Energy and Combustion Science* 36, no. 3 (June): 307–26. https://doi.org/10.1016/j.pecs.2009.11.002.

ZHANG, Yang-huan, Zhi-chao JIA, Ze-ming YUAN, Tai YANG, Yan QI, and Dong-liang ZHAO. 2015. “Development and Application of Hydrogen Storage.” *Journal of Iron and Steel Research, International* 22, no. 9 (September): 757–70. https://doi.org/10.1016/S1006-706X(15)30069-8.

List of Tables

List of Figures