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EXECUTIVE SUMMARY

The main goal of Deliverable 4.2.1 is to conduct an exhaustive review and analysis of state-of-the-art green hydrogen technologies across the entire hydrogen value chain, identify promising solutions and trends using text mining and bibliographic analysis, and evaluate their potential applications for reducing carbon emissions in port systems, with a focus on the economic, social, and environmental benefits. This report is divided into two parts.

The 1st part of the report explains the utility of hydrogen (H_2) for the transition into a CO_2-free energy sector. It explores how H_2 stores energy and carries it in space and time, making it particularly suitable to couple with intermittent renewable energy sources. The report surveys the main technologies for producing green H_2, including electrolysis, thermo and photo water splitting, and H_2 production from biological sources. This is followed by a bibliometric analysis that examines the number of patents and scientific articles related to different H_2 production technologies over time. Unlike the preceding section, which focuses primarily on green H_2 technologies, this bibliometric analysis also encompasses other forms of H_2 production (not only green). The next section explores H_2 storage, beginning with an overview of various storage methods in tanks. It then discusses emerging options, such as depleted oil and gas fields, salt caverns, and aquifers, along with the challenges these options may pose. Finally, the section examines chemical storage alternatives, including methanol, ammonia, and organic carriers. A key aspect of H_2 use is its distribution, whether inland, fluvial/maritime, or through existing gas networks. A dedicated section covers these distribution methods, providing examples of practical implementation. The first part concludes with an overview of H_2 applications and end uses, particularly in transportation, where it can play a significant role in decarbonizing the sector.

The 2nd part of this report builds upon the findings of Deliverable D4.1.1, which focuses on **mapping initiatives for hydrogen growth in the Atlantic Area**. In the present report, a major component is dedicated to exploring potential sources and applications of green H_2 in ports, particularly in Europe and the Atlantic region. Sources and applications are analyzed by compiling and cross-referencing data from a comprehensive literature review, direct communications with initiative partners, and various reliable sources such as digital press, association websites, and project repositories. The majority of this detailed information, including the identification of key initiatives, their characteristics, and practical implementations, can be found in Chapter 6.

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ABBREVIATIONS AND ACRONYMS

AA	Atlantic Area
AEM	Anion Exchange Membrane
AFC	Alkaline Fuel Cell
AHEAD	Advanced Hydrogen Energy Chain Association for Technology Development
ASU	Air Separation Unit
ATR	Autothermal Reforming
BSR	Biogas Steam Reforming
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization and Storage
CGH2	Compressed Gas H_2
DME	Dimethyl ether
DRI	Direct Reduced Iron
EHB	European Hydrogen Backbone
ETS	Emissions Trading System
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
FT	Fischer Tropsch
GHG	Greenhouse Gas
ICE	Internal Combustion Engine
IEA	International Energy Agency
IMO	International Maritime Organization
IPCEI	Important Projects of Common European Interest
LH_2	Liquid H_2
LNG	Liquified Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
MCFC	Molten Carbonate Fuel Cell
MOF	Metal-Organic Framework
NZE	Net zero emissions
OGE	Open Grid Europe
ORR	Oxygen Reduction Reaction
PAFC	Phosphoric Acid Fuel Cell
PEC	Photoelectrochemical
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
PtL	Power to Liquid
RES	Renewable Energy Source
RWGS	Reverse Water Gas Shift
SAF	Sustainable Aviation Fuel
SMR	Steam Methane Reforming
SOFC	Solid Oxide Fuel Cell
TSO	Transmission System Operator
VPSA	Vacuum Pressure Swing Adsorption
WP	Work package

1 Energy Transition

Levels of greenhouse gases in the atmosphere are a matter of concern, and according to the International Energy Agency, a large percentage of the total global emissions are related to energy [1]. Nowadays, a significant part of energy is obtained by processes that emit CO_2, like the combustion of fossil fuels. In contrast to them, the use of H_2 for energy production does not directly emit CO_2. Yet, there may be emissions during its production. If produced without emitting CO_2, H_2 is completely clean—green H_2.

This is the case of H_2 produced by electrolysis when the electricity employed is generated without emitting CO_2 (*e.g.,* from wind or other renewable sources). In these processes, the primary energy source is already clean, but producing H_2 can be useful for storing the energy. Wind and sun are examples of clean sources in which the energy produced varies over time; converting it into H_2 allows it to be stored until needed [2].

Hydrogen may also be produced from processes that emit CO_2, like natural gas reforming. In this case, like other processes that emit CO_2, the production can be coupled with Carbon Capture and Utilization or Storage (CCUS) technologies to decrease the amount of CO_2 released into the environment [3].

Although this type of hydrogen may not be as clean as H_2 purely derived from clean sources (green hydrogen), it can serve as a **transitional** solution while green hydrogen technologies develop enough to take over the energy transition. Ultimately, the goal is a zero-emission energy sector.

1.1 Addressing Renewable Energy Intermittency

One of the significant challenges of **renewable energy sources** (RES) such as wind and solar is their **intermittency**. Unlike fossil fuels, renewable energy sources do not provide a constant energy supply; in this context, renewable energies do not produce *on demand* [IRENA 2020] [4]. Wind and photovoltaic power generation depend strongly on weather conditions and time of day, leading to periods of overproduction and underproduction. This variability poses a significant challenge to maintaining a stable and reliable energy supply, creating new challenges but, most importantly, **opportunities regarding energy storage and grid flexibility**.

Hydrogen, with its unique ability to mitigate the intermittent effects of renewable energy, emerges as a key player in the energy transition. It offers a solution to the challenge of balancing supply and demand in the renewable energy sector. During periods of excess energy production, surplus electricity can be harnessed to produce hydrogen. This hydrogen, when stored, can be used later to generate electricity during low renewable energy production periods, effectively balancing supply and demand. This process of converting surplus renewable energy into hydrogen not only creates a more flexible and resilient energy system but also plays a significant role in maximizing the use of renewable resources, thereby contributing to sustainable energy goals.

1.1.1 Balancing Supply and Demand

The mismatch between energy supply and demand curves mentioned before is one of the most significant issues in the energy transition. This discrepancy can lead to inefficiencies and requires robust energy storage solutions.

Hydrogen storage offers a promising solution to this problem. Unlike batteries which are more suitable for short-term energy storage, hydrogen can be stored for **long periods and in large quantities**. This context makes hydrogen particularly well-suited for balancing seasonal energy supply and demand variations. For example, excess energy produced during sunny or windy months can be stored as hydrogen and used during high-demand or low-renewable energy production periods. This capability enhances the overall stability and reliability of the grid and energy system.

While batteries are an essential component of modern energy storage systems, they have limitations that hydrogen can overcome. Batteries typically have a limited capacity for long-term energy storage. They also degrade over time and have environmental, and resource constraints associated with their production (critical raw materials) and disposal (chemical waste).

Hydrogen, on the other hand, offers several advantages:

1. **Long-term Storage**: Hydrogen can be stored for extended periods (over 6 months) without significant losses, making it suitable for long-term storage solutions.
2. **Scalability**: Hydrogen storage systems are highly adaptable and can be scaled up to store large amounts of energy, making them a potential solution for grid-scale energy storage.
3. **Versatility**: Hydrogen can be used in various applications, including electricity generation, transportation, and industrial processes, enhancing its utility beyond energy storage.
4. **Environmental Impact**: When produced only from renewable sources, hydrogen is a clean energy carrier with water as its only byproduct when used in fuel cells.

1.2 Renewable Energy Generation: Offshore Wind and Solar Photovoltaics

1.2.1 Offshore Wind Energy

Offshore wind energy is a rapidly growing sector with significant potential for large-scale renewable energy generation. Unlike onshore installations, offshore wind farms benefit from higher and more consistent wind speeds, leading to higher capacity factors and more reliable energy production [5, 6]. The development of floating wind turbines further expands the potential for offshore wind energy by allowing installation in deeper waters with even better wind resources.

Integrating offshore wind energy with hydrogen production can create a powerful synergy. Offshore wind farms can produce large amounts of electricity that can be used to generate hydrogen through electrolysis. This hydrogen can be transported to shore and used in various applications, including electricity generation, industrial processes, and transportation.

1.2.2 Solar Photovoltaics (PV)

Solar photovoltaics (PV) is another cornerstone of renewable energy generation. Due to their scalability, modularity, and declining costs [7], solar PV systems are widely deployed. However, like wind energy, solar PV faces challenges related to intermittency and mismatches between production and demand. This issue could be addressed by coupling Solar PV systems with electrolysis units to produce hydrogen during high solar irradiance periods. This hydrogen can be stored and used to generate electricity during periods of low solar production or high demand. Additionally, hydrogen can fuel vehicles and provide energy for industrial processes, further expanding the utility of solar PV systems.

1.3 The Future of Hydrogen in the Energy Transition

The potential of hydrogen as a key component of the energy transition is immense. Governments and industries worldwide recognize hydrogen's importance and invest in its development [8-19]. For instance, the European Union has outlined a hydrogen strategy that aims to install at least 40 GW of renewable hydrogen electrolyzers by 2030 [12, 20]. Similarly, countries like Japan, South Korea, and Australia are investing significantly in hydrogen infrastructure and technology.

To fully realize the potential of hydrogen, several challenges must be addressed:

- **Cost Reduction**: The cost of producing green hydrogen through electrolysis must be reduced to make it competitive with other energy storage and production forms [21];
- **Infrastructure Development**: A robust hydrogen infrastructure, including production facilities, storage systems, and distribution networks like refueling stations, is essential for widespread hydrogen adoption.
- **Regulatory Frameworks**: Clear and supportive regulatory frameworks are needed to encourage investment in hydrogen technologies and ensure safety and reliability.
- **Technological Advancements**: Continued research and development are necessary to improve the efficiency and performance of hydrogen production, storage, and utilization technologies.

Hydrogen is pivotal in the transition to a sustainable and resilient energy system. Its ability to address the intermittent of renewable energy sources, balance supply and demand, and provide long-term, scalable storage solutions makes it a critical component of the future energy landscape.

1.3.1 Hydrogen Colors

Different types of hydrogen are associated with color. This association is often called the "**Hydrogen Rainbow**", depending on its **energy source and production method** (Figure 1Error! Reference source not found.). Regarding energy sources, hydrogen can be divided into two main groups: hydrogen produced via fossil fuels and produced from electricity.

The first group includes hydrogen obtained from natural gas or coal using various techniques. These include:

- Natural gas reforming with carbon capture (blue hydrogen);
- Pyrolysis (turquoise hydrogen);
- Natural gas reforming without carbon capture (grey hydrogen);
- Gasification of coal (brown and black hydrogen).

All these methods generate CO_2, resulting in a significant carbon footprint. However, blue hydrogen integrates Carbon Capture, Utilization and Storage (CCUS) technologies to trap and store CO_2 emissions, thereby reducing its environmental impact compared to other fossil fuel-derived hydrogen. Nevertheless, the process cannot eliminate CO_2 emissions due to incomplete capture capabilities [3].

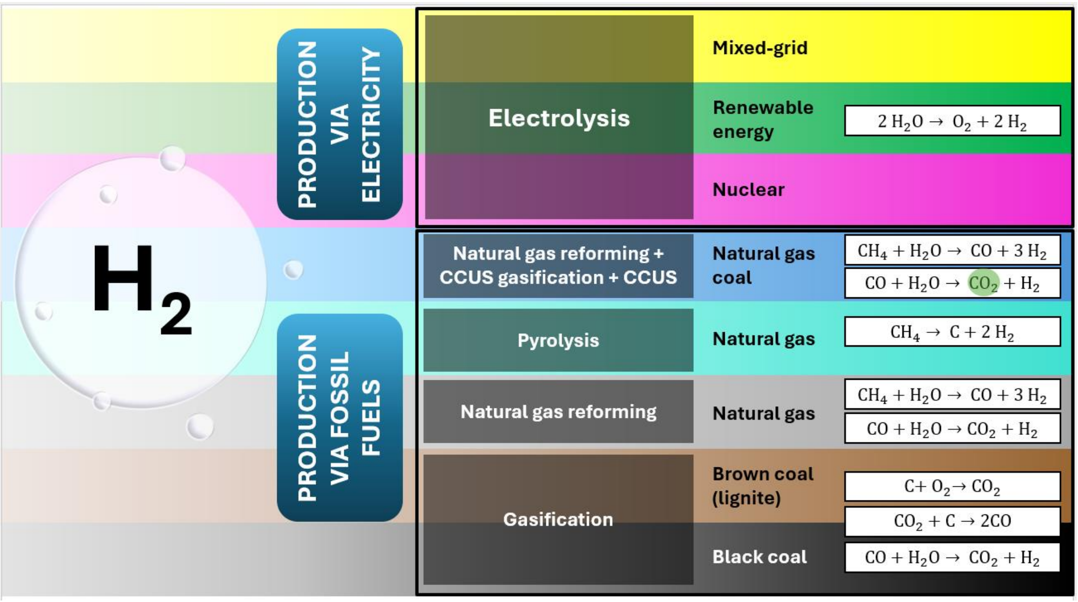


Figure 1. Types of hydrogen with its energy source, technology, and reactions involved in the process.

The second group involves the electrolysis of water using electricity from various sources:

- Mixed sources (yellow hydrogen).
- Nuclear energy (pink hydrogen).
- Renewable sources (green hydrogen).

Pink hydrogen has a low carbon footprint but raises concerns regarding nuclear waste and plant safety. Yellow hydrogen's footprint depends on the grid's energy mix, which can include both fossil fuels and renewable sources.

Green hydrogen is the most environmentally sustainable option, with a negligible carbon footprint, as it relies entirely on clean energy. Since wind and sun power generation can fluctuate, converting this energy into hydrogen enables it to be stored and used when necessary [2].

Therefore, green hydrogen represents the goal of achieving a zero-emissions energy landscape. However, its current production technologies are immature and require significant time to be implemented at a scale capable of meeting energy demands.

By integrating hydrogen production with renewable energy sources such as offshore wind and solar photovoltaics, it will be possible to create a more flexible, reliable, and efficient energy system that maximizes the use of renewable resources and accelerates the transition to a low-carbon economy. Continued investment and development in hydrogen technologies will be essential to unlocking their full potential and achieving global energy and climate goals.

2 Green Hydrogen Production

Green hydrogen production is a rapidly evolving field with several promising technologies. The most common method for hydrogen production from water decomposition is **electrolysis**, where electricity is used to split water into hydrogen and oxygen. This process is carbon-free if the electricity comes from renewable sources like wind or solar power. There are three main types of electrolyzers: **alkaline**, **proton exchange membrane (PEM)**, and **solid oxide**. Alkaline electrolyzers are the most mature technology, but PEM electrolyzers are more efficient and are tolerant to intermittent power supply. Solid oxide electrolyzers operate at high temperatures and can also use heat from renewable sources, increasing their overall efficiency. **Thermochemical water splitting** is another method for hydrogen production, which involves the decomposition of water into hydrogen and oxygen at high temperatures. This process, also known as thermal water splitting, requires temperatures above 2000°C, which can be achieved using concentrated solar power or nuclear energy. While this method has the potential to produce hydrogen without any carbon emissions, it is currently less efficient and more technically challenging than other methods, such as electrolysis. However, ongoing research aims to improve the feasibility and efficiency of this process. **Photochemical water splitting** is a third method for hydrogen production from water decomposition, which uses light energy, typically from the sun, to break down water into hydrogen and oxygen. This process mimics natural photosynthesis in green plants. While it offers a clean, renewable pathway for hydrogen production, it's still in the early stages of research and development due to challenges in efficiency and the need for advanced photocatalyst materials.

Biogas reforming is a sustainable method for green hydrogen production that involves processing biogas, a renewable source composed mainly of methane and carbon dioxide, typically produced from organic waste. The process, similar to steam methane reforming, uses a catalyst and heat to convert the methane in biogas into hydrogen and carbon dioxide. This method can be carbon-neutral or even carbon-negative, making it a promising approach for green hydrogen production.

Another promising technology is **biological hydrogen production**, where microorganisms like algae or bacteria produce hydrogen as a byproduct of their metabolism. This process is still in the research and development stage, but it has the potential to produce hydrogen from biomass and/or organic waste, making it a sustainable and potentially low-cost option.

2.1 Decomposition of water

2.1.1 Electrolysis

Water electrolysis is a key method for producing hydrogen, especially when it comes to green hydrogen production. This process involves the decomposition of water (H_2O) into its constituent elements - hydrogen (H_2) and oxygen (O_2) - using an electric current. The overall reaction can be represented as follows:

$$2\,\mathrm{H_2O} \xrightarrow{\text{yields}} 2\,\mathrm{H_2} + \mathrm{O_2}$$

Three main types of electrolyzers are used in this process: alkaline electrolyzers, proton exchange membrane (PEM) electrolyzers, and solid oxide electrolyzers.

Alkaline electrolyzers are the oldest and most mature technology. They operate at relatively high temperatures (60-80°C) and pressures (10-30 bar) and have a high tolerance for impurities in the water feedstock.

PEM electrolyzers, on the other hand, operate at lower temperatures (50-80°C) but at higher pressures (up to 50 bar). They have higher efficiency and a faster response time to changes in electricity supply compared to alkaline electrolyzers, making them **well-suited to operation with intermittent renewable energy sources**.

Solid oxide electrolyzers operate at much higher temperatures (700-1 000°C). They can achieve higher efficiencies by utilizing both electrical and thermal energy, and they can also operate in a mode that co-produces hydrogen and synthetic gas (syngas) from water and carbon dioxide.

The choice of electrolyzer technology depends on various factors, including the available electricity and heat sources, the required hydrogen production rate and purity, and economic considerations. With the increasing focus on renewable energy, water electrolysis is set to play a crucial role in the future hydrogen economy.

2.1.2 Thermochemical water splitting

Thermochemical water splitting is a promising method for hydrogen production that utilizes heat, often from high-temperature sources such as **concentrated solar power or nuclear energy**. This process involves a series of thermochemical reactions that ultimately result in the splitting of water into hydrogen and oxygen.

The process typically involves a thermochemical cycle, with water being the only consumed reactant and its byproducts being returned to the environment (H_2 and O_2). Several different thermochemical cycles can be used, each with its own set of reactions and operating conditions. Some of the most studied cycles include the **sulfur-iodine cycle, the cerium(IV) oxide-cerium(III) oxide cycle**, and the **copper-chlorine cycle**.

One of the main advantages of thermochemical water splitting is its potential for high efficiency. Because it utilizes thermal energy, it can theoretically achieve higher efficiencies than electrolysis, especially when coupled with high-temperature heat sources. Moreover, unlike electrolysis, which requires electricity, thermochemical water splitting can directly utilize heat, making it a good match for renewable or nuclear energy sources that can provide high-temperature heat.

However, thermochemical water splitting is still in the **research and development stage**, with many technical challenges to overcome, including the development of suitable materials and reactors that can withstand the high temperatures and corrosive environments involved in the process. Despite these challenges, thermochemical water splitting represents a promising pathway toward sustainable, large-scale hydrogen production.

2.1.3 Photochemical water splitting

Photochemical water splitting, also known as **photoelectrochemical (PEC) water splitting**, is a process that uses sunlight and specialized semiconductors to dissociate water molecules into hydrogen and oxygen. This method is inspired by photosynthesis, which converts water and carbon dioxide into oxygen and carbohydrates. The overall reaction involves splitting two moles of water into one mole of oxygen and two moles of hydrogen using light.

Despite the advantages of PEC water splitting, its applications are **limited by poor efficiency** due to the recombination of charge carriers, high overpotential, and sluggish reaction kinetics [22]. Significant efforts are being made to overcome these challenges, including the development of new materials and the optimization of existing ones [23].

In summary, **photochemical water splitting is a promising method** for producing hydrogen, a clean and renewable energy source, from water using sunlight. However, **further research and development are needed** to improve its efficiency and make it commercially viable [22].

2.2 Biogas reforming

Biogas reforming is another method for generating green hydrogen. Biogas is typically produced from various types of organic waste and generated by the breakdown of organic matter by anaerobic bacteria. The raw materials for biogas production include agricultural waste, manure, municipal waste, plant material, sewage, green waste, and wastewater, which are used in digesters that primarily yield methane gas and carbon dioxide, with trace amounts of nitrogen, hydrogen, and carbon monoxide.

For hydrogen production, biogas is used in a multistep process that includes reforming, water-gas-shift reaction, and hydrogen separation. Biogas reforming can be performed using different methods: **steam reforming, dry reforming, dual reforming,** and **tri-reforming**. Each of these processes has its own characteristics and challenges.

- **Steam reforming**, also known as steam methane reforming (**SMR**), is the most commercialized method. It involves high-temperature steam (700 °C–1000 °C) reacting with methane to produce hydrogen. However, **SMR is highly energy-intensive**.
- **Dry reforming** is an alternative process where carbon dioxide, abundant in biogas, is used as an oxidant. This process is particularly interesting for biogas reforming due to its high carbon dioxide content.
- **Dual reforming** and **tri-reforming** are other alternative processes that utilize the biogas' high carbon dioxide content.

Different aspects are considered for each process, including thermodynamic equilibrium, industrial scale or research laboratory development processes, kinetic models, and mechanistic study.

Despite the potential of biogas reforming for hydrogen production, **there are challenges to overcome**. These include the wide temperature range required for biogas steam reforming (BSR) between 600 °C and 1000 °C and the need for catalytic processes that are often combined. Moreover, the production of hydrogen from biogas combined with CO_2 capture and storage (CCS) has been studied [24]. This involves steam methane reforming (SMR) and autothermal reforming (ATR) for syngas production. CO_2 is captured from the syngas with a novel vacuum pressure swing adsorption (VPSA) process, which combines hydrogen purification and CO_2 separation in one cycle [24].

Hydrogen production from biogas reforming is a promising avenue for the production of green hydrogen. However, **further research and development** are required to overcome existing **challenges** and **improve efficiency**. Using biogas as a renewable resource for hydrogen production not only contributes to the generation of clean energy but also utilizes the high carbon dioxide content in biogas, making it a potentially sustainable and environmentally friendly process.

2.3 Biological hydrogen production

Biological hydrogen production uses microorganisms to convert organic matter into hydrogen gas. This process is considered a **sustainable and environmentally friendly** method for producing hydrogen.

There are two main biological processes for hydrogen production: **fermentation** and **photolysis**. **Fermentation** involves the breakdown of organic matter by bacteria in the absence of oxygen, producing hydrogen as a byproduct. On the other hand, **photolysis** consists of using light energy to split water molecules into hydrogen and oxygen. The process is carried out in a specialized container or a bioreactor.

One of the challenges in biological hydrogen production is the need to **improve the efficiency** of the process, which is influenced by several factors, including the type of microorganisms used, the conditions under which they are grown, and the type of organic matter used as a substrate. Different types of microorganisms have different metabolic pathways and produce hydrogen at different rates. Therefore, selecting the right combination of microorganisms can significantly improve hydrogen production efficiency. The cost of biological hydrogen production, which is more than one order of magnitude higher than gasoline, is also a significant challenge [25]. Therefore, **reducing the cost** of the process is a key area of focus in current research.

Biological hydrogen production is still in its early stage of development, and several challenges must be addressed to become a viable commercial solution.

2.4 Comparison of the presented solutions

Technology Maturity

Electrolysis is the most mature technology among the three. It has been used for decades in various industries, and its principles and mechanisms are well understood. Biogas reforming, while not as mature as electrolysis, is a well-established process in the natural gas industry. On the other hand, biological hydrogen production is still in its early stages of development. While promising, it requires further research and development to reach commercial viability.

Efficiency

In terms of efficiency, electrolysis has a high-efficiency rate, typically around 70-80 %. However, this efficiency can be affected by several factors, including the type of electrolyzer used and the operating conditions. Biogas reforming also has a high-efficiency rate but requires high temperatures and is associated with significant energy consumption. Biological hydrogen production currently has the lowest efficiency among the three methods. However, ongoing research is focused on improving this efficiency by optimizing microbial consortia and operating conditions.

Sustainability

All three methods are considered sustainable as they use renewable resources for hydrogen production. However, there are differences in their environmental impacts. Electrolysis has a low environmental impact, especially when powered by renewable electricity. Biogas reforming, while using a renewable resource (biogas), is associated with carbon emissions due to the reforming process. Biological hydrogen production has the lowest carbon emissions among the three methods and is considered the most sustainable. However, the sustainability of these methods also depends on the feedstock's source and the entire process's lifecycle emissions.

Cost

Currently, electrolysis is the most cost-effective method for hydrogen production, especially when using low-cost renewable electricity. The cost of biogas reforming can be competitive with electrolysis, depending on the price of the biogas and the specific process used. Biological hydrogen production is currently the most expensive method due to the high costs associated with the bioreactors and the low efficiency of the process. However, with further research and development, the cost of biological hydrogen production could be significantly reduced.

Summary

In conclusion, electrolysis is currently the most mature, efficient, and cost-effective method, but it requires a significant amount of energy. Biogas reforming is less mature and requires high temperatures, but it uses a renewable resource and can be cost-competitive. Biological hydrogen production is the least mature and currently the least efficient and most expensive method, but it has the lowest carbon emissions and the highest potential for sustainability.

2.5 Bibliometric Analysis of Hydrogen Production

A bibliometric analysis was conducted on the main technologies related to H_2 production. The analysis comprised a search of patents and scientific publications. The patent search was performed on Google Patents, having as the only temporal limit the date of search - 10th to 21st June 2024. The search was restricted to keywords explicitly found within the claims, deliberately excluding those within the abstract and title. Different keywords were systematically chosen, each paired with the keyword AND "hydrogen production". This methodical keyword selection aimed to encompass the broadest possible range of search results while avoiding overlap among some searches, for example ("steam reforming" + NOT "steam" + NOT "reforming"). A summary of the selected keywords is provided in **Table 1**.

Despite the efforts to cover the patents related to fermentation using the keywords presented in **Table 1**, line 17, the search inadvertently omitted patents that included specific microorganisms' names. After completing the database search, the number of patents per year was plotted, with each year corresponding to the publication date, not the filing date.

As previously mentioned, a scientific article search was also conducted using the Scopus database from June 10th to 19th, 2024. The search strategy employed keywords analogous to those presented in **Table 1**. However, for the expressions involving the AND NOT operators, the operators and the affected keyword(s) were placed at the end of the search query (in contrast to Google Patents, Scopus does not have the option "not", only "and not"). The keywords were searched within the Title, Abstract, and Keywords of the articles in the database. The search was limited to the document type 'Article'; thus, the documents classified in Scopus as other types (including Reviews and Conference Papers) were excluded. The data was organized according to the number of articles per annum and was subsequently visualized through plotting.

Figure 2 shows a remarkably high number of publications and patents that include the keywords "**water electrolysis**". This trend suggests a high level of interest in the topic since 2005 and indicates that it is not only a subject of scientific research but is also finding practical applications.

Table 1. Selected keywords used for the search on Google Patents. Each one was followed by the expression AND “hydrogen production”. The asterisk (*) was used to broaden the search criteria, allowing for the inclusion of various terms related to the specific keywords (*e.g.*, *bacteria will include cyanobacteria)

1	“water electrolysis”
2	“solid oxide water electrolysis”
3	“thermal water splitting” OR “thermochemical water splitting” OR “thermocatalytic water splitting”
4	“water photolysis” OR “photochemical water splitting” OR “photoelectrochemical water splitting” OR “photocatalytic water splitting”
5	“steam reforming”
6	“steam methane reforming”
7	“steam reforming” AND “methane”
8	“steam reforming” AND “biogas”
9	“steam reforming” AND “natural gas”
10	“steam reforming” AND “biomass”
11	“steam reforming” AND “hydrocarbon”
12	“dry reforming”
13	(Not “steam”) AND “methane reforming”
14	(Not “steam”) AND “biogas reforming”
15	(Not “steam”) AND “natural gas reforming”
16	(Not “steam”) AND “hydrocarbon reforming”
17	(”pyrolysis” OR “methane decomposition” OR “cracking”) AND (“hydrogen production”) AND (not(“reforming”)
18	Not “reforming” AND (bio* OR fermentati* OR *bacteria OR microorganism* OR fungi OR microb*)
19	Not "reforming" AND (fermentati* OR *bacteria OR microorganism* OR fungi OR microb*)
20	Not "reforming" AND bio* AND not (fermentati* OR *bacteria OR microorganism* OR fungi OR microb*)

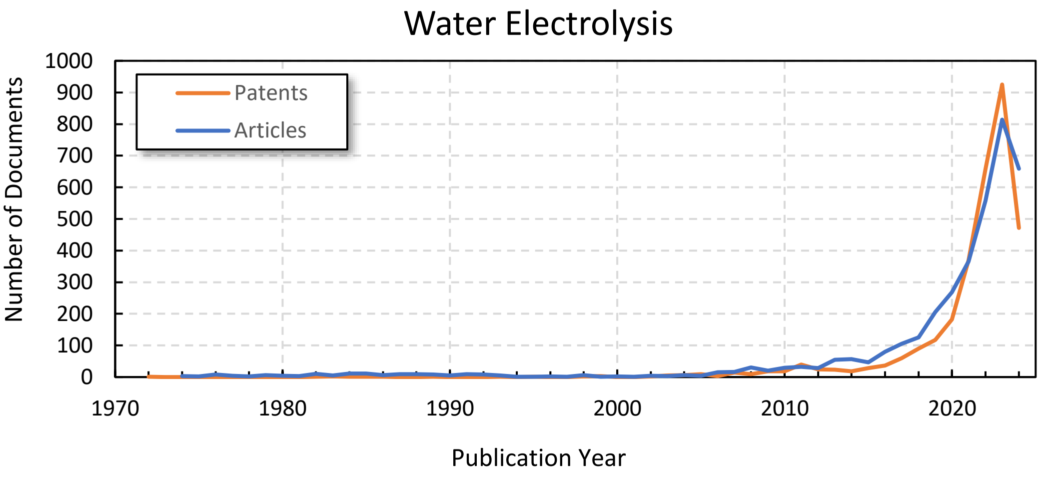


Figure 2. Number of patents and scientific articles mentioning water electrolysis per year. Data obtained from the search using the keywords from Table 1 (line 1).

Figure 3 shows that Solid Oxide Water Electrolysis, a subset of water electrolysis, still finds little application (low number of patents). Yet, since 2019, the number of scientific articles has increased, which may be in line with policies related to the European Green Deal. This figure alsoError! Reference source not found. shows that thermal water splitting and water photolysis have a modest number of scientific articles and patents, suggesting these topics have not been extensively explored so far. Nonetheless, there was a slight increase in published articles on thermal water splitting in 2016, possibly due to the 2015 Paris Agreement [14].

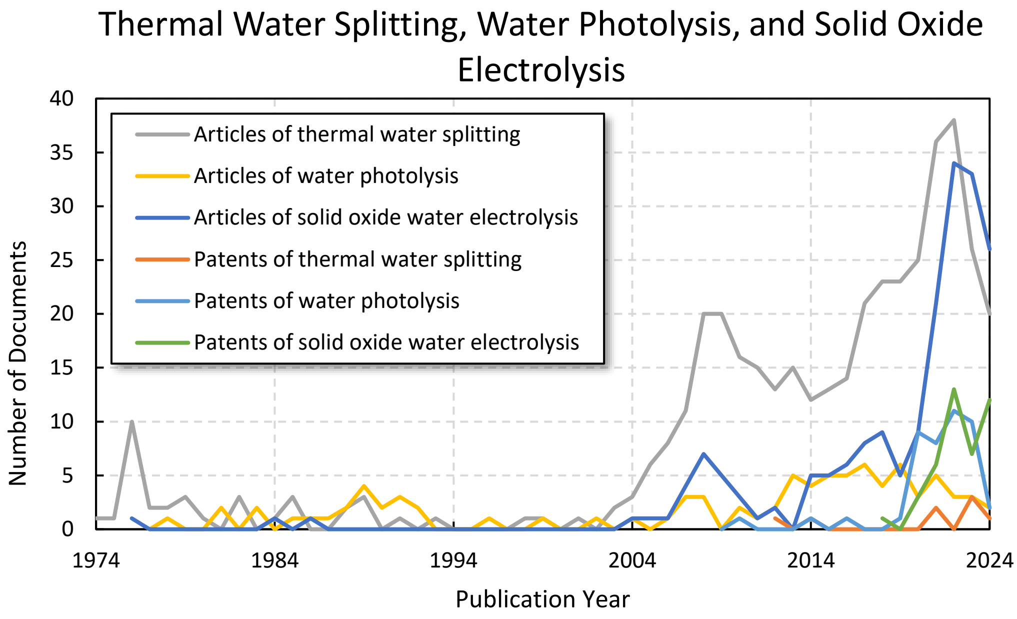


Figure 3. Number of patents and scientific articles mentioning thermal water splitting, water photolysis or solid oxide water electrolysis. Data obtained using the keywords from Table 1, lines 2, 3, and 4.

As shown in **Figure 4**Error! Reference source not found., **steam reforming** clearly dominates in the number of patents, compared to dry reforming, with the latter only recently gaining momentum in 2020. Steam reforming patents dropped in 2015 but began to rise again shortly after that. Remarkably, the number of patents related to biological entities and hydrogen production shows a trend similar to steam reforming. Both began to rise in 1999, possibly influenced by the Kyoto Agreement and the increased interest in clean fuel production. The number of patents for each was roughly equal until 2010, after which patents related to biological sources surpassed those for steam reforming and have remained higher ever since.

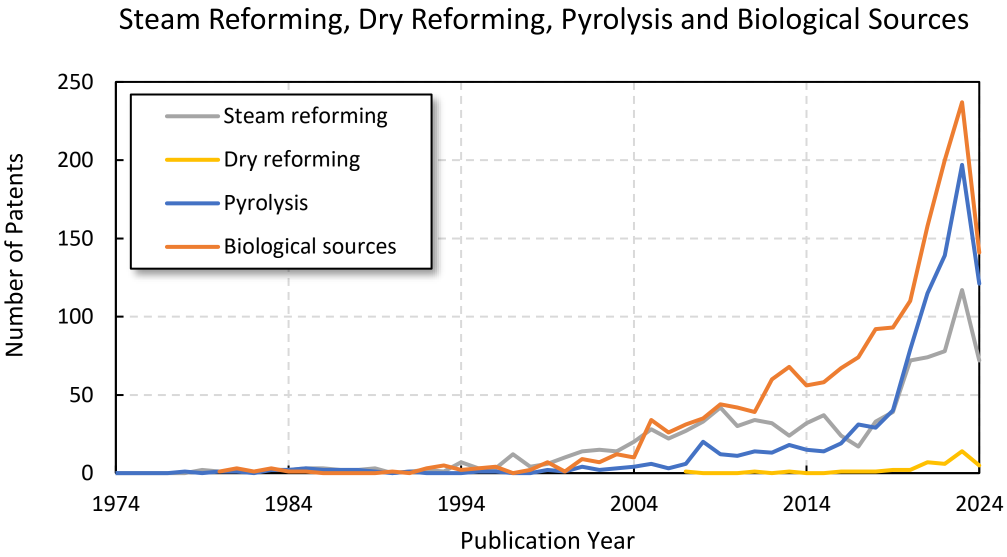


Figure 4. Number of patents obtained for four classes of H_2 production: steam reforming, dry reforming, pyrolysis and biological sources. The data was obtained using the keywords reported in Table 1, and it was combined as follows: the steam reforming set was built from the sum of lines 5 and 6 of the table; the dry reforming set was built from line 12; the pyrolysis set was built from line 17, and the biological sources set resulted from the search with the words from line 18.

Analyzing **Figure 5**Error! Reference source not found., it becomes evident that methane has emerged as the predominant raw material in steam reforming processes since 2020. Additionally, **Figure 6**Error! Reference source not found. indicates that, in the context of dry reforming, natural gas is more frequently mentioned.

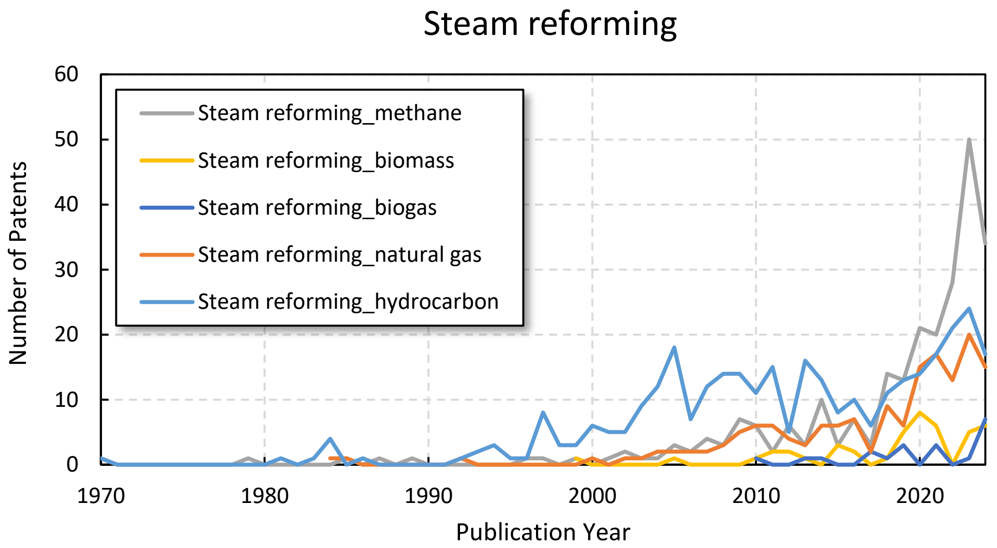


Figure 5. Number of patents mentioning Steam Reforming, grouped by different materials/fluids that may react with water steam. Data obtained using the keywords from Table 1, lines 6 to 11.

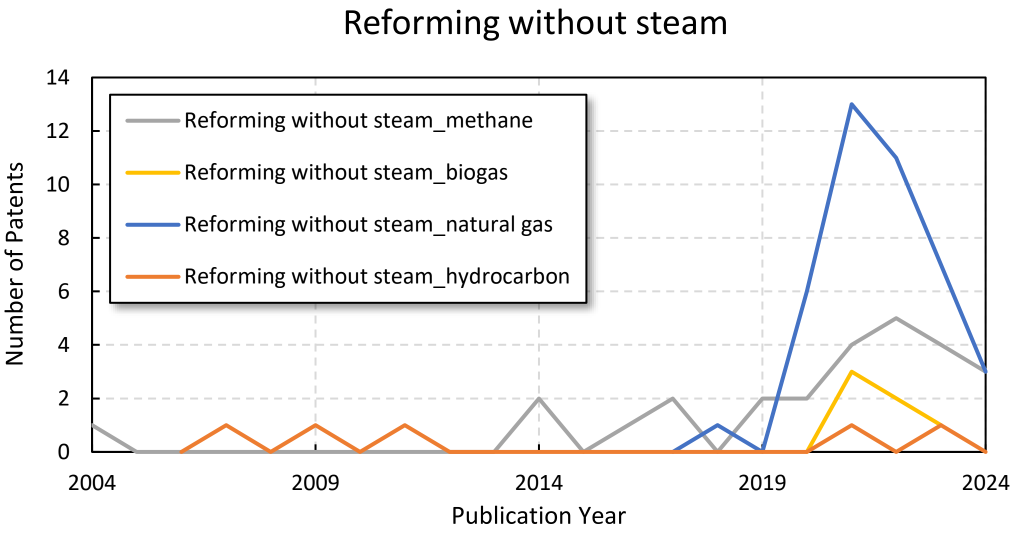


Figure 6. Number of patents mentioning reforming, in the absence of steam, grouped by H_2 donating sources. Data obtained using the keywords from Table 1, lines 13 to 16.

As previously demonstrated in **Figure 4**Error! Reference source not found., **biological sources** exhibit a prominent presence in patents related to hydrogen production. In alignment with the methodology applied to reforming, it is proposed to categorize this sector into distinct subclasses and analyze their respective developmental trends.

As depicted in **Figure 7**Error! Reference source not found.**,** a significant shift in the landscape of patents related to hydrogen production from biological sources has been observed since this sector emerged in 2005. Initially, fermentation-based methods predominated in the bioproduction sector. However, a notable transition occurred in 2020 when alternative bioproduction techniques began to eclipse fermentation in terms of patent filings. Presently, the quantity of patents associated with these other bioproduction methodologies surpasses those focused on fermentation, indicating a pivotal shift in research and development priorities within this field.

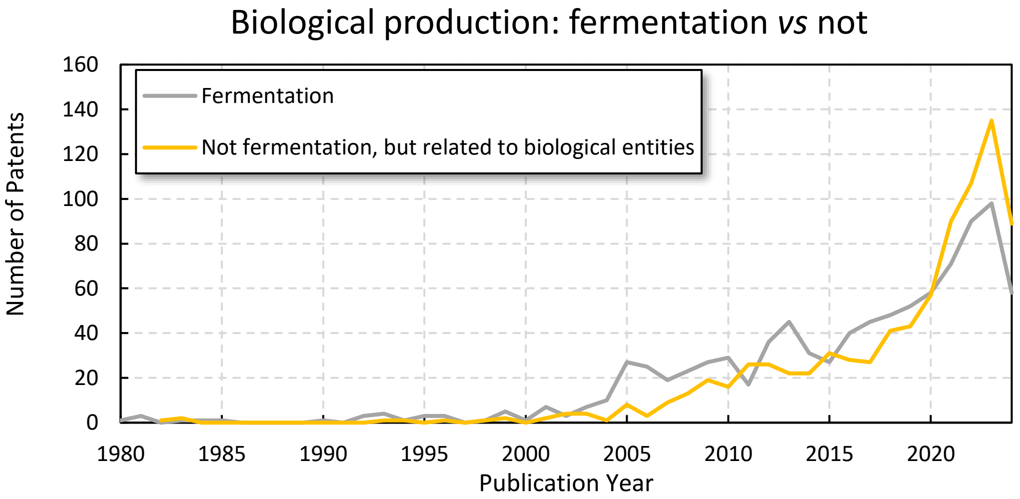


Figure 7. Evolution of patents related to hydrogen production from biological sources: fermentation and other biological sources (non-fermentation). Data obtained using the keywords from Table 1, lines 19 and 20.

Similar to what occurred with patents, the analysis of the number of scientific articles published indicates **that steam reforming** dominates over dry reforming (**Figure 8**)Error! Reference source not found.. Notably, the initial increase in the number of publications concerning dry reforming corresponds to a decrease in steam reforming publications. Biological sources follow a similar trend to steam reforming: the number of publications in this area surpasses the other two, showing a high level of interest in this particular field.

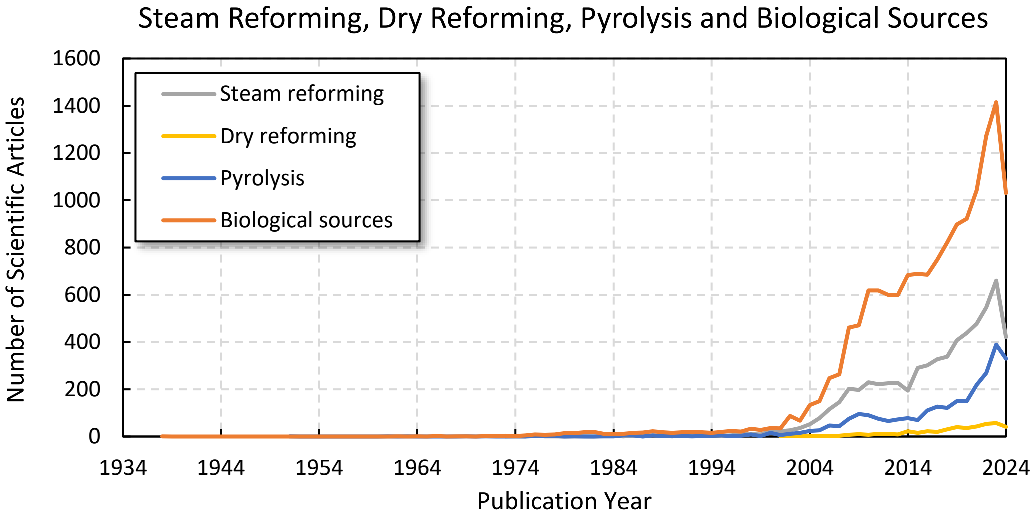


Figure 8. Number of scientific articles obtained using the keywords reported in Table 1, in the following way: the steam reforming set (orange) was built from the sum of lines 5 and 6 of the table; the dry reforming set (green) was built from line 12; the pyrolysis set from line 17, and the biological sources set (blue) resulted from the search with the words from line 18.

Similar to the trend observed in patents, an analysis of the literature on steam reforming for H_2 production reveals that methane is the predominant raw material used - **Figure 9**Error! Reference source not found.. Alternative reforming methods, such as dry reforming, are less represented in the literature, though methane remains the primary focus in this emerging research area (see **Figure 10**Error! Reference source not found.).

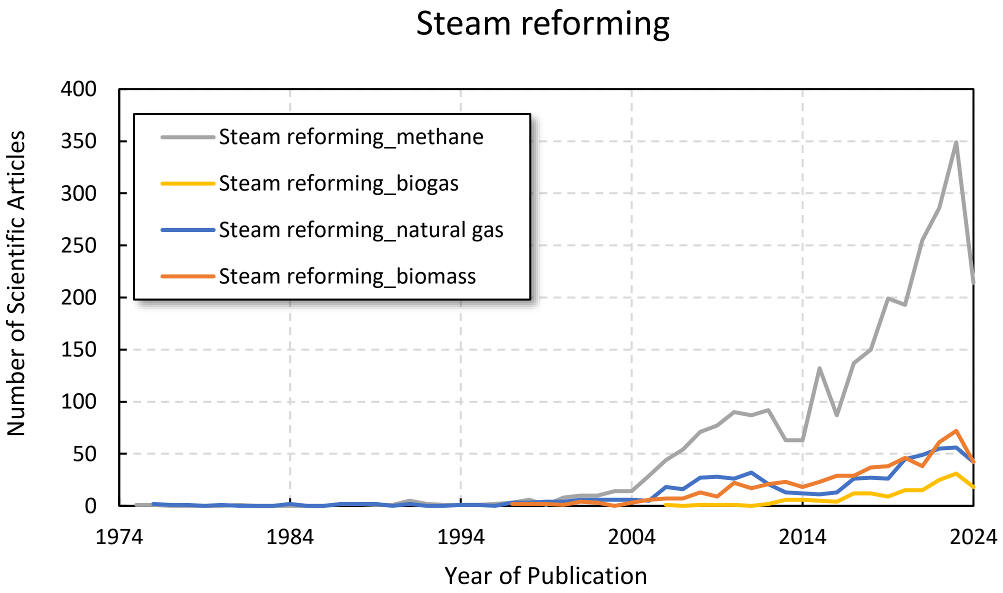


Figure 9. Number of scientific articles mentioning Steam Reforming, grouped by different materials that may react with the water steam. Data obtained using the keywords from Table 1, lines 6 to 11.

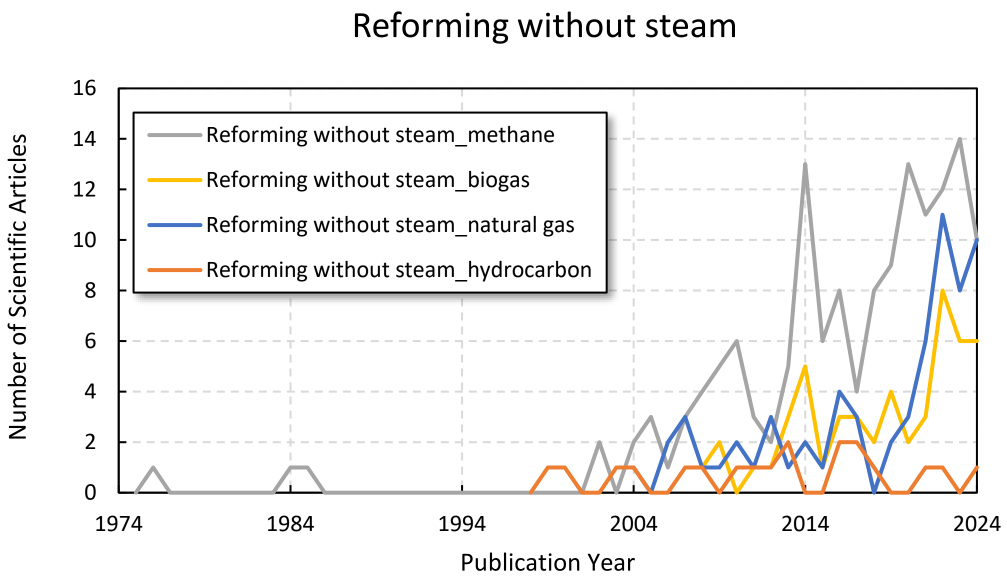


Figure 10. Scientific articles mentioning reforming, in the absence of steam, grouped by H_2 donating sources. Data obtained using the keywords from Table 1, lines 13 to 16.

Figure 11 Error! Reference source not found. shows that, much like patent data, fermentation was initially the main method of **bioproduction** discussed in the literature. However, it was later surpassed by other methods. The figure also shows that the increase in the overall number of publications related to H_2 production from biological sources occurred around 2000, which may be correlated with the Kyoto Agreement and subsequent environmental policies.

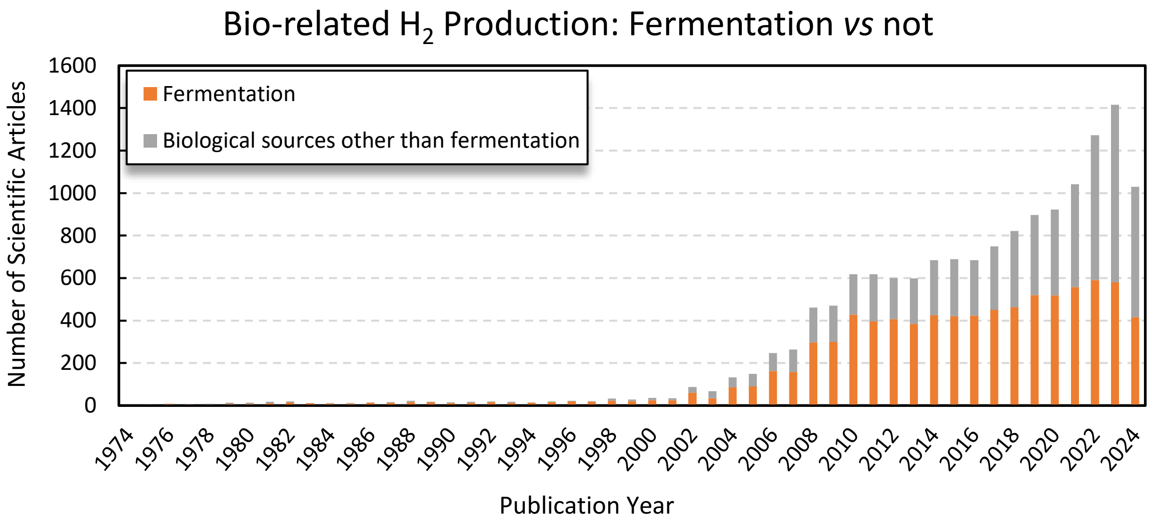


Figure 11. Evolution of scientific articles related to fermentation and other biological sources over time. Data obtained using the keywords from Table 1, lines 19 and 20. Each year has two sets (fermentation and not fermentation), with one set on top of the other; this way, the height of a bar for each year gives the total number of articles related to biological production (in line with Fig. 8)

The heavy percentage of articles, including “bio” related words but missing fermentation-related terms, was somehow intriguing. We intended to unveil which topics were hidden within this broad group of “non-fermentative biology-related” group. For such, we used data from the search in Scopus, when using the keywords from Table 1, line 20 (and “Hydrogen Production”). The Abstract and Title of the articles were loaded in the VosViewer software [26], which performed an analysis of the frequency of the terms, as well as a clustering of them. The result is shown below in Figure **12.**

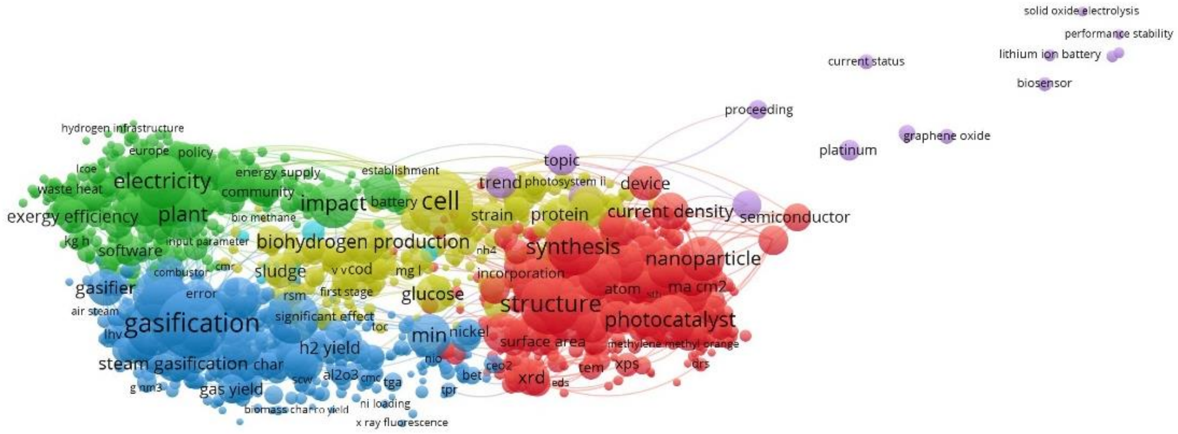


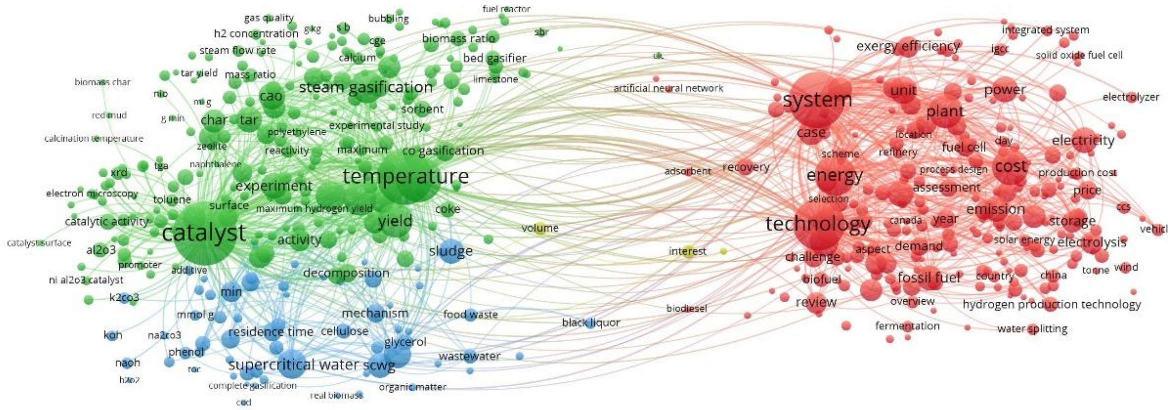
Figure 12. Result from the analysis of the terms present in the abstracts and titles of the search for biologic but not fermentation-related H_2 production.

This analysis showed that one of the terms most found when searching for bio-related H_2 production was "gasification". Gasification is a process that usually includes steps of reforming, but as the search in Scopus was by terms, the use of "not reforming" in the keywords (Table 1, lines 18, 19 and 20) was not enough to prevent gasification (*e.g.*, gasification of biomass) to be included.

We take advantage of this result to present two additional analyses related to gasification, a relevant process in the H_2 production sector:

- a frequency analysis and clustering, of terms from the articles retrieved by Scopus, when using the keywords "gasification" (AND "hydrogen production);
- a patent search with the same keywords (search restricted to the claims).

The results were combined and are shown in **Figure 13**Error! Reference source not found..



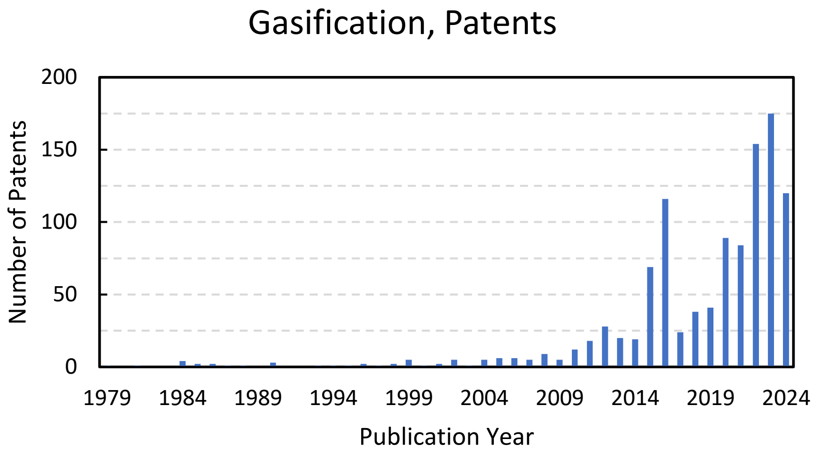


Figure 13. Frequency and co-occurrence of the terms from the articles mentioning gasification (top). Time evolution of the number of patents mentioning gasification (bottom).

In **Figure 13**, the analysis of terms reveals that 'catalyst' is one of the words more frequently mentioned, suggesting an ongoing and active search for new catalysts for the gasification process. *Temperature*, *energy* and *technology* are other terms with high frequency and connections (co-occurrences with other terms) that may also reflect the current effort to develop more efficient processes. In Error! Reference source not found.addition, a plot of the patents mentioning gasification shows an increase after 1999. This may be related to the Kyoto Agreement and the subsequent pursuit of low-CO_2 emission fuels such as H_2. A notorious rise above the trend is also evident after 2015, likely correlated with the Paris Agreement.

As previously mentioned in this report, H_2 is a CO_2 non-emitting fuel; however, the process of gasification involves steps that emit CO_2. Therefore, it is worth searching for technologies that minimize emissions through carbon capture (blue) or that do not emit at all (green).

In line with this, an additional literature search was performed using keywords associated with the various "colors" of H_2 production types. The results are illustrated in **Figure 14**Error! Reference source not found..

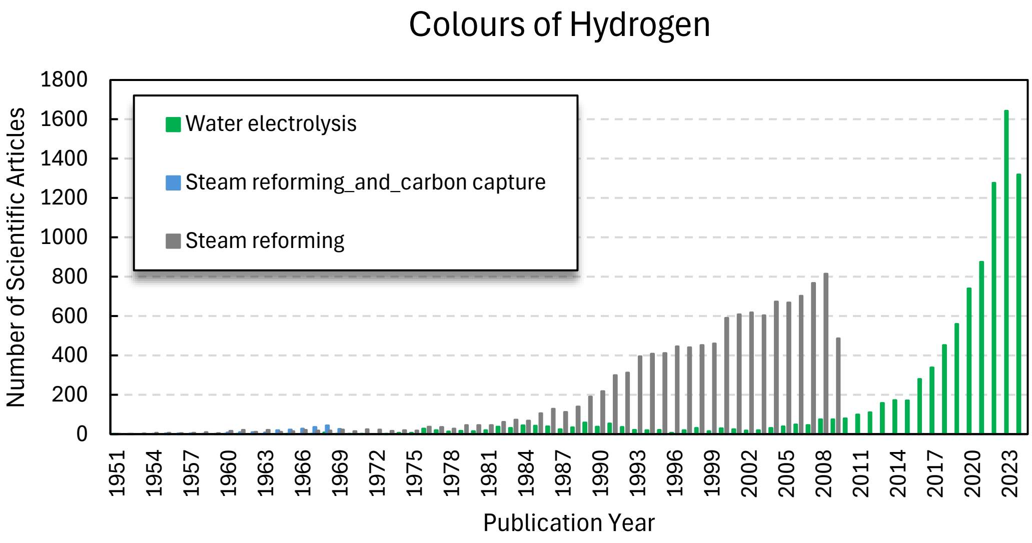


Figure 14. Number of scientific articles grouped by "color" of Hydrogen, over the years.

Water electrolysis, the main representative of green hydrogen production, has gained significant attention in recent years, as evidenced by a notable increase in literature production, exceeding 1 500 in the past year alone. This upward trend in academic interest indicates a concerted effort within the scientific community to advance this technology, which is anticipated to contribute substantially to achieving more sustainable hydrogen production methods.

Water electrolysis may be divided into PEM and alkaline, with the latter further divided into conventional and AEM. We performed a brief analysis of the articles and patents of each type, whose keywords and results are displayed in Table 2 and Figure 16. Solid oxide is also a type of electrolysis, but it was covered early in this chapter.

Table 2. Keywords selected for the search of different types of electrolysis: PEM, alkaline (conventional) and AEM

Keywords	Number of Patents found	Number of Articles found
("water electrolysis" AND (PEM OR "proton exchange membrane" OR AEM OR "anion exchange membrane" OR "alkaline electrolysis")) AND "hydrogen production"	562	1073
("water electrolysis" AND not (PEM OR "proton exchange membrane" OR AEM OR "anion exchange membrane" OR "alkaline electrolysis")) AND "hydrogen production"	3 614	4 021
"water electrolysis" AND (PEM OR "proton exchange membrane") AND "hydrogen production"	446	785
("water electrolysis" AND (AEM OR "anion exchange membrane") AND "hydrogen production")	59	262
("water electrolysis" AND "alkaline electrolysis" AND not (AEM OR "anion exchange membrane") AND "hydrogen production")	81	122

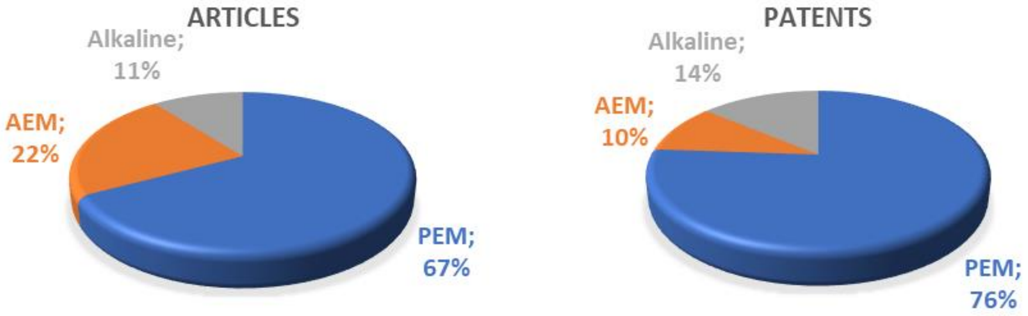


Figure 15. Articles and Patents divided by type of electrolysis : PEM, alkaline (conventional) and AEM. Alkaline refer to conventional alkaline electrolysis (without an anion exchange membrane).

The 1st line and 2nd lines of Table 2 display the number of patents/articles related to water electrolysis explicitly mentioning a specific type of electrolysis (PEM, AEM or conventional alkaline), or not mentioning, respectively. By comparing them, we may say that there is a large quantity of documents that do not mention the type (considering this classification).

Despite this, we made an attempt to divide by type, the documents that have the information to do so. Based on the results, PEM seems to be the most frequent type found in both articles and patents. Regarding AEM and alkaline electrolysis, the first seems to be more cited in articles, but the latter is more frequently found in patents. This may reflect an effort to develop anion exchange membranes (by research), while in practice conventional alkaline electrolysis is still more used.

3 Green Hydrogen Storage

Hydrogen storage is a critical aspect of utilizing green hydrogen as a clean energy carrier. Various methods and technologies are available for storing hydrogen, each with unique characteristics suited to different applications. This chapter covers various hydrogen storage methods, including compressed gaseous storage, liquid hydrogen storage, salt caverns, depleted oil and gas fields, aquifers and chemical methods. It outlines the benefits and challenges of each method, highlighting their suitability for different applications and scales.

3.1 Tank Storage Methods

Hydrogen can be stored using various tank storage methods, each with specific conditions and requirements. Table 3 compares the attributes of compressed hydrogen storage and liquid hydrogen storage, highlighting key factors such as pressure, temperature, energy requirement, energy density and tank features.

Table 3. Hydrogen Storage Parameters and Energy Requirements [27] [28] [29].

State	Temperature (°C/K)	Pressure (bar)	Density (kg/m³)	Energy Content (kWh/m³)	Energy Requirement (kWh/kg)	Tank features
Compressed Gas	15/288	150	12.6	420	2 – 3.6	Composite materials (*e.g.* carbon fibre-reinforced polymers) for strength and durability
	15/288	350	29.5	980	2.6 – 4.4	
	15/288	700	59	1,970	3.3 - 5.1	
Liquid	-253/20	1-5	71	2,370	8 - 12	Cryogenic insulation to maintain low temperatures and prevent boil-of

Compressed hydrogen storage involves compressing hydrogen and storing it in high-pressure tanks, typically at pressures ranging from 150 to 700 bar. Hydrogen storage at pressures of 150 to 300 bar is predominantly used for stationary applications due to their lower gravimetric densities. Stationary hydrogen storage systems can accommodate larger volume tanks, which are less of a constraint compared to mobile applications. In contrast, mobile applications require higher pressures, typically between 350 and 700 bar, to achieve higher gravimetric densities necessary for efficient space utilization and weight management in vehicles [27].

The tanks used for storage are made from advanced composite materials like carbon fiber-reinforced polymers, ensuring both strength and durability. This method benefits from simplicity and a well-established technology base, with infrastructure already in place for various applications, including fuel cell vehicles. Compression- technology is mature, making it widely accepted and understood within the industry. However, compressing hydrogen to such high pressures requires significant energy, ranging between 2-6 kWh/kg. The high-pressure storage also poses safety risks, necessitating robust and expensive pressure vessels to mitigate the potential for leaks and explosions. These tanks must adhere to strict safety standards and undergo rigorous testing to ensure their integrity and safety in various conditions [27, 28].

Liquid hydrogen storage involves cooling hydrogen to cryogenic temperatures, below -253°C, to convert it into a liquid state, which is then stored in insulated, cryogenic tanks [30]. This method offers a higher energy density by volume when compared to compressed hydrogen (see Table 3), making it particularly suitable for applications requiring high energy density, such as aerospace. However, the liquefaction process is highly energy-intensive (as shown in Table 3), and generally requires a very large scale to be cost-effective. The ability to store hydrogen in a liquid form allows for more compact storage solutions, which is crucial for space-limited applications. However, the liquefaction process is highly energy-intensive. Moreover, maintaining these low temperatures requires advanced insulation systems to prevent boil-off losses, adding to the complexity and cost. Safety concerns are also significant, as handling liquid hydrogen involves risks associated with extreme cold, including material brittleness and potential frostbite hazards. Despite these challenges, the high energy density of liquid hydrogen makes it an attractive option for specific high-demand applications [27, 28, 31].

3.2 Underground H_2 Storage Methods

Underground hydrogen storage (UHS) methods involve storing hydrogen in large underground formations, such as depleted oil and gas fields, salt caverns, and aquifers. These methods offer the potential for large-scale and long-term storage of hydrogen. Under the REPowerEU plan, Europe targets 10 million tonnes (Mt) of domestic hydrogen production and 10 million tonnes (Mt) of hydrogen imports by 2030, totalling 772 TWh [32]. To achieve this, the EU aims to scale up hydrogen storage to a capacity of 100 TWh by 2030, leveraging existing geological structures to provide energy security to the European region and reduce its dependency on fossil fuels [32].

Table 4 shows a comparison of different underground storage types for hydrogen, detailing their geographic distribution, energy storage capacity, discharge time, pros, cons, and pressure ranges.

Table 4. Underground Hydrogen Storage Methods - comparison [32], [33], [34]

Storage Type	Geographic Distribution (Europe)	Energy storage Capacity (TWh), Europe	H_2 Discharge time/withdrawal time (Europe)	Pros	Cons	Pressure (bar)
Depleted Oil and Gas Fields	North Sea, onshore in multiple countries	Up to 20	1 to 12 months	Established infrastructure, Extensive geological data, large storage volumes	Potential leakage from old wells, high monitoring and maintenance costs, contamination	90 - 200
Salt Caverns	Northern and Central Europe	Up to 5	1 hour to 1 month	High impermeability, Suitable for high-pressure storage, high purity	Limited geographic distribution, high development costs	40-250
Liquid Aquifers	Distributed, varies by country	Up to 4	2 to 3 months	Widespread availability, Large potential capacity	Risk of water contamination, low discharge time	80-100 [9]

3.2.1 Depleted Oil and Gas Fields

Depleted oil and gas fields offer significant storage capacities for hydrogen, up to 20 TWh per field in Europe [32]. By repurposing existing geological formations previously used for hydrocarbons, these fields can utilize established infrastructure, such as wells and pipelines, to provide a cost-effective solution in regions with a history of oil and gas extraction. Their primary advantage is the large storage capacity and well-characterized reservoirs due to extensive previous use. However, challenges include potential variations in hydrogen purity due to residual hydrocarbons and the need to ensure the reliability of the cap rock to prevent leaks. Additional purification processes are necessary to achieve the required hydrogen purity [34] [35].

3.2.2 Salt Caverns

Salt caverns offer a highly effective and secure method for large-scale underground hydrogen storage. These caverns are created in geological salt formations through a process called solution mining, where water is injected to dissolve the salt, creating large underground cavities [36, 37]. Due to their crystal structure, the impermeability of salt formations provides excellent natural sealing properties that prevent gas leaks and ensure minimal loss over time [36]. The self-sealing nature of salt, which can seal minor cracks and fissures, maintains the integrity of the storage cavern, making salt caverns particularly reliable for long-term hydrogen storage while preserving high purity levels due to minimal interaction between hydrogen and salt.

Despite high initial costs and geographical limitations, the long-term storage potential, quick discharge time (less than 1 hour), high purity levels, and safety advantages make salt caverns an attractive option for the hydrogen economy [32]. In Europe, particularly in Germany and the Netherlands, extensive research and exploration are underway to utilize salt caverns for hydrogen storage as part of broader renewable energy strategies [32].

Furthermore, integrating salt cavern hydrogen storage into highly variable renewable energy power systems helps to balance fluctuating supply and stabilize the grid, while supporting the transition to a low-carbon economy [38]. Advances in drilling and solution mining technologies are expected to reduce costs and environmental impacts, making salt caverns more economically viable and environmentally sustainable for large-scale hydrogen storage [30] [32].

3.2.3 Aquifers

Aquifers, or porous rock formations saturated with water, offer extensive hydrogen storage capacities at a lower initial cost. Widely available across many regions, they provide a more accessible option compared to other geological storage methods. The main advantage of aquifers is their broad availability and lower development costs.

They provide moderate discharge flexibility, but the geological characteristics and the risk of hydrogen dissolution in water present potential challenges in containment and recovery [34] [35]. Aquifers require detailed hydrogeological assessments and careful management to prevent water contamination and ensure efficient storage. Displacing water with hydrogen must be managed to avoid impacting local water supplies and ecosystems. Advanced monitoring systems are essential to track hydrogen movement and detect potential issues [34].

3.3 Chemical Storage Methods

Hydrogen storage in chemical compounds such as metal hydrides, ammonia, methanol, and liquid organic hydrogen carriers (LOHCs) offers advantages for storage and transportation compared to gaseous hydrogen. Each carrier has distinct properties and challenges, making them suitable for different applications.

Metal hydrides

Metal hydrides are highly promising for hydrogen storage due to their ability to store hydrogen at high volumetric densities (up to 150 kg/m^3 in the case of Mg_2FeH_6 [39]. They store hydrogen through reversible chemical reactions. Desorption, or the release of hydrogen, is an energy-intensive process due to the strong chemical bonds within the hydrides. Typically, high temperatures are required, often between 120 - 300°C, depending on the specific metal hydride (e.g., MgH_2, $NaAlH_4$, Mg_2FeH_6, $LiBH_4$). This demands efficient heat management systems, as hydrogen desorption is crucial and requires both efficiency and safety [39] [40].

Ammonia (NH_3)

Ammonia is a well-established hydrogen carrier with a high hydrogen content (17.6 wt %) and can leverage existing infrastructure used in agriculture and industry. It is stored as a liquid under moderate pressures and temperatures, simplifying logistics. Hydrogen is released from ammonia via catalytic decomposition at high temperatures (400-500 °C) using catalysts such as ruthenium or nickel. However, ammonia's toxicity and the energy required for its decomposition pose environmental and safety challenges [41]. Additionally, if pure hydrogen is required, purification technologies must separate H_2 from the co-produced N_2. Also, additional storage must be necessary to store the produced N_2 [42].

Liquid Organic Hydrogen Carriers (LOHCs)

LOHCs are organic compounds capable of absorbing and releasing hydrogen through chemical reactions. Hydrogenation of LOHCs typically occurs at temperatures between 50 to 250°C and pressures of 10 to 70 bar, while the endothermic dehydrogenation process occurs at elevated temperatures between 200 to 450°C [43]. The main challenges with LOHCs include the high energy requirements for dehydrogenation and the potential loss of LOHC material during cycles [42].

Methanol (CH_3OH)

Methanol can be produced by reacting hydrogen with carbon dioxide over copper-based catalysts at temperatures between 200 to 300°C and pressures between 35 to 100 bar [44, 45]. It is a liquid at standard conditions, simplifying storage and transport. Like ammonia, methanol can be used directly in industry, or can be dehydrogenated to release hydrogen. The dehydrogenation process to release hydrogen from methanol involves steam reforming at high temperatures (250 - 300°C) [46]. In order to be sustainable, the CO_2 used for methanol production should come from biogenic or atmospheric, i.e., non fossil, sources. This could present challenges for the scalability and/or cost-effectiveness of methanol as a hydrogen carrier.

Each of these hydrogen carriers offers benefits and faces specific hurdles that must be optimized for practical use. Their high energy densities make them important in the evolving hydrogen storage landscape. Further research and development are essential to address their respective challenges and enhance their economic viability and efficiency.

3.4 Comparative Review of Solutions

Technology Maturity

Hydrogen storage technologies exhibit varying degrees of maturity. Compressed and liquid hydrogen storage methods are among the most established, with widespread industrial acceptance and a solid technological foundation. Geological storage methods, such as salt caverns and depleted oil and gas fields, are also well-developed, with salt caverns demonstrating long-term reliability and large-scale capacity. Conversely, aquifer storage is less mature, requiring more research to ensure effective and safe hydrogen storage. Chemical storage methods, including ammonia, LOHCs, methanol, and sodium borohydride ($NaBH_4$), range from well-established (ammonia) to emerging technologies ($NaBH_4$), with ongoing advancements needed to enhance their efficiency and safety.

Efficiency

The efficiency of hydrogen storage methods varies widely based on the energy required for storage and release processes. Compressed hydrogen storage is efficient for stationary applications but less so for mobile uses due to the high energy needed for compression and the associated safety risks. Liquid hydrogen storage offers higher energy density, making it suitable for space-constrained applications, though the liquefaction process is energy-intensive. Geological storage methods, particularly salt caverns, provide highly efficient large-scale storage with minimal leakage and natural sealing properties. Chemical storage methods present mixed efficiency profiles: while they facilitate easier transport and storage, the energy demands for hydrogen release, particularly for LOHCs and ammonia, can be significant. Methanol and $NaBH_4$ show promise but need further optimization to improve their overall efficiency.

Sustainability

Sustainability considerations for hydrogen storage methods encompass environmental impact, safety, and the ability to integrate with existing infrastructure. Compressed and liquid hydrogen storage face challenges due to their energy-intensive processes and associated safety risks. However, they are supported by well-established safety standards and testing protocols. Geological storage methods, especially salt caverns, are highly sustainable due to their natural sealing capabilities and minimal environmental impact, though they are geographically limited. Chemical storage methods offer significant advantages in utilizing existing transport infrastructure and providing high energy densities. However, they also present sustainability challenges, such as the toxicity of ammonia and CO_2 emissions from methanol dehydrogenation. Sodium borohydride holds potential for sustainable storage, but its technology is still under development, requiring further evaluation of its environmental impact.

Summary

Hydrogen storage methods vary significantly in terms of technology maturity, efficiency, and sustainability. Compressed and liquid hydrogen storage are technologically more mature, but face challenges related to efficiency and environmental impact. Geological storage methods, particularly salt caverns, offer high efficiency and sustainability for large-scale storage but are limited by geographical availability and initial costs. Chemical storage methods, including ammonia, LOHCs, methanol, and sodium borohydride, provide promising solutions for easier transport and storage, though they require further development to overcome energy and environmental challenges. Each method presents unique benefits and hurdles, requiring continued research and development to optimize their practical use in the evolving hydrogen economy.

In conclusion, hydrogen storage is integral to the effective use of green hydrogen as a clean energy source. This chapter has explored diverse storage methods, each with specific advantages and challenges. Compressed and liquid hydrogen storage offer high energy density time efficient solutions. Underground storage methods, such as depleted oil and gas fields, aquifers, and salt caverns, show promise for large-scale and long-term storage. Salt caverns offer excellent impermeability, high purity levels and quick discharge times, making them highly reliable and efficient. Chemical storage using metal hydrides, ammonia, methanol, and LOHCs provides practical transportation solutions despite some environmental and safety considerations.

4 Green Hydrogen Distribution

Today, hydrogen is mainly produced close to where it is used. The distribution process plays a crucial role in effectively designing renewable **Hydrogen Supply Chains**. Identifying the most efficient and effective transportation mode is directly connected to the physical states of the hydrogen and the spatial and temporal hydrogen demands, *i.e.*, the travel distance from the production site to the end-users and the hydrogen demand profile, respectively. As production volumes and transport distances expand to meet increasing demand, significantly more hydrogen infrastructure will be needed [47].

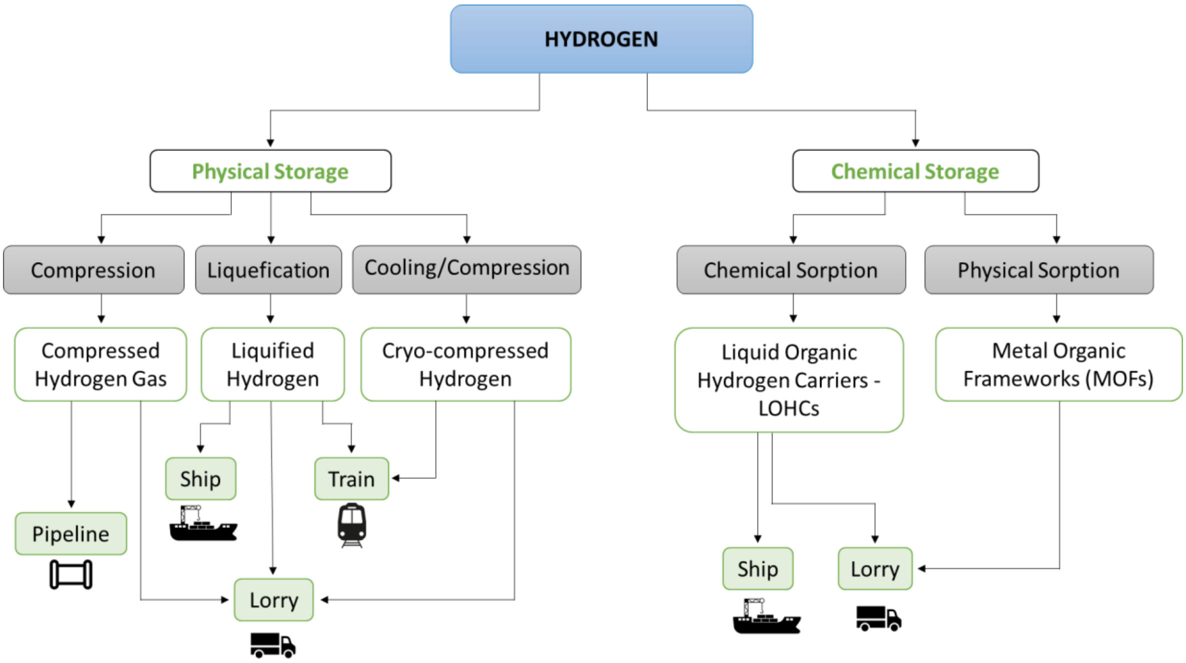


Figure 16. Hydrogen Storage and Distribution options, adapted from [48].

The transportation of hydrogen commonly relies on physical storage methods, where it is predominantly distributed either as a **compressed gas** or in its **liquid state** [48]. As depicted in Figure 16, the main transmission methods for compressed hydrogen gas are via **high-pressure pipelines**, **tube trailers**, or **railway tube cars**. In contrast, liquid hydrogen is mainly distributed via the existing **railway system**, **roads**, or **ships**. Compressed gas is preferred for shorter distribution distances and a smaller scale of hydrogen demand, while liquid hydrogen is considered as more viable for increased demand and distance due to its higher density. Another means of transport, less usual, is cooling and compressing H_2 – cryo-compressed H_2. Instead of physical storage methods, it is also possible to chemically bind H_2 to other substances or trap it inside Metallic Organic Frameworks (MOFs). Regarding means of transportation, pipeline transportation is generally the cheapest option for H_2 distribution in distances less than 1500 km. Lorries are more suitable for short distances and low volume of H_2, and shipping becomes more economically viable for voyages above 5000 km.

4.1 Land, Fluvial, Maritime, and Rail

The transportation of hydrogen is intricately linked to its storage methods. Over the years, several advancements and innovations have facilitated the transportation and distribution of hydrogen through different avenues: **land**, **fluvial**, **railway**, and **maritime** transportation. The choice between these options depends on the hydrogen demand, overall cost, and transportation distance. Onshore and offshore pipelines remain the preferred means of transporting hydrogen. They are the most efficient and cheapest way to transport it to distances under 1500 km and capacities of 200 ktpa (kilotonnes per annum) [49], while for longer distances, **land**, **fluvial**, **railway**, and **maritime** transportation can become preferential. Table 5 compares these types of transportation based on their overall cost.

Table 5. Comparison of Transportation methods.

Type of transport	Overall cost (€/kg H_2)	References
Land	CGH_2: 0.65 LH_2: 3.66	[50]
Fluvial / Maritime	LH_2: 0.03	[50]
Railway	Not Found	-

Maritime and Fluvial transportation

For **distances above 1500 km**, maritime and fluvial transportation may be the **cheapest alternative**. To ensure that maritime and fluvial transport is simple and cost-effective, hydrogen should be distributed as liquefied hydrogen (LH_2), coupled to a liquid organic hydrogen carrier (LOHC), or converted into a synthetic hydrocarbon fuel [49].

The cost of shipping by sea grows only modestly with distance, even when accounting for the non-transport components. This way, the larger the distance, the more attractive shipping is compared to other options. The International Energy Agency (IEA) estimates that future specialized H_2 tankers, with a capacity of 11 000 tonnes, could cost up to 328 million € [50].

Some challenges faced by maritime transportation refer to the possibility of ships returning with their vessels empty if no high-value liquid is being transported in the opposite direction, increasing the overall cost of transportation [50].

In February 2022, the **Hydrogen Energy Supply Chain project** initiated the development of the necessary infrastructure to transport liquid hydrogen by sea. This Australian project integrates a loading facility, a hydrogen liquefaction facility, and a liquid hydrogen storage container (41 m^3). 75 tonnes of liquid hydrogen are regularly transported to Japan in the world's first-ever maritime carrier, Suiso Frontier [49, 51].

Hydrogen can also be incorporated into an organic molecule, producing a LOHC with properties similar to oil products. LOHCs do not require cooling and can be transported and stored using the existing oil infrastructure, with the hydrogen being extracted from the LOHC at its destination [49, 50]. The Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD) project 2019 commissioned a hydrogenation demonstration facility in Brunei Darussalam to transport hydrogen as LOHC to a gas turbine at the TOA Oil Co Keihin refinery in Japan. There, it was dehydrogenated to separate hydrogen and toluene, the latter being shipped back to the exporting terminal to be used again as a hydrogen carrier. LOHC was transported in 24 m^3 ISO tank containers mounted on container ships [49].

Railway transportation

Another method of transporting H_2 involves utilizing the established **railway** systems of each country. This approach primarily facilitates the distribution of hydrogen from ports to inland regions of countries more quickly and efficiently. The hydrogen is mostly left bound in a liquid state, so standard tank wagons can be used to carry it by rail. German company DB Cargo developed this solution jointly with energy suppliers and tested it throughout the entire country, increasing the possibility of hydrogen distribution. The challenge with this method of transportation is that some countries do not have the necessary railway infrastructure to ensure proper distribution [52].

Land Transportation

Lorries can transport hydrogen in any state, and although this method of transport is **more expensive** than pipelines, their **versatility** makes them useful in places with low H_2 demand for short distances. The two leading modes of H_2 transport by land include compressed gas (CGH_2) and liquid hydrogen tankers (LH_2) [50]. LOHC remains in the early stages of commercialization for road transportation.

CGH_2 lorries are the most common alternative and can carry pressurized H_2 in vertical containers or long horizontal tubes. At their destination, the empty containers can either be exchanged for full ones or replaced. Only up to 1100 kg of CGH_2 can be transported (at 500 bar) in a single container, giving it the lowest H_2 carrying capacity of all trailer technologies. In practice, this capacity is rarely achieved due to the existing safety regulations. LH_2 cryogenic tanker lorries are commonly used for journeys of up to 4000 km, being able to carry 4000 kg of H_2. The energy required to insulate each vehicle increases the cost of this mode of transportation. It is also unsuitable for any greater distances since the H_2 heats up, leading to a rise in pressure [50, 53].

Compared to compression, the high cost of liquefaction makes LH_2 lorry transportation more expensive for shorter distances. However, as LH_2 lorries can distribute 5 to 12 times more LH_2 than CGH_2, thus the unit cost of transport becomes lower. This way, at distances greater than 350 km, LH_2 lorry transportation becomes competitive with CGH_2 for land transportation [50].

4.2 Gas Network

The **cost** of building exclusive hydrogen distribution pipelines from scratch is a massive deterrent to its viability, as it implies large-scale operations and infrastructure that would need high investments [54]. Hydrogen can be more challenging than other gases due to its low density, which requires more powerful compressors to keep it flowing at an acceptable rate. It also leaks easily from conventional steel pipes due to its molecular size, or embrittles the metal, a concern given its flammability and ease of ignition [55].

An alternative suggested is to slowly convert the existing gas network, keeping H_2-exclusive pipelines to specialized applications while blending increasingly higher amounts of hydrogen in the conventional gas composition for general use [56]. This would provide enough time to gradually adapt the pipelines to green H_2 and, eventually, other sustainable fuels, such as biomethane [57]. While there are benefits to this approach, most notably the lower initial investment cost, caution must be taken with the specific blend of hydrogen due to the possibility of embrittling pipes, gas escape, and additional purification costs to the end-user [58].

As of 2022, only around 1600 miles of pipeline are exclusively used for H_2 delivery in the USA, distributed in North California, Illinois, and the Gulf Coast [59]. According to the US Department of Energy, most are dedicated to providing for large-scale users, such as gas, petroleum refineries, and chemical plants. The National Clean Hydrogen Strategy and Roadmap draft from 2022 explicitly mentions the gradual conversion of existing gas transmission networks via blending of increasing amounts of H_2, aiming towards standardizing this approach by the end of the current decade [60].

The British project HyDeploy has already tested supplying a blend of up to 20 % H_2 to Keele University Campus for 18 months (2019 to 2021) and Winlaton Village for 10 months (2021 to 2022). This change resulted in an expected price increase of 6 % and 8 % for domestic and industrial users in the UK, respectively, while having no perceived negative impact on the gas network and appliances, which encouraged the researchers to expand tests to industrial environments [61]. The UK government has also committed to supporting these endeavors to supply blended gas to some private locations, possibly extending to other sectors of its current network [62].

Another European project directed toward the conversion of existing gas pipelines into H_2-appropriate ones is **ready4H_2** [63]. Different strategies are being employed as a multi-national initiative, including constructing new pipelines exclusive to hydrogen in the industrial environment during the early 2020s. The goal for the late years of this decade is to blend small amounts (2 % - 5 %) into natural gas for most of the network while also implementing green methane as an alternative to some applications [63].

A study by Nugroho *et al.* [64] predicts operating costs of around 7 billion €/year for pipeline distribution of centralized H_2 production in Germany. The lower electricity costs to operate electrolyzers compared to local production make it around 1 billion €/year cheaper than smaller decentralized production, balancing the investment needed for more pipelines. In November 2023, the German gas operating company FNB Gas proposed a draft for the core hydrogen network, predicting an investment of 19.8 billion €. Of the 9700 km of pipeline proposed, around 60 % would be converted to a gas network [65]. Another project in Germany is the conversion of a local gas network located at Bad Lauchstädt while also taking advantage of the natural gas caves to store produced hydrogen. The goal is to supply the Leuna Chemical Park with green hydrogen produced locally [66].

At a pan-European level, the European Hydrogen Backbone (EHB) is coordinating various projects to secure **five hydrogen corridors** to balance supply and demand in Europe. One of these, **"Southwest Europe & North Africa"**, is of particular interest to the **HYDEA project**, as it includes Portugal, Spain and France, represented by their Transmission System Operator (TSO) companies (Error! Reference source not found.) [67].

Table 6. Companies involved with the Southwest Europe Hydrogen Backbone.

Country	Company	Gas pipeline (km)
Portugal	REN-Gasodutos	1375
Spain	Enagás	12000
France	GRTgaz	32618
	Teréga	5100

Their partnership project, **H_2med**, is gearing up to construct two main pipelines to make up the hydrogen backbone for the Iberian Peninsula. CelZa line connects Celorico da Beira (Portugal) and Zamora (Spain) with an estimated length of 248 km, which will cost around 350 million € and transport up to 0.75 Mt of H_2. The other connection line would be an offshore one between Barcelona and Marseille (BarMar), destined to export green hydrogen produced in the Peninsula to France, whose backbone will be linked with Germany to supply northern Europe. This 450 km pipeline is expected to cost over 2 billion € and have a capacity of around 2 Mt. While initially coordinated among only

Portugal, Spain, and France, this project started receiving support from Germany in 2023 via the transmission system operator OGE, which oversees approximately 12000 km of pipeline network. The H_2 distribution line planned for this project is illustrated in Figure 17 [68].

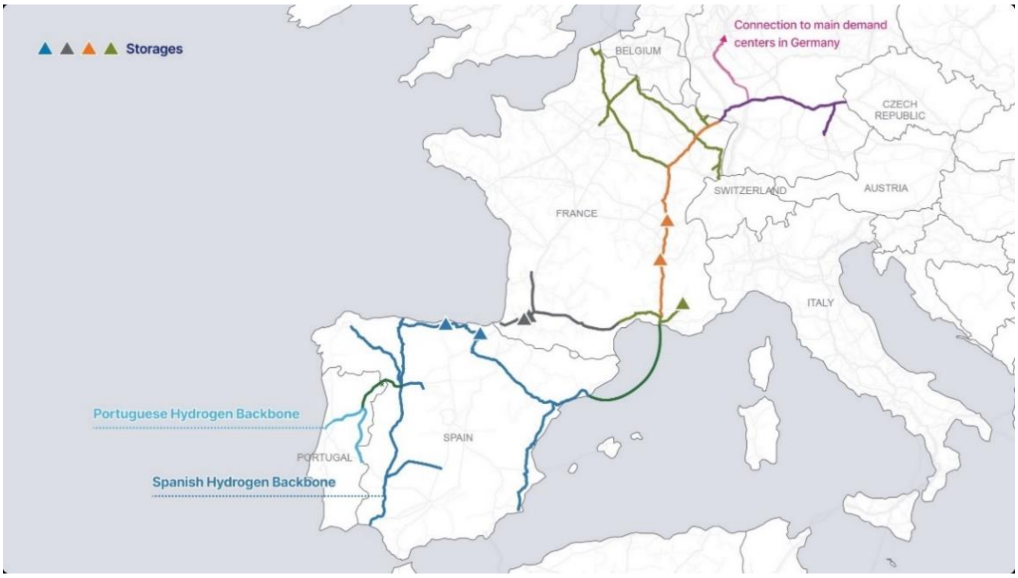


Figure 17. Map of the hydrogen backbone planned for H_2med. Special attention is directed to the connection between Portuguese and Spanish Hydrogen Backbones (CelZa line) and the one linking Spain and France (BarMar line) [68].

5 Green Hydrogen End Uses and Applications

5.1 Transportation

Green hydrogen may play a role in the decarbonization of key segments of the transport sector. **Electric vehicles** powered by **fuel cells** are a key example. The long-haul road transport of freight is another case where conventional battery charging would be impractical and where H_2 may find application. Green hydrogen can also be combined with nitrogen (N_2) or sustainably sourced CO_2, paving the way for producing **versatile synthetic fuels** such as ammonia and methanol. This offers sustainable solutions for the shipping and aviation industries [69], as shown in Figure 18.

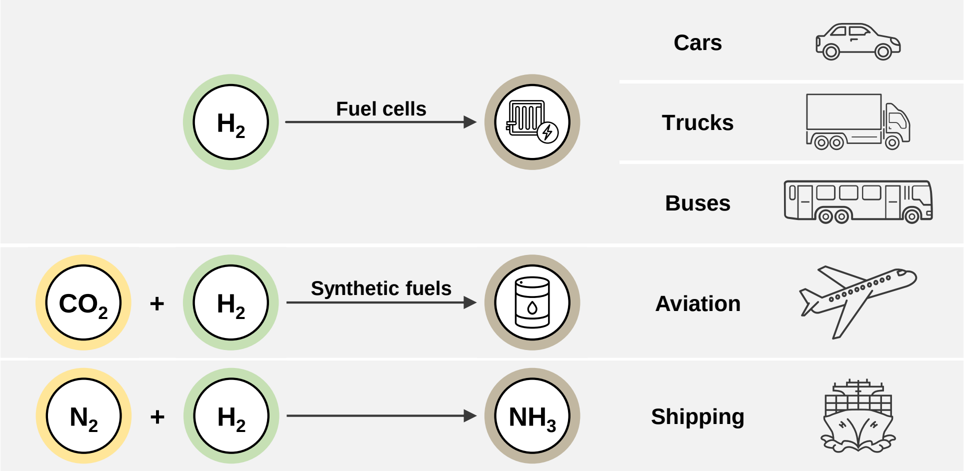


Figure 18. Different end uses and applications of green hydrogen in the transportation sector.

Fuel cells are increasingly recognized as **efficient and non-polluting power sources** with significantly higher efficiency and energy density. As a result, fuel cells are emerging as viable technologies for various sectors, including **transportation** [70]. Fuel cells are systems that can operate at different temperatures and produce electricity, water, and heat from a chemical energy source, such as hydrogen, using a catalyst [71]. With **zero carbon emissions**, fuel cell technology is ideal for replacing combustion engines in lightweight vehicles. Moreover, in the transportation industry, vehicle manufacturers and the research community have proposed fuel cell cars to solve the energy autonomy issues that plagued battery-electric vehicles in the past [72].

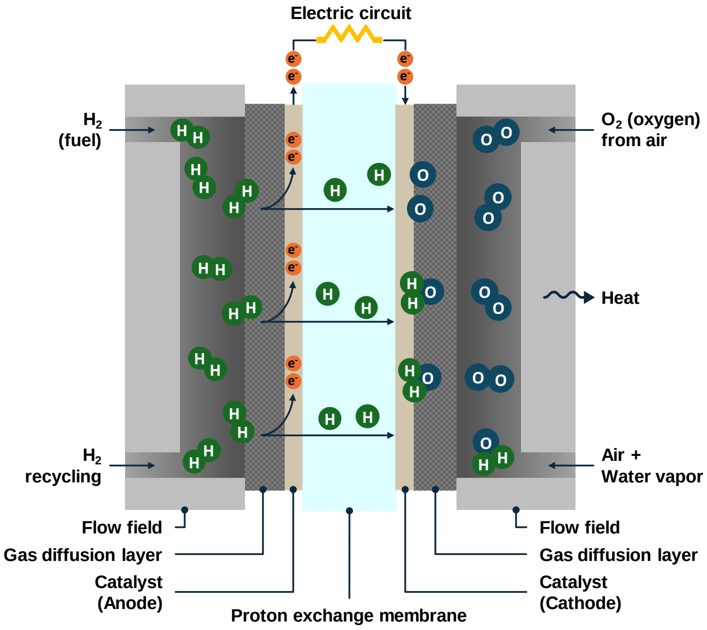


Figure 19. Proton exchange membrane fuel cell (PEMFC) schematic diagram.

Several types of fuel cells have been developed, with the classification generally based on the electrolyte material used. Proton exchange membrane fuel cells (PEMFCs), solid oxide fuel cells (SOFCs), phosphoric acid fuel cells (PAFCs), alkaline fuel cells (AFCs), and molten carbonate fuels (MCFCs) are examples of different types of cells. Among these, **AFCs** and **PEMFCs** are classified as **low-temperature fuel cells**, PAFCs as **medium-temperature** fuel cells, and MCFCs and SOFCs as **high -temperature fuel cells**. Fuel cells find applications in the commercial sector and are also a focus of ongoing research for further development [71].

PEMFC is one of the most widely used fuel cell types, employing hydrogen as fuel and oxygen as oxidant, Figure 19. The PEMFC system comprises two compartments, the anode and the cathode, separated by a proton exchange membrane. A PEMFC generates electricity by **splitting hydrogen** into protons and electrons at the anode, while oxygen at the cathode combines with protons and electrons to form water [73, 74]. As a result, **water and heat are the only byproducts** of this process, emphasizing the **environmental friendliness** of PEMFCs [71].

In the upcoming decades, fuel cells are expected to experience significant growth in the transportation sector [75]. This forecast is primarily due to their modularity, superior efficiency (>70 %), and the increased driving range of the most recent versions. In addition, the rising demand for large commercial vehicles and passenger cars is expected to boost the market for fuel cells as a superior alternative to conventional internal combustion engines (ICE) [71].

Buses are considered the **most promising vehicle type** for large-scale implementation of fuel cell technology in the automotive industry. They offer several advantages over other vehicles, including their power needs, operation schedule, space availability, and accessibility to refueling stations. Due to their large size, buses can readily store substantial amounts of hydrogen onboard, typically on the roof area [76]. A standard **PEMFC** stack can currently generate up to **200 kW** of power and is often used in transit buses ranging from 9 m to 12 m long [71, 77, 78]. While PEMFCs hold great promise, they face **several challenges** that must be addressed for widespread adoption. These include the high cost of platinum-based catalysts, durability concerns under harsh operating conditions, and water and heat management within the cell. Thus, ongoing research focuses on developing efficient and durable membranes, electrodes and reducing the platinum content [78].

Hydrogen-powered aircraft are also pointed out as sustainable alternatives for the aviation sector. However, this implementation requires **significant design changes in aircraft**, and given the slow fleet renewal cycles, the short-term implementation level required would be too costly for companies. Thus, the production of **sustainable aviation fuels** (SAF) to replace jet kerosene emerges as the best short- and medium-term solution for achieving future emission goals [79]. One option is synthetic fuels known as **power-to-liquid** (PtL) or **e-fuels**, whose production relies on the Fischer -Tropsch (FT) or the **methanol** pathways. Both options require a supply of sustainable CO_2 derived from the capturing process and green H_2 obtained from water electrolysis. The only difference lies in how hydrocarbons are synthesized and upgraded into fuel. The FT pathway requires syngas production, forcing an additional step of reducing CO_2 to CO, for instance, by the reverser water gas shift (RWGS) reaction [80]. The methanol route emerges as an alternative, where CO_2 is directly converted to methanol. However, technical challenges still need to be addressed [81]. After obtaining methanol from any of these routes, it can be dehydrated to dimethyl ether (DME), which is subsequently converted into light olefins. These olefins then undergo oligomerization and hydrotreatment, ultimately yielding the final product [79, 80].

These synthetic fuels are deemed a **sustainable long-term option** owing to their **low lifecycle emissions** and **minimal environmental impact**. Being chemically identical to fuels currently used in combustion engines, they can leverage existing infrastructure and logistical networks. Nevertheless, they still represent a niche fuel type, requiring overcoming significant challenges for large-scale development and deployment. These challenges include scaling up renewable energy production, attaining cost competitiveness, and garnering widespread support [82, 83].

The **maritime sector** is another critical area for hydrogen's potential impact. Currently, ships are mainly fueled by fossil fuels, and the International Maritime Organization (IMO) estimates that, in 2018, they accounted for 2.9 % of global CO_2 emissions, a value predicted to increase to 15 % by 2050 [84]. Reducing these emissions is thus critical for limiting global anthropogenic greenhouse gas (GHG) emissions. In this context, different studies forecasted **ammonia as a key marine fuel** for future maritime transportation, with projected adoption rates ranging from 15 % to 95 % for NH_3-powered ships [85-87].

Ammonia is commonly synthesized via the Haber-Bosch process, developed at the end of the 19th century. This approach requires a high temperature (400 – 600 °C) and pressure (20 – 40 Mpa) and takes place in the presence of an iron catalyst. However, given the growing interest in **green ammonia** production (production using renewable energy), several new processes are being developed to boost efficiency and cut production costs [88]. One obvious path ahead is to lower the temperature and pressure required for the synthesis by developing new catalysts, with ruthenium-based compounds emerging as a prime choice [89, 90]. Despite encouraging results, a major challenge lies in the fact that ruthenium alternatives are far more expensive than iron catalysts, as well as the investment needed to modify the existing infrastructure, including reactors. The advent of green hydrogen is expected to kick-start these changes [88]. Companies are starting to adopt renewable energy sources (RES) for hydrogen production, through electrolysis, and using it to synthesize NH_3 for trade and transport purposes. A notable example is the establishment of a 5 GW hydrogen/ammonia facility in Saudi Arabia. This endeavor is spearheaded by the NEOM Green Hydrogen Company (NGHC), a joint venture owned by ACWA Power, Air Products, and NEOM [91].

5.2 Heating and Power Generation

Green hydrogen can serve several purposes in **heating and power generation**. Hydrogen offers an **alternative to natural gas** in heating applications, providing a pathway to **decarbonize heating systems** in residential, commercial, and industrial settings. In power generation, hydrogen holds promise as a **clean fuel for electricity production** through fuel cells or combustion in gas turbines.

One of the key challenges of renewable energy, such as solar, wind, or waves, is its intermittent nature, which can lead to fluctuations in electricity supply and grid instability. Green hydrogen can act as a buffer when integrating renewable-based electricity into the grid by working as an **energy storage solution**. When renewable energy generation is higher than the demand, it can be converted into hydrogen by electrolysis and stored [92]. Most of the time, the secondary source considered to compensate for these fluctuations is of fossil origin, preventing the complete transition to a fully renewable system. In this case, green hydrogen can play the role of the secondary source. Stored hydrogen can be used to produce electricity, making up for the oscillations of other renewable sources, Figure 20 [93].

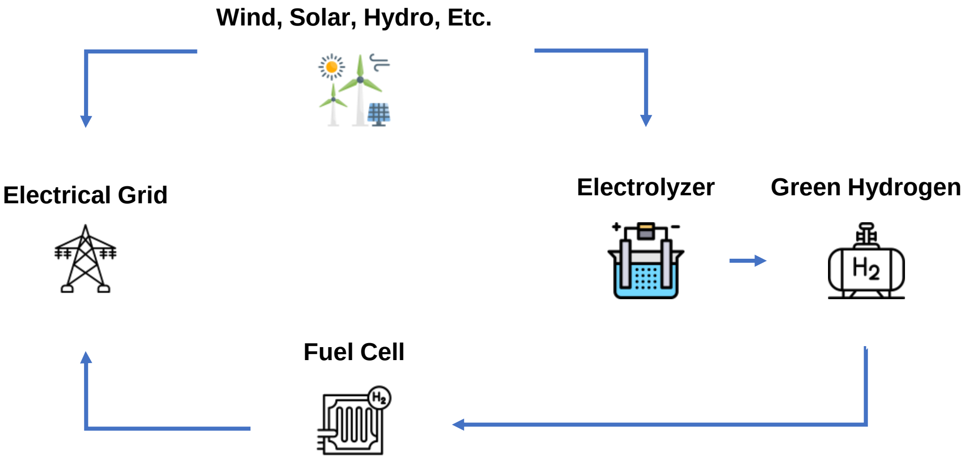


Figure 20. Backup hydrogen technology for renewable energy fluctuations.

The *NorthC* Data Centre in Groningen, Netherlands, was the first in Europe to use hydrogen as an **emergency backup generation**, confirming the potential of H_2 for energy storage. The Centre is equipped with a 500 kW fuel cell generator manufactured by the company Nedstack [49].

In 2021, a large-scale hydrogen fuel cell power plant opened in South Korea, one of the first to power the grid instead of just being a backup generator. It can produce up to 79 MW of power, relying only on hydrogen, Figure 21 [94].

Figure 21. Fuel cell power plant in South Korea [95].

Green hydrogen can **generate power** using a fuel cell. As previously mentioned, the cell produces electricity, water, and a small amount of heat by combining hydrogen and oxygen atoms. **Fuel cells** offer high efficiency and low emissions, making them **ideal for decentralized power generation** in buildings, remote locations, and transportation applications such as fuel cell vehicles. One of the advantages of hydrogen fuel cells is their **flexibility** regarding on-site applications: they can either be small and portable, applied to vehicles or electronic devices, or they can constitute entire power plants, providing electricity to locations that are not connected to the grid, Figure 22. For example, in Bridgeport Fuel Cell Park in Connecticut (USA), there is a single fuel cell with a capacity of 17 MW. At the same time, the California Institute of Technology in California (USA) has 10 fuel cells with 0.1 MW capacity each [96].

In Europe, HDF Company is developing a project to implement two plants of 10 MW each on the border of France and Germany. These plants will produce renewable energy by feeding green hydrogen to big scale- fuel cells, reaching a hydrogen consumption of 15 000 tons annually by 2030. It is estimated that 66 450 tons of CO_2 will be avoided annually by replacing coal-fired power generation with this technology [97].

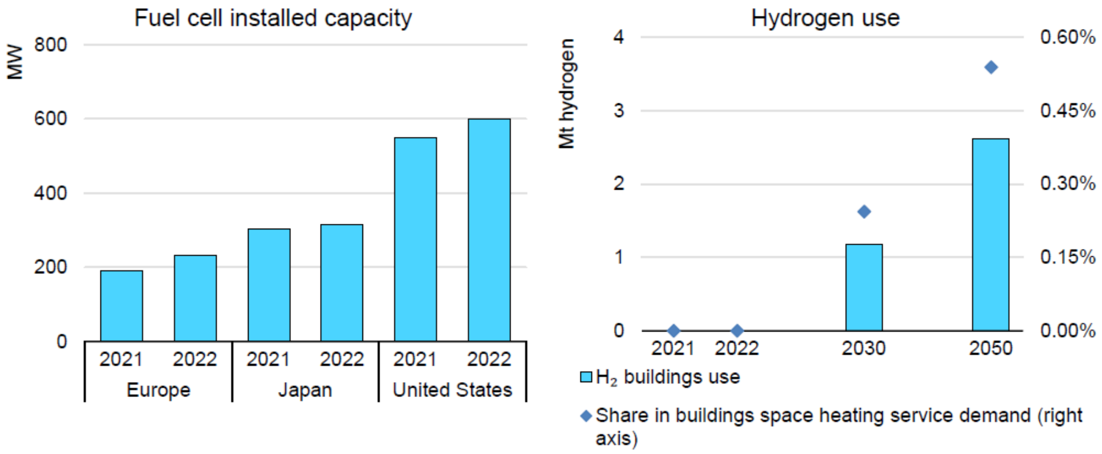


Figure 22. Fuel cell installed by region, 2021-2022, and hydrogen use in buildings in the Net Zero Emissions by 2050 Scenario, 2021-2050 [98].

Regarding heating, **replacing natural gas with hydrogen** in boilers, furnaces, and other heating appliances would reduce carbon dioxide emissions and other pollutants. This transition is crucial for meeting emissions reduction targets and combating climate change, as heating accounts for a substantial portion of global energy consumption and carbon emissions. Nevertheless, the contribution of hydrogen to the energy demand in buildings is negligible since the **energy losses** associated are quite high. Hydrogen can contribute to some niche targets, such as heating poorly insulated buildings connected to the gas grid in cold environments [98].

Demonstration projects for hydrogen applications in buildings are ongoing, with technologies and standards being prepared. Despite their integration depending on several factors, the demand for hydrogen in the building sector could reach 0.15 Mt of hydrogen by 2030. Compared with the sector's total energy demand, this value only accounts for 0.01 % [49].

Several projects, either ongoing or planned, aim to evaluate the use of pure hydrogen in buildings. Some examples include a demonstration house designed to be heated only using hydrogen in Stad Aan'T Haringvliet (Netherlands) [58]. Additionally, twelve inhabited historic homes in the Netherlands were connected to a hydrogen supply, and hydrogen boilers were installed to provide heating [99]. For future projects, a solar photovoltaic panel will be coupled to an electrolysis plant to produce green hydrogen that is expected to fully fuel a boiler in a hospital in Spain with pure hydrogen [100]. The Empa Institute in Switzerland is testing hydrogen-fueled stoves for cooking in areas connected to a hydrogen network [101].

Another pathway for power generation using green hydrogen is using it as **fuel for gas turbines**. Hydrogen gas turbines operate on the **combustion principle**, where hydrogen is burned in a high-temperature environment to produce hot gases. These gases expand and drive turbine blades, which spin a generator to produce electricity. Unlike conventional gas turbines fueled by natural gas, **green hydrogen combustion emits only water vapor as a byproduct**, making it a **zero-emission technology**. However, it can produce more NOx than natural gas [102].

In 2017, a 1 MW combined natural gas and hydrogen turbine demonstration plant was completed in Japan. The Hydrogen Cogeneration System started its trial run, followed by stand-alone testing. In 2018, the plant successfully supplied electricity and heat (steam and high-temperature water) to four nearby facilities using a cogeneration system fueled by 100 % hydrogen [103]. One of the key advantages of hydrogen turbines is their compatibility with existing infrastructure. Many gas turbines today are designed to operate on various fuels, including **hydrogen blends**. This means that with **minor modifications**, power plants can transition to using hydrogen as a primary or supplementary fuel.

Overall, integrating green hydrogen into heating and power generation represents a transformative shift towards a more sustainable and decentralized energy system. By harnessing the power of renewable energy to produce hydrogen, the reliance on fossil fuels can be reduced, mitigating greenhouse gas emissions and paving the way towards a cleaner and more sustainable energy future. However, **realizing the full potential of green hydrogen will require efforts** across policy, technology, and market development to overcome cost, infrastructure, and scalability challenges.

5.3 Industry

In 2022, **the industry consumed 53 Mt of hydrogen produced from fossil fuels**, 60 % was destined for ammonia production, 30 % for methanol, and 10 % for Direct Reduced Iron (DRI) in the iron and steel subsector. The hydrogen used nowadays is almost completely produced from fossil fuels at the facilities where it is used. If substituted by green hydrogen, it would reduce significantly the CO_2 emissions of these industries [98].

The primary uses of green hydrogen in the **chemical industry** are to produce **ammonia**, **fertilizers**, **methanol**, and **green steel**. Still, it has other applications, such as glass production, rocket fuels, and applications that leverage the physical properties of hydrogen [104].

The **ammonia industry**, in 2022, used about 32 Mt of hydrogen. In a conventional ammonia plant, hydrogen is produced by steam reforming of natural gas or coal. In contrast, in the production of green ammonia, hydrogen is produced through the electrolysis of water, and the nitrogen needed is obtained by an air-separation unit (ASU) [98].

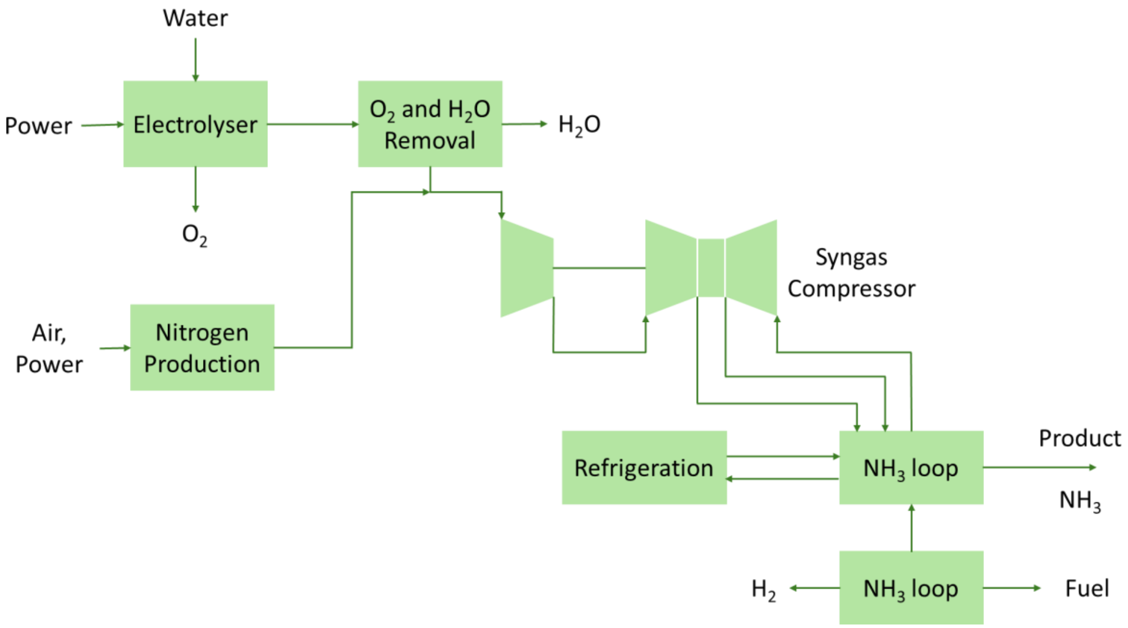


Figure 23. Process of green ammonia production, adapted from [105].

As shown in Figure 23, the hydrogen and nitrogen produced are combined to create the necessary H_2/N_2 mixture for ammonia synthesis. Afterwards, compressors and preheaters raise this mixture's temperature and pressure before entering the ammonia converter. Chemical equilibria in the converter limits the synthesis of ammonia. As a result, the unreacted gas is recycled to boost conversion, and a refrigeration cycle is utilized to separate the synthesis gas from the recycled stream [105].

Methanol production represented about 30 % of the hydrogen consumption in 2022, which is equivalent to around 16 Mt of hydrogen, and this value is expected to increase in the upcoming years. Methanol production can be more sustainable if green hydrogen and captured CO_2 are used, as shown in Figure 24. In this process, hydrogen is produced from water electrolysis and then fed into a reactor along with CO_2. Methanol and water are produced inside the reactor, and the water is recycled back to the electrolyzer [106].

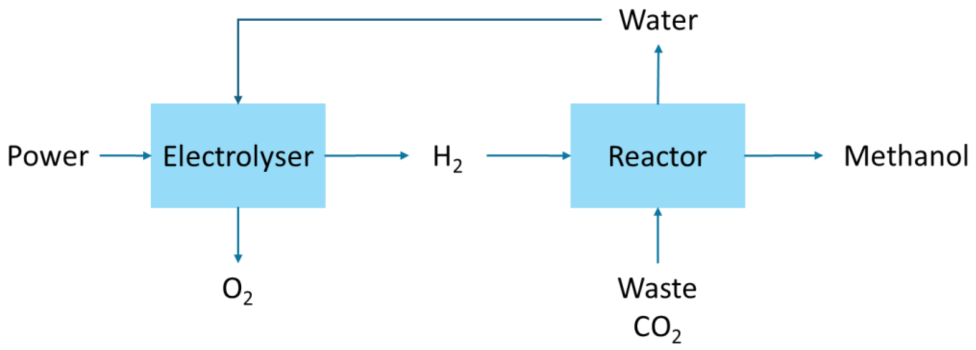


Figure 24. Process of green methanol production, adapted from [106].

As mentioned, green hydrogen can also replace fossil fuels in **steelmaking**. In conventional DRI technology, carbon monoxide and hydrogen derived from fossil fuels are used to chemically reduce iron ore for steelmaking. With some minor changes in the equipment, green hydrogen can be implemented in the process and **significantly reduce CO_2 emissions** [107]. The process modifications are represented in Figure 25.

Many projects planned for the upcoming years aim to apply this change. The **Power2Earth**, based in Sweden, aims to develop above 600 MW capacity of electrolyzers by 2028 [108]. The **Catalina Project**

(Spain) will produce 84 000 tonnes of green hydrogen per year [109, 110]. The **Unigel project** (Brazil) is expected to produce up to 100 000 tonnes of green hydrogen annually by 2027 [111].

The **primary obstacle** to using green hydrogen in industrial applications is the **higher costs**, including additional investments into hydrogen-based equipment, storage, and bunkering facilities. Besides that, due to global competitiveness, final industrial products have narrow margins, which increases the potential impact of **supply chain risks and market unpredictability** [93]. However, as previously said, in 2022, the industry consumed 53 Mt of hydrogen from fossil fuels, which emitted around 680 Mt of CO_2 emissions to the atmosphere. **By 2030**, the predicted demand for hydrogen is 70 Mt, meaning around **one-third of industrial hydrogen production capacity must be low-emission to satisfy emission reduction targets** by the NZE (Net Zero Emissions) Scenario [98].

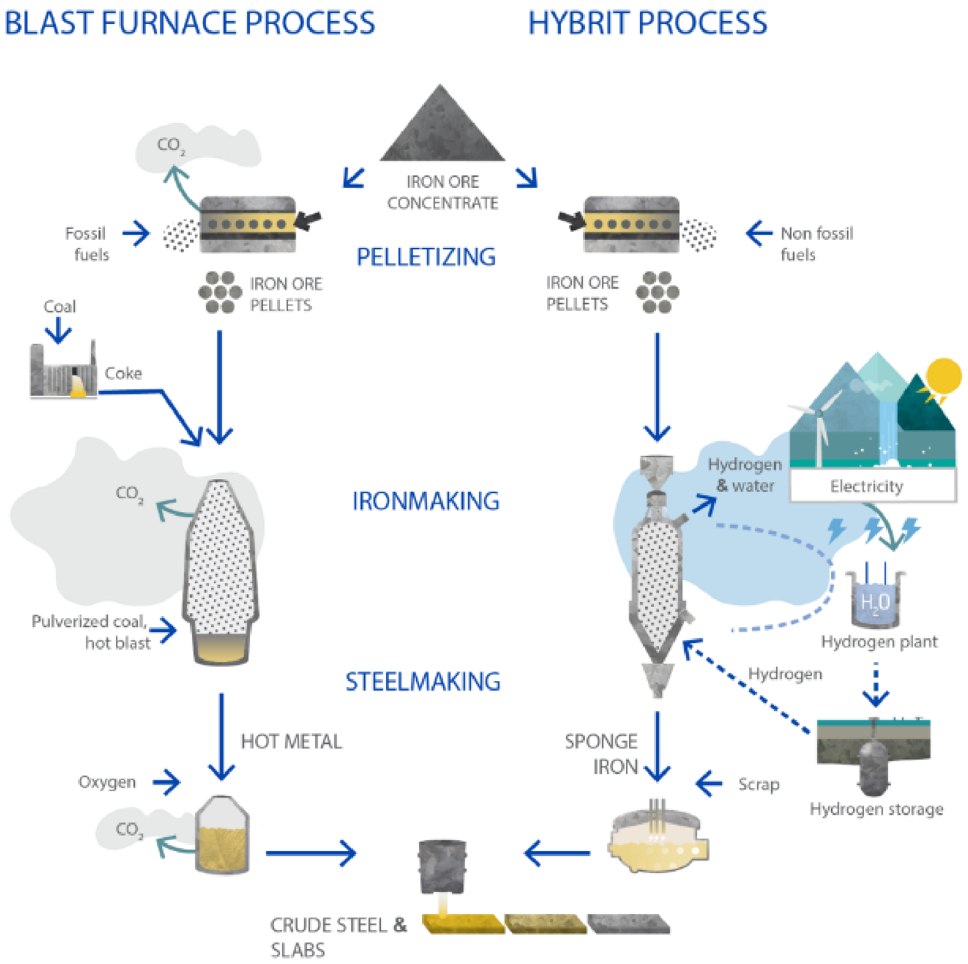


Figure 25. Conventional and green ammonia production processes, retrieved from [49].

6 Green Hydrogen in Ports

6.1 Sources to produce Green Hydrogen in Ports

6.1.1 European landscape of sources

With ambitious targets set for the European landscape through its tightened Emissions Trading System (ETS) [112], under the framework of the **"Fit for 55"** package and the FuelEU Maritime proposal [113], port authorities are expected to make substantial investments and efforts in the upcoming years. These range from maritime shipping to powering port infrastructure to comply with the **demanding restrictions on CO_2, CH_4, SO_x, and NO_x emissions**, among other pollutants. The ongoing decarbonization and energy transition process at ports aims to reduce extensively the role of non-renewable energy sources, namely fossil fuels (including heavy fuel oil for shipping), and increment the share of more sustainable sources and fuels. Several billions of euros have been mobilized in European projects and initiatives, such as **"Hydrogen hubs, valleys, and corridors"** (in-depth mapping in H_2 Infrastructure Map [114]), to evaluate, develop and incorporate promising **energy technologies in seaports**. Though most of the endeavors are being undertaken in Northern regions of Europe (*e.g.*, the Rhine-Scheldt Delta port system), with key stakeholders such as the Ports of Rotterdam (Netherlands) or Antwerp-Bruges (Belgium), there are also noteworthy investments in AA ports, from Sines (Portugal) to Shannon Foynes (Ireland). Even so, it is important to highlight that i) not all initiatives covered by this WP provided a reliable reference to the funding amounts, and ii) the investments can vary between a few million euros to over 3 billion euros, depending on the size, number of partners, complexity and initiative goals. For instance, multi-national projects that foresee the effective installment or setup of Hydrogen hubs, valleys and/or corridors across distinct countries, especially those that involve Nordic regions in Europe, tend to entice larger investments than more local, smaller size and limited initiatives. Note also that the primary funding source derives, as stated previously, from European sources, namely through transposed national Recovery and Resilience Plans, multi-billion-euro Important Projects of Common European Interest (IPCEIs), and calls/tenders from European institutions/partnerships (*e.g.*, Interreg, Horizons Europe, Clean Hydrogen Partnership, REPowerEU Plan, European Clean Hydrogen Alliance, Hydrogen Europe, Green Deal, among others). While some projects began before 2020, a significant portion of the identified initiatives was approved in line with the latest European directives and strategies for an H_2-oriented economy and sustainable energy autonomy. As such, the project timelines generally showcase a starting point following either COVID-19 and/or the war in Ukraine (2022-2023) and extend to 2027-2030 per the funding sources' guidelines for project duration. It should be noted that some projects assume, given their practical nature, horizons beyond 2030 to maintain and/or expand the installed H_2 infrastructure and value chains.

Hydrogen is a keystone of this paradigm, either as an **energy carrier** itself or as a **vector** for a final carrier. As seen in previous chapters of this report, there are numerous applications and possibilities, but also several challenges to be overcome. Producing hydrogen and other energy carriers, particularly ammonia and methanol, requires a noteworthy investment in renewable energy sources (RES), technologies, and infrastructures, as shown in **Figure 26**.

Up to 70 % of hydrogen production is dependent on electricity prices, which currently implies that the costs of "green" hydrogen can be twice to thrice those of "blue" or "grey" hydrogen, according to IRENA [116]. As seen from Deliverable D4.1.1, the European landscape mainly focuses on a "green" approach for producing these energy carriers, with few projects focusing on a "blue" approach. The latter was found to be generally associated with non-renewable sources like liquid natural gas (LNG) and "waste" CO_2. In fact, the majority of the current H_2 production (over 90 %) derives from natural gas [115] – "grey" hydrogen through steam methane reforming, which raises pertinent questions on decarbonizing Hydrogen production itself in a competitive yet environmentally-friendly manner. There are many alternatives to consider, from partially conserving "blue" H_2 production and incorporating Carbon Capture and Storage (CCS) units to a direct transition towards a "green" hydrogen-based economy, including at a seaport level.

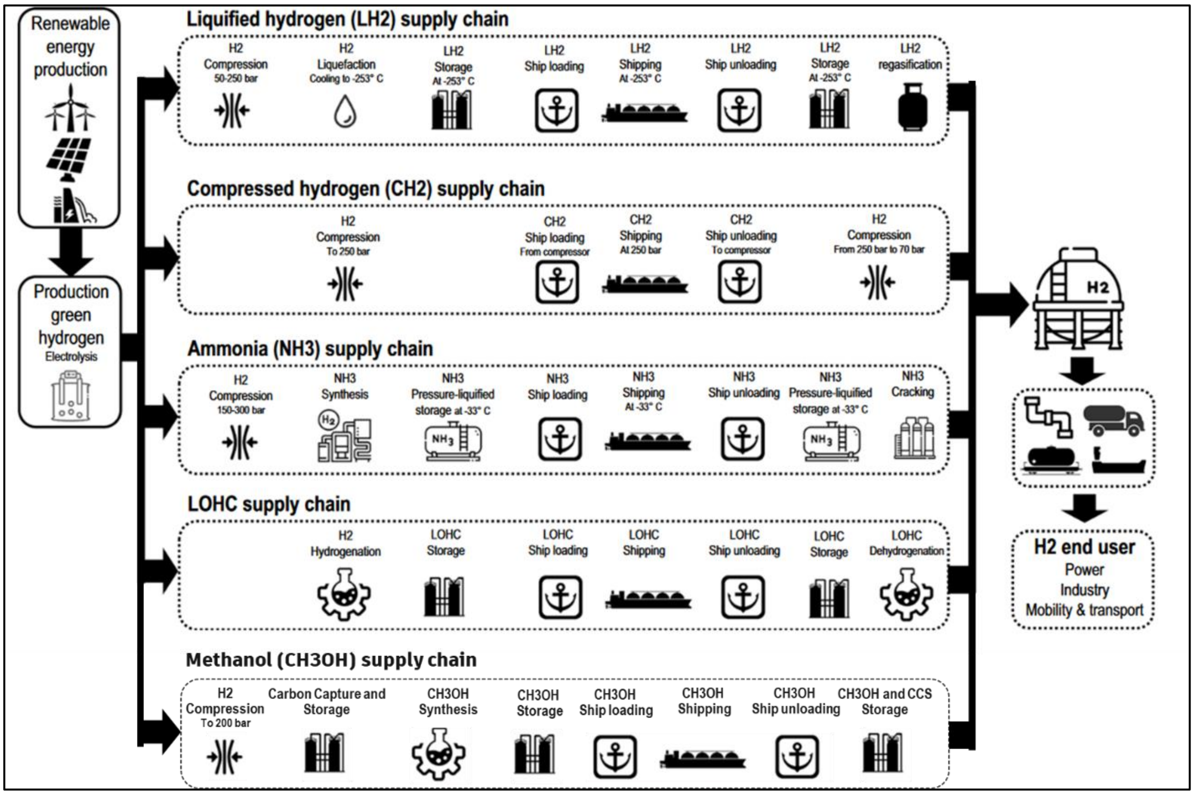


Figure 26. Energy carrier supply chain, adapted from [115].

The **“green” approach** supported by wind and solar energy **was generally prevalent in the selected port initiatives**, although hydropower and other RES were punctually identified. Note that this pattern included many projects in offshore regions, particularly offshore wind energy, given its synergies and proximity to port areas (*e.g.*, construction and transportation, maintenance and replacement operations, grid connection through sub-sea power cables, etc.). Resorting to offshore RES also promotes the energy autonomy of seaports while tackling their emissions and enabling energy storage to smoothen the transmission of the generated electricity to the mainland electrical grid. Consequently, it also bolsters the **ports’ capability of acting as “Hydrogen hubs”**. The installed RES capacity varies considerably, as expected from the wide variety of port characteristics at a European level, including AA ports. There is also a tendency towards a step-by-step installation as opposed to a straightforward full-capacity installation, with annual target values being set for each initiative. However, it was perceptible that the range of installed RES capacity would generally be in the orders of hundreds of MWs (over 100 MW) to a few GWs (below 10 GW).

The generated electricity is necessary for **producing the energy carriers**, Figure 27. Prevailing technologies considered for ports were focused on **electrolyzing units**, mainly of Alkaline or Polymer Electrolyte Membrane (PEM) typology. These are mainstream approaches, albeit with distinct capabilities and costs. Additional electrolyzer specifications were not always available from initiative sheets, unfortunately, but punctual references to supporting compression units were obtained. The installed capacities were found to be, in general, about one to two orders of magnitude lower than the installed RES capacity (~1-500 MWs range). **Seawater** was often selected as the **feedwater** for the electrolysis process, but there were initiatives in which alternative sources (*e.g.*, recycled wastewater) were used. In some initiatives, including those associated with methanol as the final energy carrier, **CCS technologies** were employed. In fact, some initiatives also provide estimates of reductions of CO_2 emissions, generally expecting a range of 10-10 000 thousand equivalent tonnes per year (not limited to methanol). Actually, implementing CCUS at seaports should play a pivotal role towards achieving net zero emissions for CO_2-intensive industries and “hard-to-abate” sectors. Initiatives related to **ammonia** punctually mentioned complementary approaches, such as the Haber-Bosch process and cracking technology.

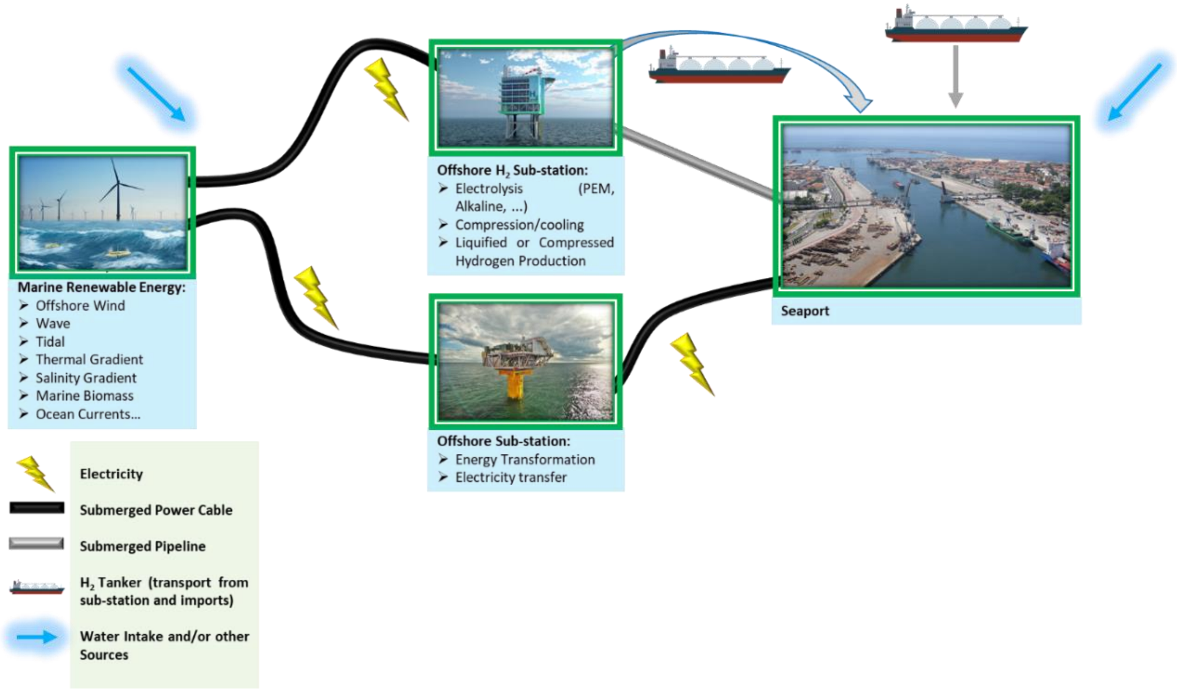


Figure 27. Maritime Energy sources and imports for H_2 production in seaports.

Not all energy carriers are expected to be produced and/or used locally. As stated before, there are initiatives related to **hydrogen corridors** either through inland pipe networks extending across several regions and/or countries across Europe or via maritime shipping lanes through bunkering of energy carriers. An overview of ongoing corridors is provided in H_2 Inframap [114] and other European sources [117], apart from those found in each initiative from WP4.1 (*e.g.*, H2Sines.RDAM, H2med, and RH2INE). There are also large investments towards importing H_2 (compressed/liquefied) and related energy carriers, as is the case with the Ports of Rotterdam and Pecém [118]. Even so, it is worth noting that risks are inherent to establishing hydrogen corridors, as highlighted in [115]. While this will be further addressed in WP4.3, it is worth stating that i) importing hydrogen can help meet the ambitious milestones set by the EU and expand the portfolio of H_2 suppliers, but it also creates a degree of external dependency (even if partial) with regards to European energy security and autonomy, and ii) the importation process can be considerably expensive and complex, from logistics to legislation. This latter remark extends even to internal transport between ports or through pipelines, which require a retrofitting of infrastructure and vessels to enable the adequate transmission of the energy carrier. In fact, the hydrogen corridor from the H2Sines.RDAM initiative was recently abandoned by several partners in part due to the aforementioned difficulties. Note that the degree of investments and upgrades varies with the typology of energy carrier, as addressed in [119] (*e.g.*, methanol and ammonia involve less infrastructural and logistical adjustments than hydrogen, being easier to store and/or handle). This will be further discussed in sub-chapter 6.2.

6.1.2 Atlantic Area landscape of sources

Looking at the **initiatives identified within the context of AA ports**, the following Tables provide a summary of the main tendencies and highlights, by country, for the distinct aspects of sources to produce Hydrogen:

Table 7. Summary of sources for hydrogen production in AA ports.

► **France**:

General information	Main national partners	Main energy sources	H_2 production technology	Final energy carrier
• 8 initiatives • 2015-2029 timelines • 0.75 million to 500 million euros • Ports of Brest, Port-Jérôme-sur-Seine, Bordeaux, Nantes Saint-Nazaire and Haropa	• Air Liquide • Verso Energy • Port of Brest • Port of Bordeaux • Port of Nantes Saint-Nazaire • Port of Haropa • Port-Jérôme-sur-Seine • University of Caen – Normandy • Hensoldt Nexeya France • Lhyfe • Storengy - ENGIE	• Solar 5/8 (onshore) • Wind 5/8 (onshore and offshore) • Industrial by-product and biomethane 4/8 • Other renewables 1/8	• Electrolyzers 5/8 • CCUS 4/8 • Biomethane 2/8	• H_2 7/8 (mainly green) • CH_3OH 1/8 (green) • NH_3 1/8 (green)

► **Ireland**:

General information	Main national partners	Main energy sources	H2 production technology	Final energy carrier
• 2 initiatives • 2024-2030 timelines • Up to 54 million euros • Ports of Galway and Shannon Foynes	• University of Galway • Port of Galway • Port of Shannon Foynes • Dublin City University • CIÉ Group • Hydrogen Ireland LBG • BOC Gases Ireland Limited • HIVE Hydrogen • Aer Arann Islands • Bord na Móna	• Solar 1/2 • Wind 2/2	• Electrolyzer 2/2	• H_2 2/2 (green) • CH_3OH 1/2 (green) • NH_3 1/2 (green)

► **Spain**:

General information	Main national partners	Main energy sources	H2 production technology	Final energy carrier
• 7 initiatives • 2018-2028 timelines	• Port Authority of Seville • Port Authority of Vigo	• Solar 6/7 • Wind 5/7	• Electrolyzer 5/7 (3 PEM, 2 alkaline)	• H_2 6/7 (mainly green)

4.4 million to >1.0 billion euros Ports of Vigo, Seville, Bilbao, Huelva and Algeciras	Port Authority of Huelva Port Authority of Bilbao Soltec Ingenieros EnergyLab Xunta de Galicia Portos de Galicia Enagás Fisterra Energy	Industrial by-product 1/7	Prototype of a hybrid and pure electric propulsion package 1/7 Others 1/7	CH_3OH 1/10 (green) NH_3 1/10 (green)

- **Portugal**:

General information	Main national partners	Main energy sources	H2 production technology	Final energy carrier
8 initiatives 2021-2030 timelines ~3.5 million to 5 billion euros Ports of Sines and Leixões	UPorto APDL APS EDP Efacec Galp INESC TEC Politécnico de Portalegre CapWatt Dourogás REN ISQ Martifer Portuguese Government	Solar 6/8 (onshore) Wind 5/8 (onshore and offshore) Other renewables 1/8	Electrolyzers 6/8 (mainly PEM or alkaline) CCUS 1/8 New membrane system 1/8 Recycled wastewater 1/8 Compression unit and pipeline 1/8	H_2 8/8 (mainly green) CH_3OH 3/8 (mainly green) NH_3 2/8 (green)

6.2 Promising Applications of Green Hydrogen in Ports

6.2.1 Applications and port services in Europe

Besides the prospects inherent to hydrogen corridors and port-to-port shipping of energy carriers, European ports can serve the role of **hydrogen hubs and/or valleys** and provide high-value services to local stakeholders, from industry to agriculture, as presented in **Figure 17** of section 4.2 and **Figure 28**. Notteboom and Haralambides [115] identified seventeen aspects related to potential impacts on ports, the wider port area, and local communities and economy [120]:

- Energy savings in lighting, storage, building infrastructure, and equipment in quays and terminals through efficient electrification.
- Retrofitting of diesel-based port equipment with low-to-zero carbon fuels, batteries and fuel cells.
- Onshore Power Supply/" cold ironing" of seagoing vessels and inland boats, even if partial.
- Bunkering of "blue" or "green" fuels and energy carriers, particularly H_2, NH_3, and CH_3OH (also natural gas, mainly in the short-term).
- On-site renewable power, mainly through onshore and offshore wind and solar energy, to promote sustainable, local, and autonomous electricity generation to be stored in the form of energy carriers (attenuate/smoothen disparities between supply and demand).
- Waste to energy and produce chemical products while avoiding direct fuel combustion and the inherent pollutant emissions.
- Offshore marine energy production and transfer, storage, usage, and distribution to the port area: production of energy carriers offshore versus onshore.
- Energy demand from growing offshore industries and the transformation of (excess) electricity to energy carriers. This may require additional energy infrastructure in ports, such as electrolyzers to convert power to H_2 in the port and pipelines bringing hydrogen produced offshore into the port and its hinterland connections.
- Decarbonizing local energy-intensive industries and "hard-to-abate" sectors, including refineries, steam crackers, "grey" energy carriers, chemical and metallurgical industries (*e.g.*, steel, iron, plastics, and cement), heat generators/pumps, feedstock/fertilizer production, among others.
- Energy distribution to urban areas, with ports serving as sustainable energy carrier "hubs" for electricity, fuels, and heating/cooling systems, among others.
- Energy conversion efficiency (power-to-carrier and vice-versa) and repurposing of fuels (feedstock, e-fuels, among others).
- Storage in ports in liquid or (compressed) gas format for posterior usage, distribution, transport, and shipping, among other purposes (*e.g.,* gas turbines and fuel cells).
- Combination with CCS, as is the case with "blue" hydrogen and methanol, to tackle further "hard-to-abate" and energy-intensive sectors.
- Zero-to-low emission fuel supply chains, with seaports acting as facilitators, importers/ exporters, bunkering, storage, production, transit of zero/low carbon fuels, and carbon capture of fossil fuels and/or "blue" hydrogen.
- Seasonal storage of excess energy (*e.g*., intermittent sources such as wind and solar) as energy carriers from the mainland grid or marine renewable energy to promote consistent availability, peak mitigation, and energy supply smoothness;
- The circular economy premise, as is the case with the closed loop premise of methanol's carbon emissions and capture/storage;

- Transport and mobility decarbonization, from fuel cells to e-fuels.

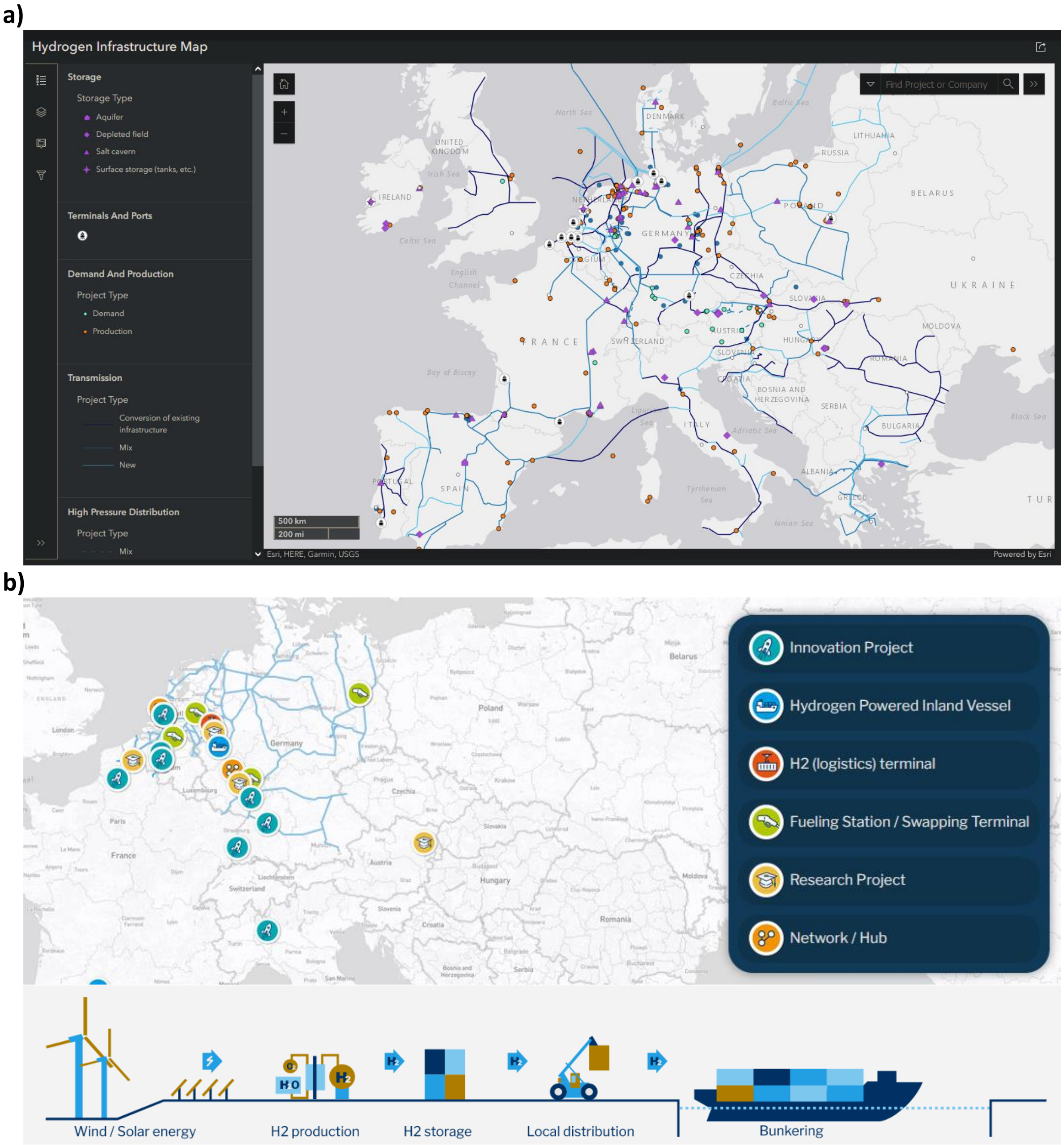


Figure 28. Schematic showcasing examples of Hydrogen corridors, valleys, and hubs from initiatives a) H_2 Inframap and b) RH2INE.

To these should be added other direct and indirect benefits, namely **job creation and capital investments** related to port management and infrastructure upgrading, port workers/staff, local and offshore industries (including marine renewables), fuel and transportation groups, R&D institutions, engineering companies (civil, electrotechnical, mechanical, chemical, metallurgical, among others), external industries and companies (steel, agriculture, plastics, high-temperature heat, consultancy, etc.), and other local beneficiaries from the established energy carrier-based network at the ports.

Moreover, as summarized in [115], "*seaports are often home to large energy plants. The availability of land and cooling water, and the presence of large industrial customers, are some of the reasons for energy-producing firms setting up business in seaport areas. While many wind farms are installed offshore, or in open plots in the hinterland, several seaports are also home to wind farms, installed on breakwaters or narrow stretches of land close to the sea. The presence of power plants and power* *distribution infrastructure generates direct jobs and value-added, not only for the power plants themselves, but also for energy distribution platforms, and terminal operations (i.e., handling of coal, gas, and other fuels). The plant is also a major creator of jobs and value-added in other industries and services such as engineering firms, construction companies, maintenance and repair companies, survey and inspection firms, and security services*". Even so, at present**, hydrogen accounts for less than 2 % of Europe's energy consumption**, and is primarily used in the production of chemical products like plastics and fertilizers.

Apart from serving as loading/unloading/processing checkpoints for hydrogen corridors, seaports can also serve as hydrogen hubs or valleys. As described in [121] and [115], respectively, the "*growing focus on hydrogen has given impetus to the development of so-called hydrogen valleys. These are regional ecosystems that link hydrogen production, transportation, and various end-uses such as mobility or industrial feedstock. The valleys are considered important steps in enabling the development of a new 'hydrogen economy'". "Indeed, ports can play a crucial role in the production and distribution of green hydrogen. They are important nodes, given existing and future local demand for hydrogen, the emerging offshore parks, and as junctions of transport nodes, some of which could shift to hydrogen or related fuels (e.g., vessels, barges, trucks). Additionally, the infrastructure and handling capabilities of seaports make them prime locations for the storage and distribution of hydrogen. Seaports can serve as hubs for the export of green hydrogen to other countries, helping to drive the global transition to clean energy. Ports aiming for a strong position in green hydrogen are challenged to be active in all parts of the Hydrogen value chain. A favorable location, a well-developed pipeline network, strong worldwide maritime connectivity, state-of-the-art terminal and logistics infrastructures, well-functioning and efficient industrial ecosystems and a strong customer base, are all important factors enabling a seaport to take up an important, pioneering, role in an emerging Hydrogen economy, positioning itself as a hydrogen import, transit and production hub. To support the concept, a Hydrogen Valley Platform was set-up, commissioned by the European Union and developed by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU). This global information sharing platform to date already features 32 global Hydrogen Valleys, spread over 21 countries, with a cumulative investment of more than 32.4 billion euro (data www. h2v. eu in late August 2022). Hydrogen valleys thus aim to build local Hydrogen ecosystems. By 2050, there would be about 50 in the EU*".

Looking at the European landscape of initiatives, there is a consistent effort towards providing energy, industrial-grade gases, and feedstock sources at an affordable and directly accessible rate. These are to be commonly supplied to major stakeholders operating either within seaport areas or in their vicinity, including local industry, mobility, and agriculture. The ambitious European initiatives, particularly those of EU countries, will exert significant pressure upon the supply front, with energy carrier demand often reaching magnitudes from tens of thousands up to millions of tonnes per year. Some initiatives exhibit more modest requirements, but hydrogen, methanol, and ammonia production will have to be significantly bolstered at seaports to keep up with demand. It will also have to be flexible, given the multitude of potential applications and end-uses (*e.g.*, local storage, marine and non-marine mobility of vessels and vehicles, port-to-port transport of energy carriers, industrial and agricultural processes – green feedstock/reactant in chemical production, metal treatment, food processing, or as an e-fuel/fuel cell – seaport infrastructure and equipment electrification, and distribution to external entities, among others). While there are important expected reductions in GHG emissions, particularly of CO_2, and ongoing efforts towards bolstering local production and use, the imbalances between energy carrier supply-and-demand will likely warrant the establishment of import/export schemes, such as the hydrogen corridors. As stated previously, this will also entice unique challenges and potentially greater costs (*e.g.*, bunkering, transport, and transfer), adding risks of dependencies from external suppliers. As highlighted in [115], "*ports vying for a hub role in the global hydrogen network are urged to align their commercial and marketing efforts with the future geographical shifts in energy* *flows, and to partner with leading private companies and local, regional and national governments in establishing closer relationships with existing and upcoming countries in the hydrogen economy. First, there is a limited amount of green energy (wind, solar) in Europe. Therefore, some argue that green energy should first and foremost be used for green electricity, i.e., to make current electricity consumption greener (electric cars, water pumps, etc.), and not just as a source to produce green hydrogen, or the transformation of imported green hydrogen to electricity. Second, hydrogen loses a fair amount of energy when produced through electrolysis of wind or solar energy, or when converted back into electricity. Some sources point to losses of up to 60% of the initial wind energy in the 'wind energy to hydrogen back to electricity' cycle. Third, there are rising concerns in the energy transition drive about the capacity of the electricity grid. In some parts of Europe, high-voltage grid operators can no longer guarantee that new wind turbines, solar parks or power stations can put their power on the grid at all times*". These and other challenges will be further discussed in WP3. The main applications are summarized in Figure 29.

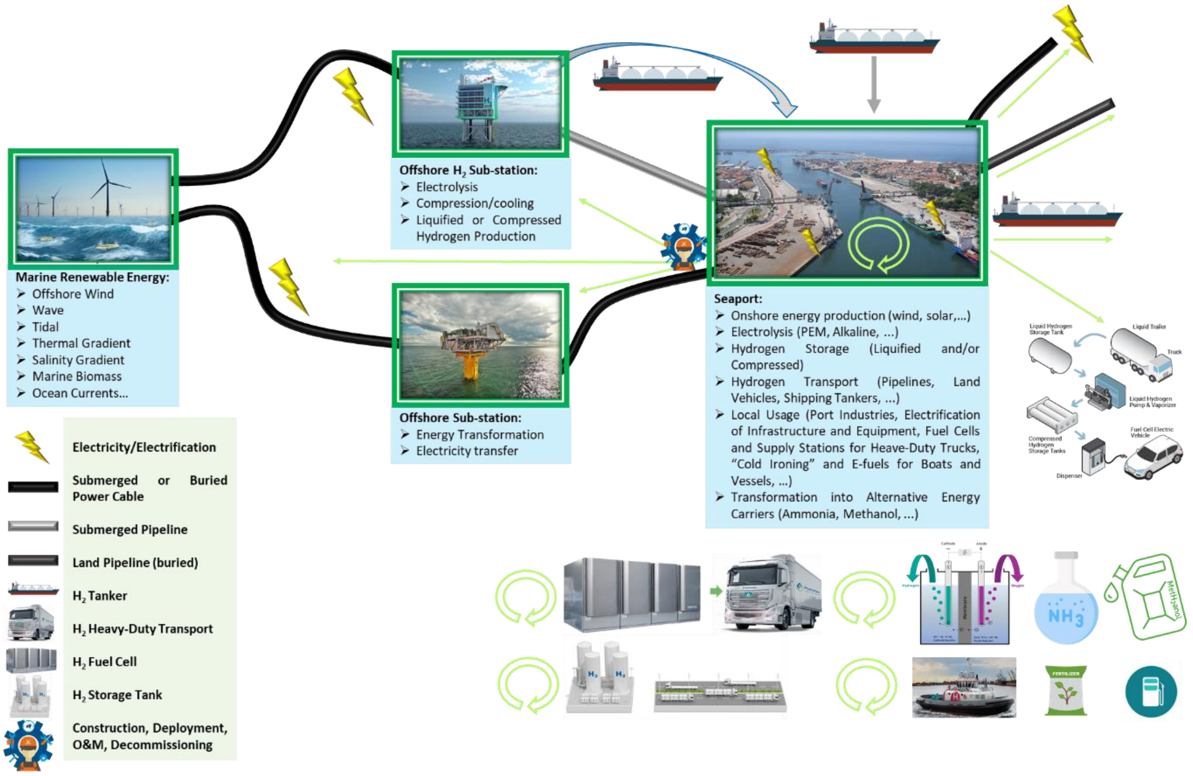


Figure 29. Sources and applications of H_2 from seaports.

The identified European initiatives show a high degree of complexity towards implementing and giving viable purpose to energy carriers at seaports. The applications are immense, ranging from retrofitting trucks, cranes, and vessels to large-scale transport pipelines and shipping. The scales of the projected production of energy carriers vary considerably, as well as the number of involved partners, reduction of GHG emissions, the connectivity and inter-dependency within each initiative, and the typology of applications and inherent investments/adaptation efforts. An interesting paradigm arises. On the one hand, European seaports are set to become H_2 "laboratories", in the sense that many initiatives are either planned or underway. While there may be punctual similarities, there is a very rich environment in terms of variety. In other words, a lot of potential combinations in terms of energy carrier typology, local needs and capacity, applications, availability, and other variables will be subjected to real case study testing. This will provide ample possibilities and an almost "artificial selection" process from which driving market trends will emerge that, in the medium-to-long term, ought to dictate the future landscape of H_2-based energy carriers at European seaports. On the other hand, there are risks inherent to this approach. Firstly, it does not seem to follow a very specific strategic line. Europe has set ambitious, yet generic goals that must be met by each member state, leaving ample margin to reach them. Thus, and despite the existence of international initiatives with key European stakeholders, there may be lost opportunities in terms of effective synergies and common strategies between the involved stakeholders (*e.g.*, regional specialization and insufficient interconnection and knowledge-sharing). A sense of "losing perspective of the big picture" may arise. Secondly, it dilutes investment among numerous initiatives rather than focusing the existing resources on establishing a clear and common supply chain and distribution/use network. This may hamper eventual economies of scale and savings from shared connections, except for encompassing initiatives like H2Med or RH2INE. Thirdly, it makes it particularly difficult to understand the alignment of national/regional initiatives with the overall strategy. There is a risk of failing to meet the major strategic objectives due to a lack of convergence in terms of the individual initiatives being undertaken, either due to project unavailability or insufficient cumulative capacity and infrastructure, for instance. Overshooting the proposed goals entices opportunities, such as greater autonomy, redundancy, and export potential, but may also bring challenges regarding pricing, storage and/or grid capacity stability. Uncertainty regarding the actual total impact of all European initiatives, from energy carrier production to GHG emission reduction, can also be a source of risk at social, political, economic, and environmental levels. Having a broad picture of how initiatives are contributing towards the general milestones over the upcoming years is of utmost importance.

Within the framework of HYDEA, the establishment of a community and a portfolio of initiatives helps to mitigate some of these challenges. Updated information on European initiatives becomes available in a summarized manner, making it easier to identify the main market trends, technologies, opportunities, synergies, and solutions that can be exploited. The engagement of port authorities, particularly those of the AA, alongside industry, organizations, companies, and public institutions provides a wide range of knowledge and resource-sharing. It has the potential to implement, in a viable manner, research clusters, incubators, demonstration projects, and other initiatives related to energy carriers. There are distinct approaches towards achieving this perspective. For example, port authorities may wish to give greater emphasis towards establishing partnerships with local entities, focusing on creating hydrogen hubs and/or valleys. In contrast, they may wish to foster international ties with large transport networks and interconnected infrastructure. There may also be a middle-ground, considering a scenario in which local initiatives are undertaken to promote regional autonomy and capacity whilst contributing, in a very specific manner, towards the general goals (*e.g.*, those set by the EU). The role of seaport authorities – leaders, secondary partners, or landlords – should also be clearly defined. All these considerations reflect upon the AA initiatives, as seen in the next sub-chapter.

6.2.2 Applications and port services in the Atlantic Area region

Looking at the initiatives identified within the context of AA ports, the following Tables provide a summary of the main tendencies and highlights, by country, for the distinct aspects of Hydrogen-related applications and services in ports:

Table 8. Summary of promising applications and port services in AA ports.

► **France:**

General information	Main national partners	Energy carrier production	Reduction of emissions	Main applications and services
• 8 initiatives • 2015-2029 timelines • 0.75 million to 500 million euros • Ports of Brest, Port-Jérôme-sur-Seine, Bordeaux, Nantes Saint-Nazaire and Haropa	• Air Liquide • Verso Energy • Port of Brest • Port of Bordeaux • Port of Nantes Saint-Nazaire • Port of Haropa • Port-Jérôme-sur-Seine • University of Caen – Normandy • Hensoldt Nexeya France • Lhyfe • Storengy - ENGIE	• 1 642 – 50 000 ktonnes of H_2/yr • CH_3OH/yr not specified • NH_3/yr not specified	• Over 500 tonnes/yr	• Storage 4/8 • Non-marine mobility 5/8 • Marine mobility 7/8 • Port-to-port transport 3/8 • Industry 5/8 • Infrastructure electrification 3/8 • Distribution 5/8

► **Ireland:**

General information	Main national partners	Energy carrier production	Reduction of emissions	Main applications and services
• 2 initiatives • 2024-2030 timelines • Up to 54 million euros • Ports of Galway and Shannon Foynes	• University of Galway • Port of Galway • Port of Shannon Foynes • Dublin City University • CIÉ Group • Hydrogen Ireland LBG • BOC Gases Ireland Limited • HIVE Hydrogen • Aer Arann Islands • Bord na Móna	• Up to 0.5 ktonnes of H_2/yr • CH_3OH/yr not specified • NH_3/yr not specified	• Not specified	• Storage 2/2 • Non-marine mobility 2/2 • Marine mobility 1/2 • Port-to-port transport 1/2 • Industry 2/2 • Agriculture 1/2 • Distribution 2/2

► **Spain**:

General information	Main national partners	Energy carrier production	Reduction of emissions	Main applications and services
• 7 initiatives • 2018-2028 timelines	• Port Authority of Seville • Port Authority of Vigo	• 0.17 – 4 500 ktonnes of H_2/yr	• 2 800 tonnes/yr – 1 MT/yr	• Storage 3/7 • Non-marine mobility 6/7

• 4.4 million to >1.0 billion euros • Ports of Vigo, Seville, Bilbao, Huelva and Algeciras	• Port Authority of Huelva • Port Authority of Bilbao • Soltec Ingenieros • EnergyLab • Xunta de Galicia • Portos de Galicia • Enagás • Fisterra Energy	• Up to 380 ktonnes of CH_3OH/yr • NH_3 not specified		• Marine mobility 5/7 • Industry 6/7 • Infrastructure electrification 1/7 • Distribution 1/7

► **Portugal**:

General information	Main national partners	Energy carrier production	Reduction of emissions	Main applications and services
• 8 initiatives • 2021-2030 timelines • ~3.5 million to 5 billion euros • Ports of Sines and Leixões	• UPorto • APDL • APS • EDP • Efacec • Galp • INESC TEC • Politécnico de Portalegre • CapWatt • Dourogás • REN • ISQ • Martifer • Portuguese Government	• 10 – 180 ktonnes of H_2/yr • Up to 230 ktonnes of CH_3OH/yr • Up to 300 ktonnes of NH_3/yr	• 110 ktonnes/yr – 1.2 MT/yr	• Storage 7/8 • Non-marine mobility 5/8 • Marine mobility 4/8 • Port-to-port transport 3/8 • Industry 8/8 • Agriculture 1/8 • Infrastructure electrification 5/8 • Distribution 6/8

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