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Hydrogen: Technologies, Policies and Strategies

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Statement of originality

I, Costanza Scano, hereby declare that the work presented in this dissertation, titled "Hydrogen: Techologies, Policies and Strategies" is entirely my own original work. I affirm that it has not been fully or partially submitted previously in any other Italian or foreign university for assessment purposes.

I further confirm that the content of this dissertation is the result of my own intellectual endeavours, and I have appropriately cited all sources used. This work does not infringe upon the intellectual property rights of any third party, and its contents do not constitute plagiarism.

I understand the consequences of submitting work that is not my own and affirm the honesty and integrity of this academic contribution.

Costanza Scano

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ABSTRACT

This thesis investigates the potential of hydrogen as a sustainable energy carrier to support the global transition to decarbonized energy systems. The study focuses on hydrogen technologies for production, storage, transportation, and applications. The policy framework is explored through national policies and strategies at global, European, and national levels. Renewable hydrogen, produced via electrolysis powered by renewable energy, is identified as a cornerstone of the energy transition. Blue hydrogen, which relies on carbon capture and storage (CCS), is also analysed, with an emphasis on the technological advancements required to make this pathway scalable and cost-effective. Storage technologies are categorized into physical-based methods, such as compressed and liquefied hydrogen, and material-based approaches, including metal hydrides and chemical carriersUnderground hydrogen storage in salt caverns offers potential for seasonal energy needs but faces geological and safety challenges. The European Hydrogen Strategy outlines ambitious targets for 2030, serving as a guiding framework for hydrogen development across member states. Countries across Europe and beyond are adopting diverse approaches, reflecting their unique resources, industrial strengths, and strategic priorities. While some nations focus on scaling up domestic production and infrastructure, others emphasize positioning themselves as key players in the global hydrogen market through export-oriented strategies. A review of national energy and climate plans highlights the importance of setting clear targets, aligning policy frameworks with broader decarbonization goals, and fostering international cooperation to accelerate hydrogen's integration into energy systems. This research emphasizes the importance of aligning policy, technology, and infrastructure to unlock hydrogen's transformative potential.

1. INTRODUCTION

In recent years, hydrogen has gained significant attention as a versatile energy carrier and a promising solution for decarbonizing various sectors. Global demand for hydrogen increased by 2.5% in 2023, reaching approximately 100 million metric tons (Mt) by 2024. Currently, hydrogen production is predominantly reliant on fossil fuels, with natural gas reforming accounting for around two-thirds of total production (IEA, 2024). My thesis project delves into this dynamic and evolving landscape, focusing on hydrogen technology and related policy frameworks. By examining global, European and national strategies, I aimed to provide a comprehensive analysis of hydrogen's role in industry decarbonization and energy transition. A key part of this work involved a critical review of Italy's Piano Nazionale Integrato Energia e Clima (NECP) to assess the country's progress and strategic direction prior to the official launch of its national hydrogen strategy. This examination highlighted Italy's position within the broader context of international efforts to promote hydrogen as a clean energy vector.

The development of my thesis was shaped by my internship at ECCO, an independent, non-profit Italian think tank committed to climate action and the energy transition. ECCO plays a pivotal role as an agent of change, dedicated to accelerating climate initiatives at the national, European, and global levels. Its mission is rooted in providing independent expertise and fostering innovative, science-based solutions to address the urgent challenges posed by climate change. By leveraging communication, advocacy, and diplomacy, ECCO seeks to transform public interest into tangible climate progress.

Throughout my research, I benefited from continuous input and insights from my colleagues at ECCO, who directed me toward emerging trends and critical areas of study. Moreover, attending relevant webinars and conferences allowed me to stay updated with the latest discussions and developments in hydrogen technologies and policies. The think tank's name, “ECCO,” encapsulates its core themes, Energy and Climate Change, and underscores the urgency of acting for climate innovation.

Through rigorous, fact-based analysis and strategic approaches, ECCO positions itself as a catalyst for impactful, sustainable change.

The structure of this elaborate reflects the exploration of hydrogen as a key element in the global energy transition. Chapter 2 sets the stage for hydrogen technologies, starting with an overview of the various "colours" of hydrogen and processes involved in hydrogen production, storage, transport, and utilization, with specific focus on technological innovations and their applications across sectors.

Chapter 3 takes a broader view, providing an analysis of international policies and initiatives aimed at hydrogen development. This section reviews both global and European frameworks, shedding light on the key regulatory and strategic efforts driving the hydrogen economy worldwide. The chapter also discusses various international hydrogen initiatives, offering a broad perspective on how countries are positioning themselves in this rapidly evolving field.

In Chapter 4, the thesis focuses on Italy’s national policies and strategies for hydrogen, including an in-depth review of the country’s *Piano Nazionale Integrato Energia e Clima* (NECP). This chapter critically examines ongoing projects, such as the development of hydrogen infrastructure and the debate between green and blue hydrogen, along with the potential role of nuclear energy in Italy's hydrogen future. Key aspects like hydrogen blending with natural gas and the establishment of a "hydrogen backbone" are also addressed, offering a clear view of Italy’s efforts to integrate hydrogen into its energy landscape.

Finally, the conclusions chapter summarizes the key findings and discusses future perspectives on hydrogen, both from a technological and policy standpoint. This work draws on extensive research, insights from my internship at ECCO, and ongoing dialogue with experts to present a forward-looking view of hydrogen's role in the energy transition, particularly in the context of Italy and Europe.

The structure combines technical details, policy analysis, and future projections to provide a comprehensive understanding of the current and future hydrogen landscape.

2. HYDROGEN TECHNOLOGIES

This chapter will examine the various hydrogen technologies currently available, including especially those already on the market and some of those still at the laboratory scale. It will focus on production, transportation, and storage methods. In the field of hydrogen, different "colours" are used to classify H_2 by the production processes, each with its associated implications on the environment. This section will clarify these distinctions, outlining the main types of hydrogen, from green and blue to grey, and others.

2.1 Colours of Hydrogen

Hydrogen serves as an energy carrier rather than an energy source, and it can be generated through various methods. The specific method or resource used to produce hydrogen often determines its "colour" classification. Each type of hydrogen has a unique production cost that varies depending on the source material and the efficiency of the production technology. The price of hydrogen production is often closely tied to the cost of electricity (Figure 1).

Green hydrogen: is produced through **electrolysis**, a process whereby electricity is used to split water molecules into oxygen (O_2) and hydrogen (H_2). In order for the hydrogen to be classified as green, it is necessary that the electricity used to produce it should come exclusively from **renewable sources**. This method is the most environmentally sustainable and entirely emissions-free (Acciona, 2022; Corbetti et al., s.d.).

Yellow hydrogen: is a relatively recent addition to the field of hydrogen production. It encompasses hydrogen generated through **electrolysis**, with the energy source being either direct solar power or indirect solar energy. However, this classification is not universally agreed upon, as some employ the term to describe hydrogen generated through electrolysis **powered by grid electricity**, which may derive from a combination of renewable and fossil fuel sources (Acciona, 2022).

Blue hydrogen: this classification pertains to hydrogen produced through the process of **steam methane reforming** (SMR), which involves the use of steam to react with hydrogen molecules from natural gas. The emissions generated during this process are captured and stored using carbon capture, utilisation and storage (CCUS) technologies. Although some view blue hydrogen as "carbon neutral," a more precise characterisation would be "low-carbon," given that current CCUS solutions capture approximately 90% of the CO_2 and methane leaks are inevitable during natural gas extraction (Acciona, 2022; Corbetti et al., s.d.).

Turquoise hydrogen: is produced from methane via **pyrolysis**, a process whereby the gas is heated in the absence of oxygen to thermally break the chemical bonds, resulting in the generation of hydrogen and solid carbon (Acciona, 2022; Corbetti et al., s.d.). The solid carbon produced by this process could potentially be used as a raw material, for example, in the production of black carbon for tyres. While this process does not result in direct CO_2 emissions, the entire lifecycle can still be associated with significant levels of greenhouse gases.

Pink hydrogen: also known as purple or red hydrogen, is produced through **electrolysis** powered by nuclear energy (Acciona, 2022; Corbetti et al., s.d.). Although this process results in minimal carbon emissions, other environmental impacts must be considered, including the production of radioactive nuclear waste.

White hydrogen: naturally occurring hydrogen is found in significant quantities deep within the Earth's crust and is produced through geochemical processes. The value chain for white hydrogen bears resemblance to that of natural gas production, encompassing exploration, site selection, drilling, extraction, and product separation. Although minimal carbon emissions are generated during its extraction, as with pink hydrogen, it may have other environmental impacts (Acciona, 2022; Corbetti et al., s.d.).

Grey hydrogen: The production of grey hydrogen is achieved through the utilisation of the same **steam methane reforming** process employed for the generation of blue hydrogen (Acciona, 2022; Corbetti et al., s.d.). However, in this instance, all the emissions generated are released into the atmosphere, resulting in a highly carbon-intensive product.

Brown/black hydrogen: is achieved through the **coal gasification process**, with brown hydrogen originating from lignite and black hydrogen from bituminous coal. This hydrogen type is the most environmentally detrimental, as the production process releases both CO_2 and carbon monoxide (Acciona, 2022).

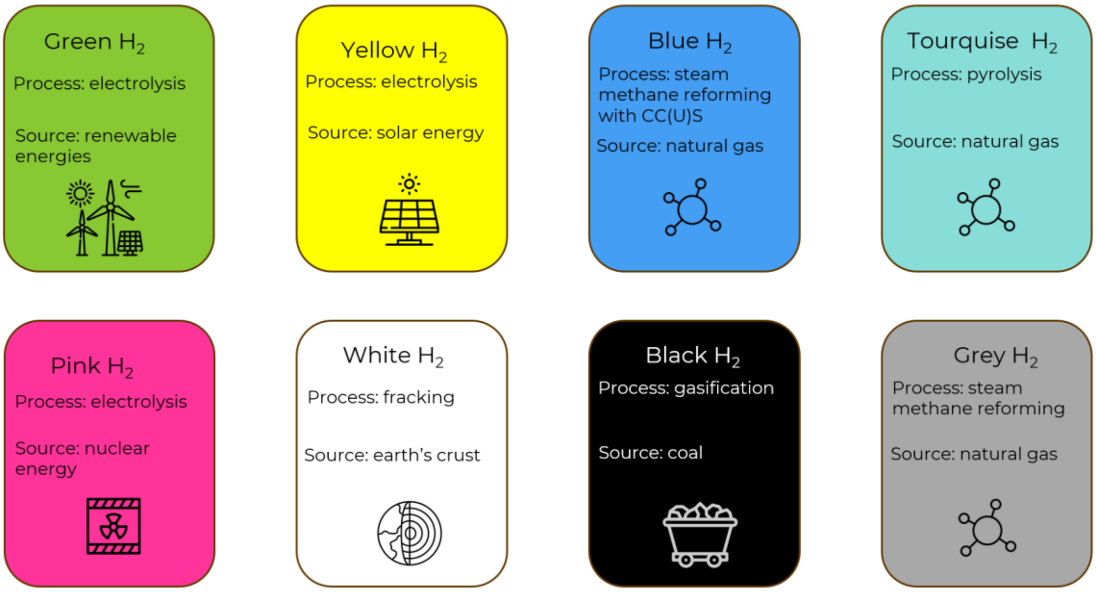

Figure 1- Schematic representation of hydrogen colours, detailing production processes and sources.

2.2 Production of Hydrogen

As evidenced by the colours of hydrogen, there are numerous methods for synthesizing this element. Hydrogen production is a versatile process that can be achieved through a variety of methods. Steam methane reforming (SMR), pyrolysis, electrolysis and coal gasification are the main processes that are widely employed for the large-scale production of hydrogen. Each method is based on distinctive chemical reactions, energy inputs, and feedstocks, which result in varying environmental impacts and by-products. This paragraph provides a detailed examination of each process, including their chemical mechanisms and implications for hydrogen production.

In 2023, global hydrogen demand rose by 2.5% compared to 2022, reaching an anticipated 100 Mt by 2024. Currently, hydrogen production is predominantly based on fossil fuels, with **steam methane reforming** comprising approximately two-thirds of total output. Unabated fossil fuel processes, particularly natural gas, dominate hydrogen production, and this trend is projected to persist into 2024 (IEA, 2024).

SMR is one of the most prevalent methods to produce hydrogen, particularly in industrial contexts. This process employs methane (CH_4), the principal constituent of natural gas, and high-temperature steam. SMR is an endothermic process, whereby a significant input of heat is required for its progression. Typically, SMR is conducted at temperatures between 700 and 1,000°C in the presence of a nickel-based catalyst. The overall reaction can be decomposed into two principal stages: the reforming reaction and the water-gas shift reaction (Simpson & Lutz, 2007).

The reforming reaction itself involves the breakdown of methane in the presence of steam, resulting in the production of carbon monoxide (CO) and hydrogen (H_2).

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

This reaction is endothermic, with a positive enthalpy change (ΔH = 206 kJ/mol), indicating that the conversion of methane and water into hydrogen and carbon monoxide necessitates the input of heat. The SMR process typically achieves hydrogen yields of around 70-85%, contingent on the operational parameters and the configuration of the reformer.

Subsequently, the carbon monoxide generated is transformed into carbon dioxide (CO_2) through the water-gas shift reaction.

$$CO + H_2O \rightarrow CO_2 + H_2$$

The water-gas shift reaction is exothermic ($\Delta H = -41$ kJ/mol), releasing heat as carbon monoxide reacts with additional steam to form carbon dioxide and additional hydrogen. The combination of these two reactions allows SMR to achieve a high overall hydrogen yield, with a typical output ratio of four moles of hydrogen for each mole of methane consumed (Bhat & Sadhukhan, 2009).

Methane **pyrolysis**, frequently designated as methane splitting or thermal decomposition, represents a process whereby methane is thermally decomposed into hydrogen and solid carbon in the absence of oxygen. In contrast to SMR, pyrolysis circumvents the generation of CO_2 directly, thereby offering a potentially lower-emission pathway for hydrogen production. The process requires temperatures in the range of 500 to 1,000°C. While a catalyst is not a prerequisite, the use of certain metal catalysts can facilitate a reduction in the required temperature and an enhancement in efficiency.

The core reaction in methane pyrolysis is as follows:

$$CH_4 \rightarrow C\ (solid) + 2H_2$$

This reaction is endothermic (ΔH = 74,91 kJ/mol), consuming heat to convert methane into hydrogen gas and solid carbon. The solid carbon produced can be captured and potentially repurposed, offering a means of carbon sequestration. Additionally, the absence of oxygen in the process eliminates the formation of CO_2 as a byproduct, which can make pyrolysis a more environmentally friendly alternative to SMR and coal gasification (Midilli et al., 2021; Patlolla et al., 2023).

Coal gasification is a more complex process that transforms coal into a hydrogen-rich syngas mixture through partial oxidation. Unlike combustion, where coal is burned with excess oxygen to produce CO_2 and water, gasification operates under limited oxygen and steam to generate a syngas consisting primarily of hydrogen, carbon monoxide, and carbon dioxide. This process typically takes place at temperatures between 800 and 1,200°C.

The initial gasification reaction can be represented by the following reaction:

$$C + \frac{1}{2}O_2 \rightarrow CO$$

This is a partial oxidation reaction that yields carbon monoxide. Subsequently, the carbon reacts with steam to produce hydrogen and more CO via the water-gas reaction:

$$C + H_2O \rightarrow CO + H_2$$

The resulting CO from this reaction can undergo a further transformation through the water-gas shift reaction to produce additional hydrogen and CO_2:

$$CO + H_2O \rightarrow CO_2 + H_2$$

Coal gasification, while capable of producing large quantities of hydrogen, is highly carbon-intensive, as it generates CO_2 at multiple stages (Midilli et al., 2021).

An electrochemical method used nowadays is the **electrolysis**, this method produces H_2 splitting water into hydrogen and oxygen using an electric current. Unlike traditional methods like steam methane reforming or coal gasification, electrolysis is a relatively clean process that can produce hydrogen with little to no direct carbon emissions—especially when powered by renewable electricity sources. This makes it a promising option for producing "green hydrogen" and supporting a low-carbon energy future. Electrolysis can be achieved through several different technologies, which are primarily distinguished by the type of electrolyte used. The principal forms of electrolysis are alkaline electrolysis, proton exchange membrane electrolysis, alkaline electrolysis with anion exchange membrane and solid oxide electrolysis cells. Each technology possesses distinctive characteristics and operates at varying temperatures and efficiencies.

At its core, electrolysis splits water into hydrogen and oxygen according to the following reaction:

$$2H_2O\ (l) \rightarrow 2H_2\ (g) + O_2\ (g)$$

This reaction is endothermic, requiring a significant energy input, supplied by electricity. The overall energy required depends on the efficiency of the electrolyser and the specifics of the setup, including the type of electrolyte and the operating conditions.

Before delving into the different electrolysis processes, the following table summarizes the costs of hydrogen production (€/kg) for the SMR, SMR with CCS and the electrolysis.

Table 1- Cost of H_2 from different production processes

Production process	**Average cost of H_2 in Europe in 2023**
SMR	3.76 €/kg H_2 (European Hydrogen Observatory, 2023)
SMR with CCUS	4.41 €/kg H_2 (European Hydrogen Observatory, 2023)
Electrolysis	7.94 €/kg H_2 (European Hydrogen Observatory, 2023)
Pyrolysis	3.76 €/kg H_2 (simil to SMR) (Patlolla et al., 2023)
Coal gasification	1.34 €/kg H_2 (from a study based in China) (Li et al., 2022)

The electrolysis process is carried out in an electrolyser, which consists of an anode, a cathode, and an electrolyte that facilitates the movement of ions between the two electrodes. The reactions at the electrodes vary depending on the specific technology used.

Alkaline (ALK) electrolysis (Figure 2) has been used for hydrogen production for several decades and is characterized by using an aqueous alkaline solution as the electrolyte, typically potassium hydroxide (KOH) or sodium hydroxide (NaOH). ALK operates at moderate temperatures, generally between 60-80°C, and is relatively simple and cost-effective compared to other electrolysis technologies.

At the cathode water molecules gain electrons (reduction) to form hydrogen gas and hydroxide ions (OH^-):

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

At the anode the hydroxide ions formed at the cathode migrate through the electrolyte and are oxidized to produce oxygen gas and release electrons:

$$2OH^- \rightarrow O_2 + 2H_2O + 4e^-$$

The overall reaction for ALK, combining both half-reactions, aligns with the general equation for electrolysis. While ALK is less efficient than PEM electrolysis at high current densities, it remains a cost-effective option due to its relatively low cost of materials (Rashid et al., 2015).

Alkaline electrolysers (Figure 22) operate at temperatures between 60 and 80°C, with a Technology Readiness Level (TRL) of 9 for stationary applications and 7 for flexible applications. Their electric consumption is currently around 50 kWh per kilogram of hydrogen produced, with a target reduction to 48 kWh/kg by 2030 (Undertaking, C. H. J, 2022).

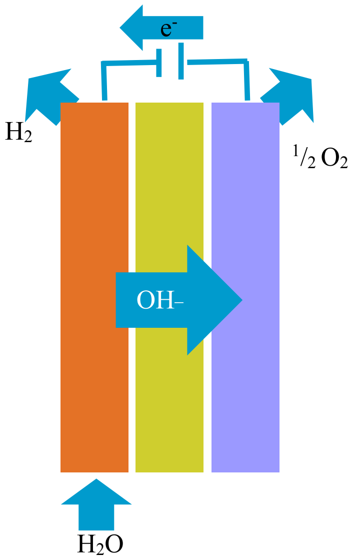

Figure 2- Scheme of an alkaline electrolyser: water enters on the cathode (orange side) where water molecules are reduced to produce hydrogen gas and hydroxide ions. The OH^- ions then flow through the electrolyte towards the purple side, which is the anode. At the anode, the OH^- ions are oxidized, releasing oxygen gas as a byproduct.

In terms of capital expenditure (CAPEX), the current costs are approximately €600 per kW, but this is expected to decrease to €400 per kW by 2030. The ramp-up time from a hot start is around 60 seconds, which is projected to improve to just 10 seconds. For cold start-up, ALK systems currently require about 1 hour, with the goal of reducing this to 5 minutes by 2030.

Alkaline electrolysers are relatively stable, with a degradation rate of 0.12% per 1000 hours, anticipated to drop to 0.10% by 2030. They have a current density of 0.6 A/cm^2, which is expected to rise to 1.0 A/cm^2, reflecting enhanced efficiency. Additionally, they currently use 0.6 mg of critical raw materials (CRMs) as catalysts per watt, but future targets aim to eliminate this need entirely (Undertaking, C. H. J, 2022).

Proton exchange membrane (PEM) (Figure 33) electrolysis employs a solid polymer electrolyte membrane that facilitates the transfer of protons from the anode to the cathode. This technology operates at higher efficiencies than ALK and is generally preferred due to its rapid response to fluctuating power inputs, which makes it well-suited for coupling with renewable energy sources such as solar and wind. At the anode, the oxidation of water produces oxygen gas, protons (H^+) and electrons.

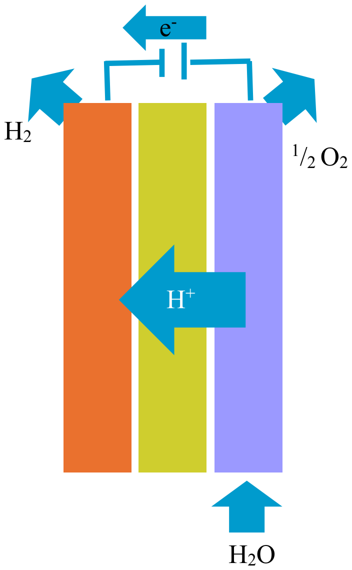

Figure 3- Scheme of PEM electrolyser: the anode (right, purple) is where water enters and undergoes splitting, releasing oxygen. Protons (H^+) generated at the anode pass through the membrane to the cathode (left, orange), where they combine with electrons to produce hydrogen gas.

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$

At the cathode, the protons migrate through the PEM to the cathode, where they are reduced by the electrons to form hydrogen gas.

$$4H^+ + 4e^- \rightarrow 2H_2$$

Operating at a temperature range of 50 to 80°C, PEM electrolysers are at a TRL of 8, indicating their maturity in the market. Presently, they consume around 55 kWh per kilogram of hydrogen, with a target reduction to 48 kWh/kg by 2030. PEM electrolysers also do not require additional thermal input. The CAPEX for PEM electrolysers is higher, at €900 per kW, which is expected to drop to €500 per kW by 2030 as technology and economies of scale improve. PEM electrolysers have a fast ramp-up time from a hot state, taking only 30 seconds, and this could decrease to 10 seconds by 2030. Cold start-up times are currently around 2 hours but may be reduced to 1 hour in the future. PEM electrolysers exhibit a degradation rate of 0.19% per 1000 hours, which is targeted to lower to 0.12% by 2030. Their current density stands at 2.2 A/cm², projected to reach 3.0 A/cm², allowing higher output for the same footprint. While they use 2.5 mg of CRMs as catalysts per watt today, future designs may reduce this to just 0.25 mg/W (Undertaking, C. H. J, 2022).

PEM electrolysis is renowned for its capacity to produce high-purity hydrogen and is typically more compact and efficient than ALK. However, it is also more expensive due to the use of costly membrane materials and catalysts, such as platinum and iridium.

Solid Oxide Electrolysis Cells (SOECs) (Figure 44) represent a high-temperature option for hydrogen production, operating between 650 and 1000°C. SOECs use a solid oxide or ceramic electrolyte, which enhances efficiency by enabling ion conduction and allowing a significant portion of the energy required for electrolysis to be supplied as heat. This makes SOECs particularly suitable for applications where waste heat is available, such as in industrial settings.

Currently, SOEC systems have a Technology Readiness Level of 5-6. They consume around 40 kWh of electricity per kilogram of hydrogen produced, along with an additional 10 kWh/kg of thermal energy, both projected to decrease slightly by 2030 to 37 kWh/kg and 8 kWh/kg, respectively. However, they remain among the most costly, with a CAPEX of €2130 per kW, though future developments aim to reduce this to €520 per kW. In terms of operational flexibility, SOEC electrolysers require around 600 seconds to ramp up from a hot state, with improvements targeted at reducing this to 180 seconds. Cold start-up times are currently substantial, taking up to 12 hours, which may be optimized to around 4 hours. While SOECs experience a relatively high degradation rate of 1.9% per 1000 hours, efforts are in place to improve this to 0.5%. Their current density stands at 0.6 A/cm², with a future goal of achieving 1.5 A/cm². Notably, SOECs do not require critical raw materials (CRMs) as catalysts, offering a sustainability advantage in terms of resource use and cost-efficiency (Undertaking, C. H. J, 2022).

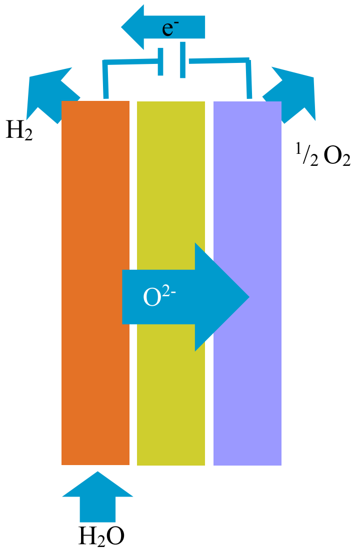

Figure 4- Scheme of a SOEC: the anode is on the right (purple color), where water vapour enters and undergoes the electrochemical reaction, producing oxygen and oxide ions. The cathode is on the left (orange), where the oxide ions migrate through the solid electrolyte to react and generate hydrogen.

The reactions that occur inside the electrolyser are the following:

- at the cathode, water molecules are reduced to produce hydrogen gas and oxide ions.

$$H_2O + 2e^- \rightarrow H_2 + O_{\square}^{2-}$$

- at the anode, the oxide ions migrate through the solid electrolyte and undergo oxidation, resulting in the formation of oxygen gas.

$$O_{\square}^{2-} \rightarrow \frac{1}{2} O_2 + 2e^-$$

SOECs have the potential to achieve efficiencies in excess of 90%, as they are capable of exploiting both electrical and thermal energy. Nevertheless, elevated operational temperatures present challenges related to material durability, necessitating further development for widespread commercial utilisation.

In an alkaline electrolyser utilizing an **anion exchange membrane** (AEM) (Figure 22), represent a promising but nascent technology for hydrogen production. These electrolysers operate at moderate temperatures, typically between 50 and 70°C, and currently have a TRL of 3 to 4. In an alkaline electrolyser utilizing an anion exchange membrane (AEM), water is split into hydrogen and oxygen through electrochemical reactions at the cathode and anode. At the cathode, the reduction of water molecules results in the gain of electrons, leading to the formation of hydrogen gas and hydroxide ions in the following manner:

$$2\,H_2O + 2\,e^- \rightarrow H_2 + 2\,OH^-$$

The hydroxide ions then migrate through the anion exchange membrane to the anode, where they are oxidized. During this reaction, the hydroxide ions release electrons, producing oxygen gas and water:

$$4\,OH^- \rightarrow O_2 + 2\,H_2O \;+ 4\,e^-$$

The water produced at the anode can be recirculated within the system or removed, depending on the design and operational requirements.

The current electricity consumption of AEM electrolysers is approximately 55 kWh per kilogram of hydrogen produced. This is set to be reduced to 48 kWh/kg by 2030. Nevertheless, these systems currently represent one of the costliest options in terms of capital expenditure, with an approximate cost of €1,000 per kW. It is anticipated that advancements will result in a reduction to €300 per kW by 2030, thereby enhancing the economic viability of the technology. The time required for the system to transition from a hot state to operational readiness is approximately 30 minutes. This is anticipated to decrease to 150 seconds with the implementation of future improvements. Similarly, cold start-up times are lengthy, at 30 minutes, with a target of 2.5 minutes as the technology matures. At present, AEM electrolysers exhibit a high degradation rate, exceeding 1% per 1000 hours. However, this could be reduced to 0.5% by 2030. The electrolysers operate at a current density of 0.5 A/cm^2, with the objective of increasing this to 1.5 A/cm^2, which would enhance efficiency and output. Furthermore, AEM systems currently utilize 1.7 mg of critical raw material (CRM) catalysts per watt, a requirement that future designs aim to eliminate entirely. This will enhance both sustainability and cost-effectiveness (Undertaking, C. H. J, 2022).

The following table (**Errore. L'origine riferimento non è stata trovata.**) synthesises the different electrolysis methods, comparing their costs, efficiencies, temperature ranges, and technical readiness levels. This provides an overview of the competitive landscape, and the areas targeted for improvement.

Table 2- Comparison of electrolyzer technologies, detailing their operating temperatures,, energy consumption, capital expenditures (CAPEX), start-up times, degradation rates, current densities, and the use of critical raw material (CRM) catalysts. The table highlights the characteristics and current state-of-the-art specifications of Alkaline (ALK), Proton Exchange Membrane (PEM), Anion Exchange Membrane (AEM), and Solid Oxide Electrolysis Cell (SOEC) technologies (Undertaking, C. H. J, 2022).

Electrolyzer Technology	Operating Temperature (°C)	Electrical Consumption (kWh/kg)	CAPEX (€/kW)	Hot Start Ramp-up Time (s)	Cold Start Time (min)	Degradation Rate (% per 1000 hours)	CRM Catalyst Usage (mg/W)

ALK	60 - 80	50	600	60	60	0.12	0.6
PEM	50 - 80	55	900	30	120	0.19	2.5
AEM	50 - 70	55	1000	1800	30	>1.0	1.7
SOEC	650 - 1000	40 (Thermal consumption 10)	2130	600	720	1.9	0.0

Overview on current hydrogen initiatives from the IEA database

In 2023, hydrogen production projects reaching Final Investment Decision (FID) had a combined capacity of 1.7 MtH_2 annually. By the end of 2024, this figure doubled, with FID-approved projects now totaling an annual production capacity of 3.4 MtH_2. However, projects that have reached FID represent only 4% of all announced projects, which are projected to collectively reach 49 MtH_2/year by 2030—six times the capacity of 2023. Of these announced projects, most involve electrolysis, with the remainder focused on hydrogen production through CCUS technologies. Among FID-approved projects, 55% utilize electrolysis, while 45% rely on CCUS. Electrolyser capacity with FID approval increased from 6 GW in 2022 to approximately 13 GW, driven largely by developments in China and the Middle East, including the NEOM project in Saudi Arabia, which at 2.2 GW and $8.4 billion in investment, stands as the world's largest carbon-free green hydrogen plant, with ALK electrolysers. Today, electrolyser capacity globally has reached around 20 GW, with Europe playing a significant role. However, China still leads, hosting approximately 50% of installed electrolyser capacity.

There are 2,175 electrolyser projects globally, spanning various development stages. Most of these are still in the feasibility study phase, and the specific technology is unspecified for the majority. A comprehensive examination of the data extracted from the database revealed that projects reaching the Final Investment Decision (FID) stage account for a mere 2% of the total announced capacity. Specifically, the combined production capacity of FID-stage projects is 20,519.35 MWel, which represents a mere 2% of the total announced capacity of 1,070,672.71 MWel. This finding indicates that, although only a limited number of projects have reached this pivotal stage, there is considerable potential for future expansion within the sector.

The analysis also demonstrates that alkaline electrolysers represent the majority of FID-approved projects, accounting for 95,145 MWel of capacity, while other technologies constitute the remaining portion. This breakdown is illustrated in detail in Figure 5 below.

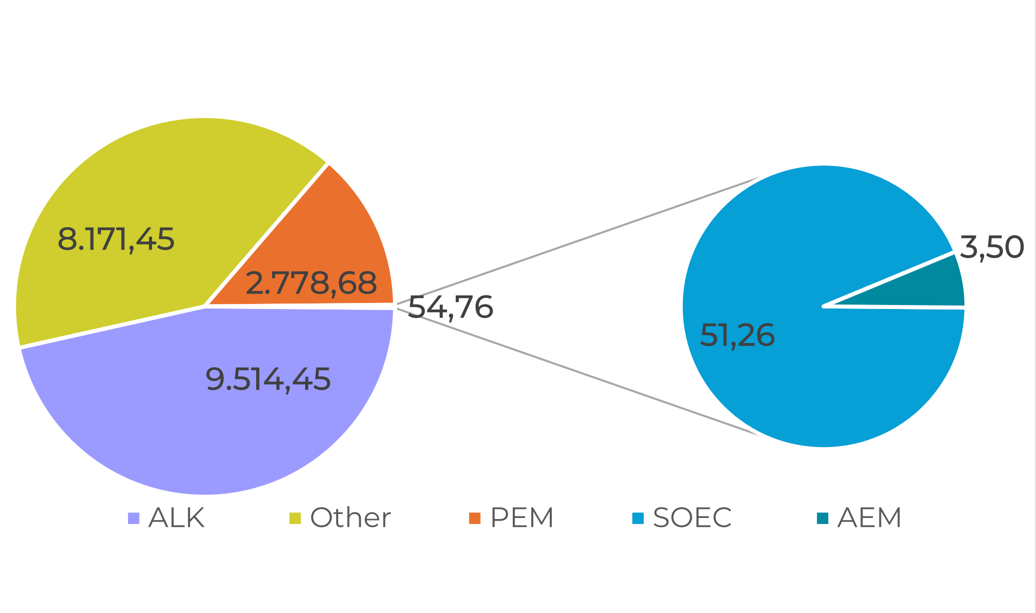

Figure 5 - The pie chart illustrates the estimated MWel capacity at the final investment decision (FID) stage, classified according to technology type.

For hydrogen production with carbon capture, utilization, and storage (CCUS), production capacity has reached around 1.5 Mtpa in 2024, with the United States as the main leader. The US accounts for about three-quarters of the production capacity of projects that have reached the final investment decision, a leadership partly due to its extensive experience in large-scale oil and gas projects

2.3 Storage of Hydrogen

The development of effective hydrogen storage techniques is a crucial step towards the widespread adoption of hydrogen as a sustainable energy carrier. These methods can generally be categorized into two groups: physical-based and material-based storage. In the case of physical-based storage, hydrogen is compressed or liquefied for storage in tanks. In contrast, material-based storage employs the use of specialised materials that facilitate the storage of hydrogen through chemical or physical reactions. Another option for large-scale hydrogen storage is underground hydrogen storage (UHS), which involves injecting hydrogen into subsurface geological formations such as salt caverns, depleted oil and gas reservoirs, or aquifers. UHS provides significant capacity for storing hydrogen at a relatively low cost, making it suitable for balancing seasonal energy demands. However, challenges such as hydrogen purity, leakage risks, and the geological suitability of storage sites must be carefully addressed to ensure safety and efficiency at the end of this chapter a paragraph will be dedicated to give an overview on hydrogen initiatives for underground hydrogen storage. The following figure illustrates the classification of storage types (**Errore. L'origine riferimento non è stata trovata.**6,

Figure 7 - Visual illustration of the different hydrogen storage methods (Tarhan, C., & Çil, M. A. (2021))7).

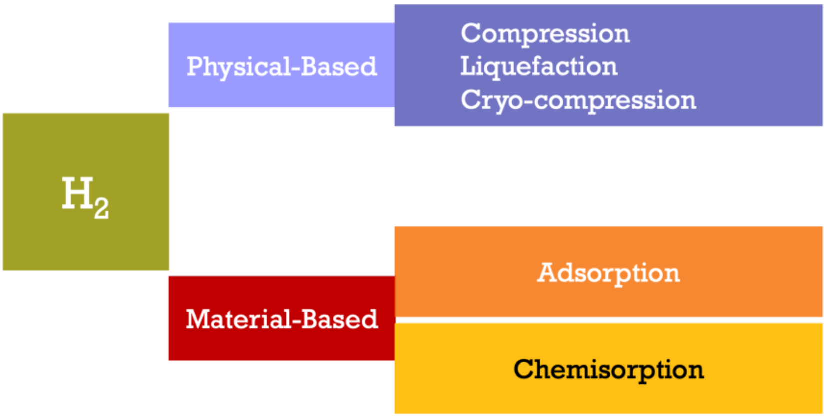

Figure 6 - Hydrogen Storage Techniques

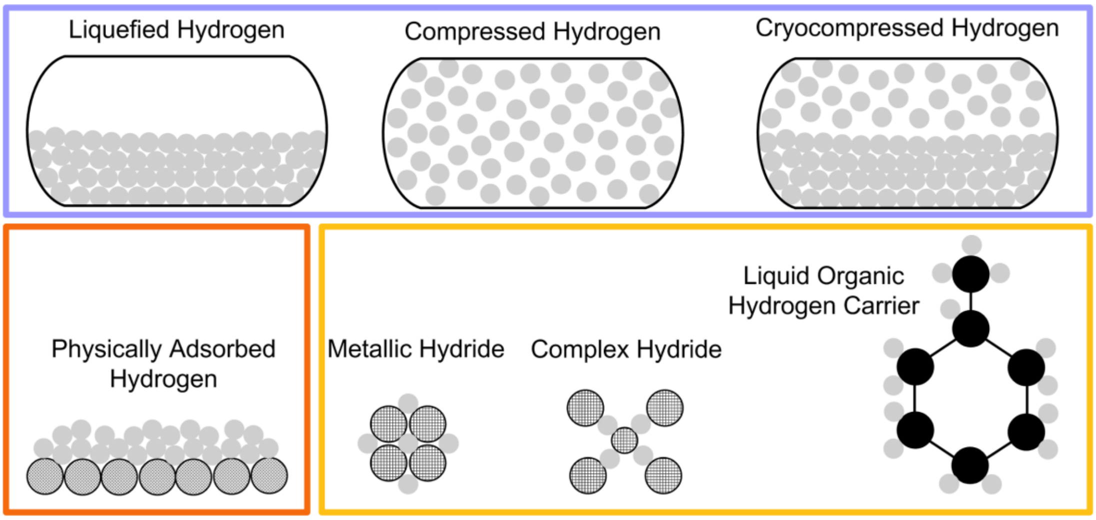

Figure 7 - Visual illustration of the different hydrogen storage methods (Tarhan, C., & Çil, M. A. (2021))

2.3.1 Physical-Based Hydrogen Storage

The advantages of physical-based hydrogen storage include high storage capacity and the ability to rapidly and controllably release hydrogen. Some of the technologies employed in this category have been extensively utilised in the chemical industry and transportation sectors. However, there are also notable disadvantages, such as the high energy consumption that diminishes overall efficiency. The requirement for containers that can withstand high pressures or cryogenic temperatures presents an additional challenge. Furthermore, safety risks, including the potential for leaks, explosions, and fire hazards, are inherent to these methods. Additionally, the costs associated with these methods can be considerable and may present a significant financial barrier. Geological hydrogen storage can be also

Compressed hydrogen is typically stored at pressures ranging from 200 to 700 bar. The technology is mature and widely adopted, with systems designed to withstand the high pressures involved. Type I vessels, made entirely of metal, are the least expensive but can only store hydrogen at lower pressures, up to about 200 bar, and tend to be heavy due to the thick metal walls required to maintain structural integrity. More advanced designs, such as Type II (metal with fiber wrapping), Type III (carbon fiber with a metal liner), and Type IV (fully composite with a polymeric liner) can store hydrogen at pressures up to 700 bar, with each successive type offering better strength-to-weight ratios but at increased cost (Barthelemy et al., 2017; Møller et al., 2017; Moradi & Groth, 2019).

The storage of **liquefied** hydrogen (LH_2) necessitates the cooling of hydrogen to a temperature of -253 °C, whereby it is transformed into a liquid with a density of approximately 71 g/L. This markedly enhances its volumetric energy density to approximately 8 MJ/L, thereby rendering it considerably more space-efficient compared to compressed gaseous hydrogen at 700 bar, which has a volumetric energy density of around 4.8 MJ/L. Nevertheless, the practical energy density may be somewhat reduced due to the necessity of insulation and the weight of the tank. To remain in a liquefied state, hydrogen must be cooled below its critical temperature of -240 °C, as it is unable to be condensed above this temperature. The technology employed in LH_2 storage is well established, offering rapid hydrogen release rates comparable to those of compressed hydrogen and requiring relatively minimal adiabatic expansion energy. The low expansion energy helps to prevent damage in the event of a sudden leak. Although liquid hydrogen achieves a density approximately 1.5 to 2 times that of high-pressure compressed hydrogen, resulting in more compact tank sizes, its storage tanks are maintained at low pressures, allowing the use of thinner, less expensive materials, such as stainless steel or aluminum alloys with sufficient insulation. The liquefaction process it is a highly energy-intensive process, consuming 30-40% of the net heating value of hydrogen (Moradi & Groth, 2019). This high level of energy consumption makes the process costly. A further considerable challenge is that of boil-off, whereby approximately 1.5-3% of the stored hydrogen is lost daily as a result of thermal input from the surrounding environment. The reduction of boil-off necessitates the utilisation of double-walled vacuum-insulated tanks, which, however, result in an increase in weight and a consequent reduction in the overall gravimetric energy density. Furthermore, larger storage tanks with lower surface-to-volume ratios tend to exhibit reduced evaporation loss (Schlapbach & Züttel, 2001; Tarasov et al., 2007). Furthermore, the storage of LH_2 presents significant infrastructure and public acceptance challenges, particularly in public spaces and parking facilities, due to the high boil-off rates.

Cryo-compressed hydrogen storage combines the aspects of both compressed gaseous hydrogen and cryogenic hydrogen. At cryogenic temperatures and pressures between 250 and 350 bar, cryo-compressed hydrogen achieves densities around 80 g/L, roughly 10 g/L higher than liquefied hydrogen, with significantly reduced boil-off losses (Barthelemy et al., 2017). Some researchers showed that cryo-compressed hydrogen tanks, filled to 85% of their capacity, can maintain a dormancy period exceeding seven days without significant hydrogen loss. However, this technology requires double-walled, Type III vessels that are more costly and designed to withstand these demanding conditions (Ahluwalia et al., 2018). While the energy input remains high, hydrogen release and refuelling rates are rapid. The development of the necessary infrastructure to support cryo-compressed hydrogen storage, however, continues to be a significant challenge, limiting the widespread adoption of this technology (Preuster et al., 2017; Usman, 2022).

2.3.2 Material-Based Hydrogen Storage

Materials-based hydrogen storage is considered a secure and efficient approach for storing significant quantities of hydrogen in smaller volumes at ambient temperatures and pressures. The materials utilized in these technologies must exhibit several essential properties, including high volumetric and gravimetric hydrogen densities, widespread availability, ease of processing, cost-effectiveness, and rapid reaction kinetics.

Hydrogen storage in materials is primarily achieved through two mechanisms: **adsorption** and **chemisorption**. In adsorption, hydrogen molecules or atoms adhere to the surface of a solid material. This process typically involves weak van der Waals forces, allowing for the reversible attachment of hydrogen without altering the material’s structure significantly. Chemisorption, on the other hand, involves the chemical binding of hydrogen to the material, often through the formation of hydrides. The materials used for chemisorption include metallic and chemical hydrides, ammonia, and liquid organic hydrogen carriers (LOHCs). During this process, hydrogen molecules undergo dissociation, leading to the formation of hydrogen atoms that integrate into the material's internal structure. Consequently, hydrogen can be stored in a chemically bonded form within compounds containing hydrogen atoms.

Adsorption, or physisorption, is one method of materials-based hydrogen storage, where hydrogen is stored on the surface of materials through weak van der Waals forces. To maximize hydrogen storage, materials used for physisorption must have a high surface area, and storage requires low temperatures (below 77 K) and high pressures (Nijkamp et al., 2001). Carbon-based nanomaterials, such as activated carbon, single and multi-walled carbon nanotubes (CNTs) (Mohan et al., 2019), and metal-organic frameworks (MOFs) (Langmi et al., 2014), are commonly used. These materials can be chemically or physically treated to optimize their hydrogen storage capabilities. Carbon nanotubes are especially advantageous due to their low mass density, high surface area, and chemical stability. In specific conditions, hydrogen adsorption on CNTs can achieve gravimetric storage capacities of 7.75 wt% and volumetric capacities of 0.209 kg H_2/L (Mohan et al., 2019). MOFs also demonstrate promise due to their high specific surface area and suitable pore sizes, with hydrogen storage capacities ranging from 5–9 wt% and 40–60 g/L at 77 K under high pressure (Langmi et al., 2014).

Chemisorption, or chemical adsorption, is a process whereby a material is bonded to hydrogen through the formation of hydrides or similar compounds. The distinction between chemisorption and physisorption lies in the formation of stronger and more enduring chemical bonds. The materials most commonly employed for chemisorption-based hydrogen storage include metallic and chemical hydrides, ammonia (NH_3), and liquid organic hydrogen carriers (LOCHs). In this process, the hydrogen molecules undergo a dissociation reaction, whereby they break down into individual atoms. These atoms then integrate into the material's internal structure, forming stable chemical bonds. This allows for the storage of hydrogen in a chemically bonded form, which may offer greater stability and higher energy densities than other storage methods. For instance, metallic hydrides permit the penetration of hydrogen atoms into the metal lattice, thereby forming either a solid solution or even distinct hydride phases, depending on the prevailing conditions, such as temperature and pressure. In contrast, chemical hydrides, ammonia, and LOHCs are characterised by more complex molecular interactions, facilitating hydrogen storage in liquid or gaseous forms through the formation of chemical compounds that contain bonded hydrogen atoms. The distinctive properties and challenges associated with each of these materials contribute to the versatility and extensive research focus on chemisorption as a method for hydrogen storage in a range of applications (Usman, 2022).

Metal hydrides represent a straightforward method for hydrogen storage, where hydrogen atoms are absorbed into the interstitial sites of a metal lattice. This absorption occurs without the need for hydrogen atoms to replace metal atoms, as they can position themselves within the gaps between metal atoms, enabling relatively free diffusion within the matrix. When absorbed, hydrogen atoms can recombine to form H_2 molecules within the metal, which can then exert internal pressure on the lattice. Over time, this pressure can destabilize the metal structure, leading to a degradation. Degradation is especially problematic for metals like iron, steel, and titanium, as it reduces ductility and compromises structural integrity. Nevertheless, certain metals, such as magnesium, are frequently employed in hydrogen storage applications due to their high absorption capacity. For instance, magnesium hydride (MgH_2) has the capacity to store up to 7.6% hydrogen by weight (I. P. Jain et al., 2010). This renders it advantageous for applications that require a moderate to high hydrogen capacity, particularly given its relatively low cost and lightweight properties. Furthermore, magnesium hydride is highly recyclable, offering the potential for reuse and enhanced sustainability. Metal hydrides generally offer the benefit of rapid kinetics, allowing for quick hydrogen absorption and desorption cycles, which makes them suitable for applications where rapid hydrogen release is essential. However, the overall storage capacity tends to be lower than that of more complex hydride systems, limiting their use in applications that require exceptionally high hydrogen densities(Abe et al., 2019; Ren et al., 2017; Usman, 2022).

Complex metal hydrides, in contrast, utilize hydrogen storage through the formation of covalent bonds within coordination complexes such as $[AlH_4]^-$ in alanates (Bogdanovic et al., 2009) or $[BH_4]^-$ in borohydrides (A. Jain et al., 2018). These compounds typically consist of metallic cations paired with anionic groups, resulting in structures that exhibit high hydrogen storage densities. For example, lithium borohydride ($LiBH_4$) can achieve up to 18.5% hydrogen by weight, significantly surpassing the storage capacities of simpler metal hydrides. While complex metal hydrides offer high storage densities, their high thermodynamic stability often necessitates elevated temperatures for hydrogen desorption. For instance, hydrogen release from $LiBH_4$ typically occurs above 380°C, which poses challenges for practical applications(Ding et al., 2020). Alanates, like sodium aluminium hydride ($NaAlH_4$), are somewhat more manageable, with desorption occurring between 185 and 260°C and yielding around 7.4% hydrogen by weight(Orimo et al., 2007). Although alanates offer lower capacities than borohydrides, they can be catalysed by elements like titanium to improve release rates and decrease operating temperatures. Additionally, amides and imides, such as lithium amide ($LiNH_2$), provide a different approach to hydrogen storage, incorporating nitrogen in their structure to facilitate hydrogen release at moderately lower temperatures, although they can produce ammonia as a byproduct(Zhang et al., 2016). Despite their substantial storage potential, complex metal hydrides often suffer from slow kinetics, posing challenges for applications requiring quick hydrogen uptake and release. Advances in this area include the use of catalysts and compositional modifications aimed at lowering desorption temperatures and improving hydrogen cycling efficiency. Such research endeavours continue to expand the potential for complex metal hydrides, particularly in applications that demand high-density hydrogen storage despite the operational complexities(Usman, 2022).

Liquid Organic Hydrogen Carriers (LOHCs) are defined as stable organic compounds in liquid form that are capable of chemically binding hydrogen. They provide a flexible and scalable solution to hydrogen storage, enabling the utilisation of existing infrastructure for the transportation and storage of fuels. The hydrogenation process, in which hydrogen binds to an organic molecule to form a liquid hydride, necessitates approximately 1 kWh of energy for each kilogram of hydrogen stored (Zhu & Xu, 2015).

Conversely, the dehydrogenation process, which releases hydrogen for energy production, has an associated energy consumption of up to 10.36 kWh/kg of hydrogen. Consequently, the total energy consumption required to store and subsequently release 1 kg of hydrogen ranges from 11.3 to 13.3 kWh(IEA, 2022; Preuster et al., 2017). The cycles of hydrogenation and dehydrogenation present a challenge, necessitating the optimisation of operational conditions in order to maximise efficiency and reduce energy consumption. Cycloalkanes, including cyclohexane, methylcyclohexane (MCH), and decalin, have been the primary focus of LOHC research due to their hydrogen storage capacities, which range from 6.2% to 7.3% by weight, and their ability to remain liquid at room temperature. Methylcyclohexane is an especially promising candidate due to its high hydrogen storage capacity and the stability and non-carcinogenic nature of its dehydrogenation product, toluene. The presence of the methyl group in MCH facilitates dehydrogenation under milder conditions compared to cyclohexane, with complete hydrogen release achievable at approximately 325 °C and 1 bar of pressure. However, despite these advantages, the dehydrogenation cycles of cycloalkanes demand a considerable amount of energy, with enthalpies reaching approximately 68.3 kJ/mol H_2. Innovation in chemical structures into the design of LOHCs has facilitated the development of innovative solutions to address energy challenges. The incorporation of heteroatoms, such as nitrogen, into the cycloalkane framework has been demonstrated to diminish the degree of dehydrogenation, as substantiated by the literature (Usman, 2022).

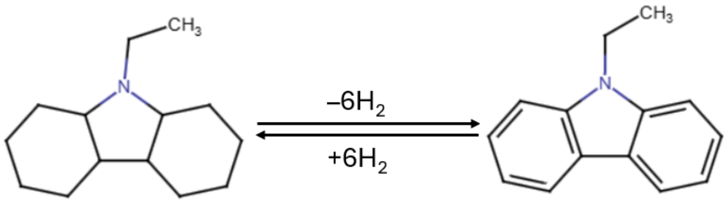

Figure 8 - Reversible reaction of dehydrogenation (–6H_2) and hydrogenation (+6H_2) from dodecahydro-n-ethylcarbazole to N-ethylcarbazole.

For example, dodecahydro-*N*-ethyl carbazole, a nitrogen containing compound, exhibits a dehydrogenation enthalpy lower than 51 kJ/mol and reduced temperatures of approximately 170 °C (Figure 8).

Although the handling of this substance can be complex due to the solidity of the dehydrogenation product, there are solutions that can effectively manage these issues. Other commercially available LOHC options include benzyl toluene and dibenzyl toluene (Figure 99), which demonstrate advantages in thermal stability and handling, remaining liquid throughout the hydrogenation-dehydrogenation cycle. While these compounds have a hydrogen storage capacity of approximately 6.2% by weight, their high viscosity and elevated dehydrogenation temperatures (exceeding 270 °C) may prove an obstacle to their use in mobile applications (Biniwale et al., 2008; Usman, 2022).

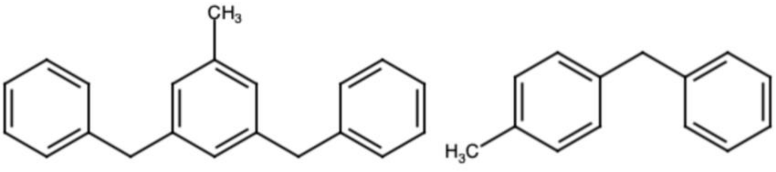

Figure 9 - On the left 3,5 dibenzyl toluene, on the righ is the 4-benzyltoluene

Ammonia (NH_3) is increasingly recognized as a viable hydrogen carrier due to its favourable properties and the existing infrastructure for its production, storage, and transportation. It is considered a promising hydrogen vector, thanks to its globally established infrastructure. With approximately 17.65% hydrogen content, ammonia offers a higher volumetric energy density (12.92–14.4 MJ/L) compared to other hydrogen carriers like methanol and methylcyclohexane, making it efficient for both long-term and short-term storage solutions (Klerke et al., 2008). Current global production of ammonia stands at approximately 180 million tonnes annually (Serpell et al., 2023), primarily through the Haber-Bosch process, which typically requires around 54.28 kWh to incorporate 1 kg of hydrogen into ammonia. From each kilogram of hydrogen, about 5.6 kg of ammonia is produced. This process is energy-intensive and contributes significantly to CO_2 emissions. Transitioning to low-carbon methods, such as electrochemical synthesis using renewable energy, could yield "green ammonia," further enhancing its sustainability credentials. The conversion of ammonia back into molecular hydrogen involves a cracking process that requires temperatures exceeding 900 °C and consumes approximately 9 kWh to produce 1 kg of hydrogen (Aziz et al., 2020). The complete cycle of hydrogen storage and reconversion via ammonia results in a total energy consumption of 64 kWh for each kilogram of hydrogen, not accounting for the energy consumption of electrolysis. Ammonia can then go through two main uses: catalytic cracking to produce hydrogen for fuel cells, which requires high temperatures(>900°C), or direct utilization in ammonia fuel cells. Additionally, the purification of hydrogen post-cracking is crucial due to the sensitivity of fuel cells to impurities, adding further energy costs. On the other hand, direct ammonia fuel cells, particularly solid oxide fuel cells (SOFCs), present an alternative approach, as they can internally decompose ammonia without the need for an additional separation system. This method is still in the early stages of development but shows promise for stationary applications where continuous operation is needed (Serpell et al., 2023). However, the use of ammonia as a hydrogen carrier is not without challenges. Its toxicity and corrosive nature necessitate careful handling and infrastructure to prevent leaks, which could pose health risks. Furthermore, the energy requirements for cracking and compressing ammonia to release hydrogen can diminish its efficiency as a hydrogen carrier compared to direct hydrogen storage. Despite these challenges, ammonia's potential as an energy carrier for sectors with limited access to renewable energy sources, combined with efforts to decarbonize its production processes, positions it as a significant player in the transition toward a low-carbon energy future. Prioritizing the production of green ammonia could not only mitigate emissions from the current fossil-fuel-dependent ammonia industry but also provide a more sustainable pathway for hydrogen transport and storage, aligning with global climate goals.

2.4 Transport of Hydrogen

The current state of hydrogen trade is characterized by minimal activity, primarily confined to localized transportation of hydrogen between neighboring countries and the trade of hydrogen-based products such as ammonia and methanol. According to the Net Zero Emissions by 2050 Scenario, interregional trade in hydrogen is expected to exceed 70 million tons in hydrogen-equivalent (H2-eq) terms by 2050, representing nearly 20% of global low-emissions hydrogen demand. The term "hydrogen-equivalent" standardizes the hydrogen content across various hydrogen carriers, such as ammonia or methanol, enabling a consistent comparison to pure hydrogen when estimating demand and trade volumes. It is currently projected that export-oriented projects will contribute approximately 16 million tons per annum (Mtpa) H2-eq by 2030, suggesting a potential transition toward more international markets.

However, it is important to note that recent announcements have mainly focused on domestic markets, with only marginal increases in anticipated export volumes since the latest Global Hydrogen Review 2023. The market remains uncertain, with 11 Mtpa H2-eq of these projects still in the early stages of development and an additional 5 Mtpa H2-eq undergoing feasibility studies. A significant aspect of the hydrogen trade is the role of ammonia, which constitutes 85% of the trade from announced projects, reflecting the existing infrastructure and experience within the chemical industry for shipping ammonia. Projections indicate that regions such as Australia and the United States could export approximately 10 Mtpa H2-eq by 2030, with Europe identified as the primary import market (IEA, 2024).

Overview on current hydrogen technologies for the IEA database

For underground hydrogen storage, there are not many large-scale projects. A total of 60 projects have been announced, with the operational and FID-stage projects mostly limited to demonstration-scale facilities. One of the primary projects, located in the Netherlands, involves a salt cavern that can store up to 6.5 kt of hydrogen annually and is among the country’s most significant initiatives (HyStock, 2023). For large-scale storage, one major concept-phase project in Germany aims to repurpose a natural gas field to store up to 321.7 kt per year (SEFE, s.d.). Additionally, another large salt cavern project, currently at the concept stage, is designed to store up to 107 kt of hydrogen annually.

2.4.1. Hydrogen pipeline

The majority of hydrogen pipelines are constructed from high-strength steel and are designed to operate at pressures ranging from 30 to 100 bar (Lipiäinen et al., 2023; Liquide, 2005). Globally, dedicated hydrogen pipeline networks extend approximately 5,000 kilometres, with a notable concentration in the United States. In Europe, approximately 1,500 kilometres of operational hydrogen pipelines are in place, primarily serving the chemical and petrochemical sectors (IEA, 2024, p. 20; Lipiäinen et al., 2023)

As indicated in the IEA's report, "Global Hydrogen Review 2024," which includes the figure titled "Technology Readiness Levels of Production of Low-Emissions Hydrogen and Synthetic Fuels, and Infrastructure," the technology readiness level of newly constructed hydrogen pipelines has reached a higher level than that of repurposed natural gas pipelines. This is largely attributable to the heightened maintenance and monitoring requirements associated with repurposing existing natural gas infrastructure, particularly considering concerns surrounding hydrogen embrittlement. The management of natural gas pipelines differs from that of those designed specifically for hydrogen, with repurposing efforts frequently constrained by safety protocols that have yet to mature into a fully established technology (IEA, 2024).

Overview on current hydrogen initiatives from the IEA database

Regarding hydrogen pipelines, there are a total of only 105 projects worldwide, with a total announced length of 42,009 km. Of this, only 17% is at the final investment decision stage or operational, and just 12 km consists of repurposed pipelines. One of the longest pipeline projects is the Italian H2 Backbone, that is part of the SoutH2 Corridor (SoutH2 Corridor, 2023), currently in the feasibility study phase more on this project will be discussed further in section 4.2.2 .

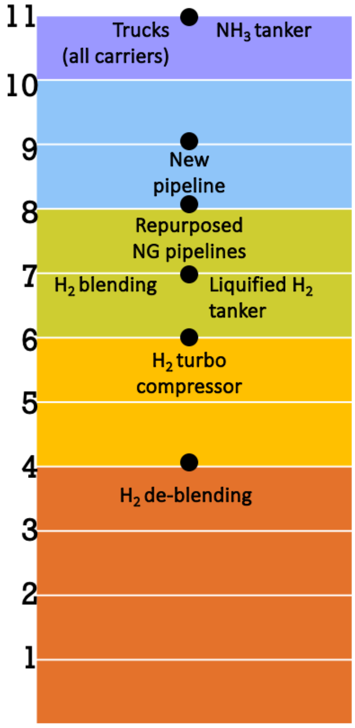

Figure 10- Technology Readiness Levels of transmission and distribution infrastructure for hydrogen (reworked version of International Energy Agency Global Hydrogen Review 2024(IEA, 2024))

2.4.2. Hydrogen blending

Blending hydrogen with other gaseous energy carriers is recognized as a transitional approach to support the deployment of hydrogen infrastructure while demand grows. It can also reduce risks for large-scale production projects during the ramp-up phase. However, blending projects face issues around efficiency, cost implications for end consumers, and safety concerns that have sparked local opposition. Despite these challenges, numerous projects are underway, bolstered by policy decisions that encourage blending hydrogen into existing gas networks. Blends of natural gas and hydrogen are already used in several regions, with future goals to replace fossil-based hydrogen with low-emission alternatives. Gas operators are also actively assessing the feasibility and safety of integrating hydrogen into natural gas networks, with minor modifications needed to adapt existing infrastructure (Erdener et al., 2023). While some hydrogen blending projects are already operational, there are plans for larger-scale initiatives at both the distribution and transmission levels. These efforts are part of a broader strategy to establish the groundwork for hydrogen's role in the energy transition. At the same time, deblending technology—used to separate hydrogen from natural gas in blended networks—remains in early development and is not yet widely available at a large scale. Progress in this area is being made, with recent demonstration projects showing promising results in producing high-purity hydrogen through technologies like membrane separation and pressure swing adsorption. As more hydrogen is integrated into gas networks, further advancements in deblending will be essential for flexible and efficient use of hydrogen across diverse applications.

Hydrogen blending integration into the existing natural gas infrastructure is also highlighted as a pathway for immediate decarbonization in NECP. In Italy hydrogen blending with natural gas is prohibited more than a 5% rate. The problem with hydrogen and NG blending is to separate the two gases: Snam in a workshop held by by Politecnico di Milano, showed that hydrogen can be separated with three main technologies: separation membranes, pressure swing adsorption and cryogenic separation (*Snam*, s.d.).

Figure 11- Graphical rapresentation of differnt methods for the separation of natural gas and hydrogen mixture.

As highlighted by Snam, each technology for hydrogen separation has its own set of pros and cons. For example, separation membranes are ideal for achieving sufficiently purified natural gas, and polymer membranes have a high TRL and are readily available on the market (Snam, s.d., p. 14). However, these membranes are not perfect for obtaining ultra-pure hydrogen and require recompression of the H_2-rich stream. According to studies by SNAM, H2GAR WG3[1] (Snam, 2024), and feedback from major technology providers like Linde, Air Liquide, and Mitsubishi, polymer membranes currently represent the best solution for protecting end users who are sensitive to hydrogen content, such as those using Compressed NG.

Pressure swing adsorption stands out for being suitable for producing high-purity hydrogen from H_2NG mixtures that are sufficiently rich in hydrogen and is backed by a mature technology with a high TRL. On the downside, this method results in natural gas that is not fully purified and at low pressure, necessitating the recompression of the NG-rich stream.

Lastly, cryogenic separation offers the advantage of achieving extremely high purity for all the components in the H_2NG mixture. However, this method comes with significant drawbacks, including high costs and complex plant infrastructure.

The main drawback of hydrogen blending for industrial application that require H_2 as a feedstock in their processes is the necessity for purity levels, due to the fact that H_2 must be employed for reactions with a range of other substances. The quantities that can be transported are often too small to make this worthwhile.

2.4.3. Shipping hydrogen

Shipping hydrogen over long distances presents significant challenges, and various methods have emerged to facilitate this process. The primary approaches include transporting hydrogen as liquefied hydrogen, ammonia, and liquid organic hydrogen carriers (LOHCs), each with unique infrastructure requirements, energy losses, and trade-offs. Shipping hydrogen in its liquefied form requires cooling it to −253°C, which is energy-intensive and demands specialized cryogenic tankers and port

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[1] H2GAR is a collaborative initiative among most relevant European TSOs with the primary objective to share expertise on the injection of hydrogen into the natural gas pipeline, and aims to assess the readiness to transport hydrogen, whether in pure form or as part of a blended gas mixture. The working group 3 (WG3) has the goal to identify the most cost-effective and energy-efficient solutions.

facilities. Liquefaction losses can account for approximately 25-30% of the hydrogen's original energy content, with additional energy input needed to maintain these low temperatures during transport. Boil-off losses may also occur, although modern tanks are designed to minimize these (IEA, 2022). Despite these challenges, liquefied hydrogen allows for high-density storage and is suitable for large-scale transport, though only a few ports are currently equipped for such extreme conditions, necessitating substantial investments in deep-water berths and cryogenic storage. Ammonia offers an alternative as it can be transported using established global infrastructure, minimizing the need for new facilities. Converting hydrogen into ammonia is relatively efficient, with conversion losses generally around 13-15% (Serpell et al., 2023). However, reconverting ammonia back into hydrogen at its destination (a process called cracking) can result in additional losses of 20-30% (IEA, 2022; Serpell et al., 2023). While this adds energy costs and complexity, the existing logistics network for ammonia makes it a viable option for scaling up hydrogen transport. LOHCs present a versatile alternative as they allow hydrogen to be chemically bound to liquid compounds that can be transported using standard chemical tankers without specialized cooling. This method takes advantage of existing oil and chemical storage infrastructure, which provides flexibility across ports worldwide. Energy losses occur primarily during the hydrogenation and dehydrogenation processes, with hydrogenation losses around 10-15% (IEA, 2022; Sekine & Higo, 2021) and dehydrogenation losses ranging from 20-30% (Sekine & Higo, 2021). Despite these, LOHCs benefit from compatibility with conventional infrastructure, reducing the need for dedicated logistics investments. While ammonia facilities are expanding to meet rising demand and LOHCs can leverage existing oil storage setups with minimal changes, the liquefied hydrogen market is still developing. Successful demonstration shipments have been completed, such as from Australia to Japan, yet scaling up will require substantial infrastructure investments. The choice of transport method depends on balancing energy losses, infrastructure availability, and scalability, as each approach involves specific efficiency trade-offs and impacts on the hydrogen supply chain (IEA, 2022).

2.5 Utilization and Applications

Currently, hydrogen is predominantly used in fertilizer production, oil refining, and petrochemicals, which together account for about 2% of global CO_2 emissions. In 2022, global hydrogen demand reached approximately 95 million tonnes (IEA, 2023b), and this number increased by about 2.5% to 97 Mt in 2023 (IEA, 2024). Hydrogen's pivotal role in industrial processes, such as ammonia production, underscores its significance. However, there is growing recognition of hydrogen's potential to reduce emissions across emerging sectors like heavy industry, transportation, and power generation, leading to heightened interest and investment in low-emission hydrogen technologies.

The table below illustrates both actual and projected hydrogen demand across various sectors, highlighting the anticipated growth in applications aligned with the International Energy Agency's Net Zero Emissions by 2050 Scenario (IEA, 2023b):

Table 3- Projected Hydrogen Demand by Sector (2022-2040) (IEA, 2023b)

Year	Total Demand	Refining (Mt H_2)	Industry (Mt H_2)	Transport (Mt H_2-eq)	Power Generation (Mt H_2-eq)	Other (Mt H_2)
2022	95	42	53	0	0	0
2025	150	35	71	16	22	6
2030	215	26	92	40	48	10
2040	430	10	139	193	74	14

In 2022, the refining industry consumed approximately 44% of total hydrogen demand, primarily for hydrodesulfurization—a process critical for producing cleaner fuels. However, this reliance is expected to decline sharply, with refining's share projected to fall to just 2% by 2040. As the industry shifts towards more efficient processes and alternative technologies, transitioning to low-emission hydrogen in refining presents both opportunities and challenges regarding economic viability and infrastructure readiness. Energy-intensive industries such as chemicals, steelmaking, and heavy transport face significant hurdles to electrification due to the need for extremely high temperatures and hydrocarbon-based feedstocks, as well as limitations in grid capacity. These sectors, along with ammonia and methanol production, represents a significant portion of hydrogen consumption. In 2022, industrial applications accounted for 56% of total demand, a figure expected to drop to 32% by 2040 as more sustainable practices emerge. Ammonia production, crucial for fertilizers, relies on hydrogen through the Haber-Bosch process, while methanol serves as a feedstock for various chemical products. Incorporating low-emission hydrogen technologies in these areas could greatly reduce emissions, supporting global climate objectives (IEA, 2023b, 2023a, 2024).

The transportation sector is expected to witness the most dramatic changes, with hydrogen-based fuels projected to grow from negligible amounts in 2020 to approximately 193 Mt of hydrogen equivalent by 2040, constituting 45% of total demand. This growth will primarily focus on heavy-duty vehicles, shipping, and aviation, as these sectors explore hydrogen's potential to replace traditional fossil fuels. To facilitate this transition, targeted policies and incentives will be crucial in overcoming barriers to market uptake. Simultaneously, the power generation sector is poised for significant increases in hydrogen demand, moving from zero Mt in 2020 to an anticipated 74 Mt by 2040. This surge will be driven by the integration of hydrogen and ammonia-based generation technologies. Countries like Japan and South Korea are leading efforts to develop dedicated auctions and support systems for these technologies, recognizing hydrogen's potential to provide a stable and low-emission energy supply (IEA, 2024).

The growth in demand for hydrogen shows a big change in how energy is used. This shows that we need to produce energy in a cleaner way and improve how we use it to meet the targets set out in global climate agreements. As industries change, hydrogen will play an important part in creating sustainable energy systems (IEA, 2023b).

2.6 Hydrogen Safety

Hydrogen safety is a critical aspect in the development and expansion of the hydrogen economy, addressing risks related to its production, storage, and transportation its fundamental. Hydrogen's properties, including its high flammability, wide explosive range (4–75% by volume in air), and low ignition energy (as little as 0.017 mJ), require robust safety protocols to minimize the potential for accidents. Its small molecular size makes it prone to leakage, challenging the integrity of storage and transport systems. Hydrogen can cause material failure (embrittlement), which can lead to leakage that could be followed by a mixture of air in a certain space to form a gas cloud. If the gas could encounters an ignition source, hydrogen cloud easily create an explosions. Even without ignition sources, high-pressure hydrogen leakage may cause spontaneous combustion and explosion. For these, and more, reasons safety considerations need to extent across multiple stages of the hydrogen value chain, demanding attention to material selection, system design, and operational practices.

2.6.1 Hydrogen embrittlement

For the above-mentioned physical-based hydrogen storage and pipeline transport a typical phenomenon that could put at risk hydrogen safety is **hydrogen embrittlement**, a metallurgical phenomenon that occurs when hydrogen atoms interact with ferrous metals under specific pressures and temperatures, compromising the material's structural integrity. This process can result in a significant reduction in ductility and strength, often leading to cracking or sudden failure of components. Hydrogen embrittlement is particularly critical in hydrogen storage systems, as it can rapidly deteriorate the materials used in tanks, pipelines, and other containment structures.

Hydrogen atoms, due to their small size, diffuse into the metal's lattice structure, accumulating at grain boundaries or defects. This weakens the atomic bonds and creates stress concentrations, which under operational loads can propagate cracks. The risk is especially high in high-strength steels and alloys commonly used in industrial applications, as these materials are more susceptible to embrittlement.

Choosing materials resistant to hydrogen embrittlement is essential. Standards like ASTM and ISO guide material selection, favoring alloys with lower yield strength, higher ductility, or protective coatings. Surface treatments such as nickel plating or polymer-based coatings prevent hydrogen diffusion, while thoughtful design, including rounded shapes and the elimination of sharp edges, reduces stress concentrations and cracking risks.

Operational practices are equally critical. Controlled pressure and temperature conditions, regular inspections, and maintenance help detect and address early material degradation. Advanced sealing technologies, purging with inert gases, and static electricity management mitigate risks. Compliance with safety standards, continuous monitoring, and adopting detection systems ensure reliability. These measures collectively enhance the safety and scalability of hydrogen storage systems, supporting its broader adoption as a clean energy carrier.

2.6.2 Key regulation for hydrogen safety

Hydrogen safety is governed by a robust framework of technical regulations and operational guidelines to mitigate the unique risks associated with its production, storage, and use. Hydrogen's wide flammability range, low ignition energy, and potential for embrittlement in metallic components necessitate specific safety protocols. In Italy, several key regulations address these challenges like Decree 23 October 2018 establishes fire prevention technical rules for the design, construction, and operation of hydrogen distribution systems for vehicles. It specifies safety distances, ventilation requirements, and emergency procedures.

The Decree 7 July 2023 provides technical guidance on fire prevention for hydrogen production facilities using electrolysis and related storage systems. It outlines methodologies for risk analysis and prescribes safety measures tailored to production and storage risks.

Legislative Decree 9 April 2008, n. 81 focuses on workplace health and safety, emphasizing the prevention of explosive atmospheres, elimination of ignition sources, and mitigation of explosion damage. These principles are also reflected in chapter V.2 of Decree 3 August 2015, which provides analogous criteria for assessing and reducing explosive atmosphere risks.

The in Europe the Directive 2014/68/UE (Pressure Equipment Directive, PED), transposed into Italian law by Legislative Decree 15 February 2016, n. 26, regulates pressure equipment to ensure the integrity of hydrogen storage and transport systems under high pressure.

Advanced systems for fire and gas detection, anti-surge protections in compressors, and real-time monitoring of critical parameters like pressure and temperature are essential. These measures, supported by adherence to the regulatory framework, ensure that hydrogen systems operate safely, minimizing risks to people and infrastructure.

3. INTERNATIONAL POLICIES FRAMEWORK AND INITIATIVES FOR HYDROGEN

The global momentum towards a hydrogen-based economy is gathering pace, with hydrogen positioned to play a pivotal role in achieving climate neutrality and reinforcing energy security. This chapter explores the national and international context, examining the policies and initiatives that are driving the advancement of hydrogen technologies. The European Union, with its ambitious legislative framework and strategic objectives, is at the vanguard of efforts to promote hydrogen as a key clean energy vector. Furthermore, global collaboration through international projects and initiatives has been pivotal in advancing hydrogen production, transport, and transformation. This chapter provides a detailed analysis of the most influential international policies and highlights significant global and European projects, which together address the technological and infrastructural challenges involved in building a sustainable hydrogen economy.

3.1 Global Policy Framework

The global landscape of hydrogen policies is experiencing rapid expansion as an increasing number of countries adopt dedicated strategies to promote hydrogen as a clean energy vector. In the last year alone, 19 nations—primarily from emerging markets and developing economies (EMDEs)—have introduced new hydrogen strategies, with an overarching focus on decarbonization, energy security, industrial growth, and the development of export-ready hydrogen markets. Interestingly, these recent strategies do not anticipate hydrogen imports, indicating a commitment to self-reliance and a drive to build robust domestic industries geared for export. Altogether, countries with hydrogen strategies now account for over 84% of global energy-related CO_2 emissions, highlighting hydrogen's integral role in the decarbonization roadmap (2024, IEA). Globally, almost 60 nations have set national hydrogen agendas, accompanied by nearly 100 billion USD in public funding directed toward hydrogen projects. However, a significant portion of this funding—around two-thirds—remains at the announcement stage, reflecting a level of uncertainty. Notably, 95% of these funds come from advanced economies, underscoring the disparity in policy maturity and funding capacity between developed and emerging markets (2024, IEA).

This wave of policies marks a shift from setting targets to actively implementing them, with advanced economies allocating almost 1.5 times more funding to the supply side of hydrogen than to the demand side (IEA, 2024). Many countries envision hydrogen as an export commodity, fostering domestic industries aimed at international markets, specifically, the number of emerging markets and developing economies joining this trend is rising, with 19 new national hydrogen strategies released since October 2023, including in Africa, Southeast Asia, and Latin America.

Association of Southeast Asian Nations country members have advanced significantly, with Indonesia, Malaysia, and Viet Nam adopting hydrogen strategies (IEA, 2024; Shibata et al., 2024). In Europe, countries such as Bulgaria, Estonia, Ireland, Lithuania, and Romania have issued new strategies, many of which set renewable hydrogen targets. Lithuania and Romania, for example, have ambitious electrolysis capacity goals, while Ireland emphasizes offshore wind potential. Meanwhile, Germany and France have updated their strategies, with Germany prioritizing import diversification and France launching a higher electrolyser target by 2030 (IEA, 2024). Countries with existing plans, like Chile (Gobierno de Chile, 2023) and Canada (Government of Canada, 2024), have published detailed updates on project pipelines and incentives to accelerate development.

In advanced economies, subsidies and direct grants have become a common means of offsetting the CAPEX associated with large-scale hydrogen production infrastructure. These direct grants, which constitute 99% of subsidies globally, facilitate the de-risking of investments, enable the achievement of lower capital costs, and align project developers' activities with the long-term economic goals of the hydrogen industry. In contrast, in EMDEs, tax incentives are more prevalent, reflecting disparate economic and regulatory priorities (IEA, 2024). Furthermore, competitive bidding has emerged as a prominent mechanism for fostering market formation and price discovery. Countries such as Egypt, India, and Oman have deployed auctions to stimulate competition and create transparent price signals (IEA, 2024). Some European countries have adopted a more innovative approach by experimenting with Contracts for Difference (CfD) mechanisms that provide revenue guarantees for hydrogen producers. The United Kingdom, for instance, has implemented CfD tenders offering prices as high as 10 USD per kilogram of hydrogen, whereas Denmark has adopted competitive bids at prices as low as 0.16 USD per kilogram (GOV.UK, 2023).

Globally, public policy support for hydrogen is advancing beyond financial incentives and towards the standardization of certification schemes, which are essential for establishing a universally recognized definition of low-carbon hydrogen. During the COP28 negotiations, 37 governments pledged to work towards mutual recognition of national certification systems based on shared design principles. In Latin America, 14 countries launched "CertHiLAC," a certification initiative backed by multilateral development banks to create regional alignment (OLADE, 2024). The International Organization for Standardization (ISO) is contributing to this effort by developing a standardized methodology for calculating greenhouse gas (GHG) emissions from hydrogen production, conditioning, and transportation, expected to culminate in a formal ISO standard by 2025 or 2026 (ISO, 2023). Latin America, notably Brazil and Chile, is becoming a focal point for hydrogen development. Brazil has implemented the Brazilian Hydrogen Certification Scheme (SBCH2), establishing a greenhouse gas threshold of 7 kg CO_2-equivalent per kilogram of hydrogen for low-carbon classification (GOV.BR, 2024). Chile, with its updated action plan, is advancing concrete measures to develop hydrogen infrastructure, production, and export capabilities (Gobierno de Chile, 2023). By aligning their domestic policies with international standards, both nations are positioning themselves as competitive players in the future global hydrogen market.

The evolving landscape of hydrogen policy presents both opportunities for advancement and challenges that must be overcome. While there has been a notable increase in policy support, the discrepancy between the funding allocated to supply and demand, the uncertain status of the funding that has been announced, and the still-developing infrastructure for global certification and standardisation highlight the path forward. As the sector continues to expand, the harmonization of regional standards, funding mechanisms, and market incentives will be pivotal to accelerating hydrogen's role as a global energy carrier and meeting the ambitious targets set forth by net-zero scenarios. The pace and efficacy of these policy advancements will ultimately determine the role of hydrogen in the future energy mix, with far-reaching implications for both climate mitigation and economic development on a global scale.

3.2 EU Hydrogen framework

Following the overview of the current state of global hydrogen policies, this section will provide a more detailed examination of the policies within the European Union's political framework concerning hydrogen. Given the crucial role that hydrogen technologies play in the EU's decarbonisation efforts, they are supported by a comprehensive framework of both legislative and non-legislative policies. These policies can be categorized into four main areas: cross-cutting, hydrogen production, transport, storage and distribution, and hydrogen end-use. This section will also cover the various funding mechanisms and initiatives dedicated to advancing hydrogen technologies within the EU,

3.2.1 EU Hydrogen Policies and regulatory framework

Cross-cutting policies form the foundation for the EU’s hydrogen economy, supporting overarching goals for decarbonization, industrial competitiveness, and energy system integration. At the core of the EU’s climate agenda, the *European Green Deal*[2], introduced in 2019, sets ambitious targets to achieve net-zero greenhouse gas emissions by 2050 and a 55% reduction by 2030. This policy framework is more than a climate initiative; it represents a growth strategy aimed at transforming the EU’s economy into one that is resource-efficient, globally competitive, and decoupled from unsustainable resource use. Hydrogen is integral to these targets, particularly in hard-to-abate sectors such as industry, transportation, and energy storage, where its potential to drive emissions reductions is essential. *The European Climate Law*[3], adopted in

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[2] The European Green Deal (europa.eu)

[3] European Climate Law-European Commission (europa.eu)

June 2021, turns the EU's climate goals into legal obligations, establishing binding targets that codify the net-zero emissions goal for 2050 and the interim 2030 goal. To achieve these milestones, the EU has implemented the *"Fit for 55"*[4] legislative package, which revises and introduces a range of laws focused on renewable hydrogen production, energy efficiency, and carbon trading. These laws collectively create a robust regulatory foundation for the hydrogen economy, addressing each stage of the hydrogen value chain: production, distribution, storage, and end-use. Relevant regulations under Fit for 55 include the EU Emissions Trading System[5] (ETS), the Renewable Energy Directive, the Carbon Border Adjustment Mechanism[6] (CBAM), and directives aimed at sustainable fuel infrastructure and energy performance in buildings.

The *Energy System Integration Strategy* and the *European Hydrogen Strategy*[7], both introduced in 2020, emphasize hydrogen's versatility and its capacity to act as a bridge between various energy systems. Recognizing hydrogen's potential in industrial applications like cement, steel, and fertilizers, as well as in long-haul transport, these strategies aim to establish hydrogen as a key technology for hard-to-abate sectors. The European Hydrogen Strategy sets ambitious production goals, targeting 6 GW of renewable hydrogen capacity by 2024 and expanding to 40 GW by 2030, a move that is pivotal for scaling the EU's clean hydrogen market and advancing energy storage solutions. Complementing these policies, the *EU Industrial Strategy*[8] aims to position the EU as a leader in climate-neutral industries by 2050. This includes establishing the European Clean Hydrogen Alliance (ECH2A) in 2020, which brings together stakeholders from industry, government, and finance to create a viable investment pipeline for hydrogen projects across the EU (European Commission, 2020). This alliance supports the development of a competitive and sustainable hydrogen market

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[4] 'Fit for 55': delivering the RU's Climate Target on the way to climate neutrality
[5] EU's Emission Trading System-European Commission (europa.eu)
[6] Carbon Border Adjustment Mechanism-European Commission (europa.eu)
[7] Powering a climate-neutral economy: An EU Strategy for Energy System Integration-European Commission (europa.eu)
[8] European industrial strategy - European Commission (europa.eu)

that will play a significant role in reducing greenhouse gas emissions while creating jobs and fostering economic growth.

In response to the geopolitical challenges presented by the war in Ukraine, the EU also launched the *REPowerEU*[9] plan in 2022. This plan is crucial for reducing the EU's dependency on Russian fossil fuels and accelerating the energy transition. Within this framework, the EU aims to domestically produce 10 million tons of renewable hydrogen and import an additional 10 million tons by 2030. REPowerEU not only seeks to safeguard the EU's energy security but also amplifies the 2030 renewables target from 40% to 45%, underlining the strategic importance of hydrogen in achieving these goals. The *Green Deal Industrial Plan*[10], introduced in early 2023, enhances the EU's capacity to manufacture net-zero technologies, including hydrogen production infrastructure.

The EU's **hydrogen production policies** are designed to promote renewable and low-carbon hydrogen production by establishing clear targets and regulatory frameworks. The *Energy Efficiency Directive*[11] (EED), although not hydrogen-specific, indirectly supports the sector by enhancing energy efficiency across the EU, which is crucial for making hydrogen production more cost-effective and sustainable. Similarly, the *Renewable Energy Directive*[12] (RED) establishes clear targets to increase renewable hydrogen: by 2030, 42% of hydrogen used in industry must be from renewable sources, increasing to 60% by 2035, with a requirement that 1% of hydrogen in the transport sector be renewable by 2030. The *EU Emission Trading System* (EU ETS), a cap-and-trade mechanism, also encourages cleaner hydrogen production methods by including low-carbon hydrogen in the system, making renewable options more attractive as carbon prices rise. To prevent carbon leakage and support EU industries, the *Carbon Border Adjustment Mechanism* (CBAM) places a carbon price on imported goods, thus incentivizing the use of renewable hydrogen in high-carbon sectors like

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[9] REPowerEU plan
[10] The Green Deal Industrial Plan
[11] Energy Efficiency Directive
[12] Renewable Energy Directive

steel and cement. Additionally, the Gas Market Decarbonisation Package aligns existing gas market regulations with the EU's clean energy goals, fostering a regulatory environment conducive to hydrogen integration. The *Net Zero Industry Act*[13] promotes investment in low-cost renewable hydrogen production by supporting strategic technologies like electrolysers and fuel cells, essential to the EU's climate neutrality objectives. Finally, the *Critical Raw Materials Act*[14] secures access to materials needed for hydrogen technologies, ensuring stable supply chains for electrolyser production and other hydrogen-related equipment, thereby facilitating the scale-up of hydrogen infrastructure. Together, these policies build a comprehensive framework that supports the growth of hydrogen production and its integration into the EU's energy system.

Here is a summary table of the main EU policies for hydrogen production:

Table 4- EU hydrogen production policies

Policy	**Objective**	**Impact on Hydrogen Production**
Energy Efficiency Directive (EED)	Improve energy efficiency across the EU	Reduces energy consumption in hydrogen production, indirectly lowering costs and supporting sustainability.
Renewable Energy Directive (RED)	Increase renewable energy in hydrogen and other sectors	Sets specific targets: 42% renewable hydrogen in industry by 2030 (60% by 2035) and 1% renewable hydrogen in transport by 2030.
EU Emission Trading System (EU ETS)	Reduce GHG emissions via cap-and-trade	Encourages cleaner hydrogen production by making low-carbon options more economically viable with rising carbon prices.
Carbon Border Adjustment Mechanism (CBAM)	Prevent carbon leakage and support EU industries	Imposes carbon prices on imports, incentivizing renewable hydrogen use in carbon-intensive sectors like steel and cement.

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[13] Net Zero Industry Act

[14] Critical Raw Materials Act

Gas Market Decarbonisation Package	Align gas regulations with clean energy goals	Establishes a supportive regulatory environment for integrating hydrogen into the EU energy system.
Net Zero Industry Act	Support strategic, net-zero technologies	Promotes investment in electrolyses and fuel cells, essential for scaling low-cost renewable hydrogen production.
Critical Raw Materials Act	Ensure stable access to key materials	Secures raw materials for electrolyser and hydrogen equipment production, supporting the growth of hydrogen infrastructure.

Policies for **hydrogen transport, storage, and distribution** are crucial to developing a sustainable hydrogen economy. Key frameworks under the Fit for 55 package—such as the FuelEU Maritime, ReFuelEU Aviation, and Alternative Fuels Infrastructure Regulation—set the foundation for expanding hydrogen infrastructure. These initiatives build on the European Commission's *Sustainable and Smart Mobility Strategy*[15], published in 2020, which envisions a transport system that integrates sustainable fuels, infrastructure, and demand management to drive decarbonization. The strategy specifically targets hydrogen, projecting it to cover 31-40% of road transport fuels by 2050 and e-fuels to account for 10-17%. It aims to deploy 500 hydrogen refueling stations by 2025 and 1,000 by 2030.

Aligned with these goals, the *Trans-European Network for Transport* (TEN-T) supports a seamless, multimodal EU transport network and is undergoing revisions to meet the EU's 90% emissions reduction target by 2050. The updated guidelines will ensure hydrogen refueling stations every 200 km along key corridors by 2030, reinforcing connectivity and sustainable mobility. Furthermore, *Alternative Fuels Infrastructure Regulation*[16] establishes binding targets to ensure hydrogen refueling availability in urban centers and along core EU corridors, addressing the infrastructure gap that has previously hindered hydrogen vehicle adoption.

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[15] Sustainable and Smart Mobility Strategy

[16] Alternative Fuels Infrastructure Regulation

In maritime and aviation sectors, *FuelEU Maritime*[17] and *ReFuelEU Aviation*[18] drive decarbonization by setting carbon intensity limits and mandating minimum shares of sustainable aviation fuels (SAFs). FuelEU Maritime supports the use of renewable fuels from non-biological origin (RFNBOs), including hydrogen-based fuels like ammonia and methanol, with incentives to boost early adoption. ReFuelEU Aviation sets progressive SAF targets, beginning at 2% in 2025 and reaching 70% by 2050, with a sub-target for hydrogen-based synthetic aviation fuels. These initiatives offer long-term clarity and encourage scaling up renewable hydrogen use across key EU transportation sectors.

End-use hydrogen policies support its adoption across industry, transport, and building sectors, making it more viable through financial incentives, emission standards, and green infrastructure initiatives. The *Energy Taxation Directive*[19] is a key example, aiming to shift the tax burden from labor to pollution. Under the Fit for 55 package, this directive proposes taxes based on environmental performance, with carbon-intensive fuels taxed more heavily while renewable and low-carbon hydrogen receives lower rates, making it a competitive market alternative. For transportation, the *CO_2 emissions performance standards for cars, light-duty*[20] and *heavy-duty vehicles*[21] *and* set progressively stringent emission reduction targets, encouraging automakers to adopt low- and zero-emission technologies, including hydrogen fuel cells. By 2035, all new commercial vehicles in the EU must be zero-emission, a move that further accelerates demand for hydrogen-powered vehicles. Supporting this transition, *Public Procurement for Clean Vehicles*[22] mandates that public fleets integrate clean vehicles, like fuel cell electric vehicles to help grow hydrogen's presence in public transit and heavy transport.

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[17] FuelEU Maritime
[18] ReFuelEU Aviation
[19] Energy Taxation Directive
[20] CO_2 emissions performance standards for cars and light duty vehicles
[21] CO_2 emissions performance standards for cars and heavy-duty vehicles
[22] Public Procurement for Clean Vehicles

These policies drive hydrogen market growth and advance the EU's broader decarbonization goals by embedding hydrogen in key sectors and establishing ambitious standards for emissions and energy efficiency.

3.2.2 EU Fundings and Initiatives

In response to the COVID-19 crisis, the European Union in 2020 rolled out an unprecedented financial stimulus package of €2.018 trillion, aimed at supporting recovery, resilience, and long-term development across Europe. This package includes the EU's 2021–2027 Multiannual Financial Framework (MFF) of €1.211 trillion (European Parliament, 2024), reinforced with €806.9 billion through the NextGenerationEU initiative (europa.eu, s.d.). The additional funding aims to provide a targeted boost to address essential recovery needs, economic resilience, and sustainability objectives, with multiple programs directly supporting the growth of hydrogen technologies and infrastructure.

The following table provides an overview of the most significant funds available in EU for the development of hydrogen technology.

Table 5- EU funding instruments for the development of hydrogen technologies

Funding Instrument	**Budget Allocation**	**Relevant Areas for Hydrogen**
Recovery and Resilience Facility (RRF)	€723.8 billion (2021-2027)	Member State projects that integrate hydrogen into green recovery efforts.
InvestEU	€372 billion mobilized, €26.2 billion guarantee	Projects for hydrogen infrastructure, R&D, and market development.
Cohesion Policy	Regional allocations based on impact	Hydrogen projects in energy transition for carbon-intensive regions, supported by regional and just transition funds.
Modernisation Fund	Varies (based on 10-country eligibility)	Funds hydrogen projects, including green hydrogen production and applications in transport and power sectors.

Connecting Europe Facility (CEF)	Energy (€5.8 billion), Transport (€25.8 billion)	Cross-border hydrogen transport, storage projects, and electrolysers of 100 MW+ capacity.
Innovation Fund	Up to €20 billion	Large-scale hydrogen projects in industries, CCS/U, and renewable energy innovations, including competitive hydrogen auctions.
Horizon Europe	€95.5 billion (2021-2027)	Research, development, and innovation in hydrogen technology deployment and hydrogen-focused projects.
LIFE Programme	€5.43 billion	Early-phase hydrogen demonstration projects and governance support for clean energy transition.
Clean Energy Transition Partnership	€800 million for R&D initiatives	Research and development initiatives for hydrogen technologies as part of broader clean energy transition goals.
State Aid (CEEAG, GBER, IPCEI)	Variable, state-dependent funding	Cross-border, high-risk hydrogen projects with strategic impact on EU energy objectives.

3.2.3 Hydrogen Strategies in EU countries

On the **European Hydrogen Observatory website,** which was updated in May 2024, there is a map that shows how many countries have a national hydrogen strategy and how many have a draft and which country have none

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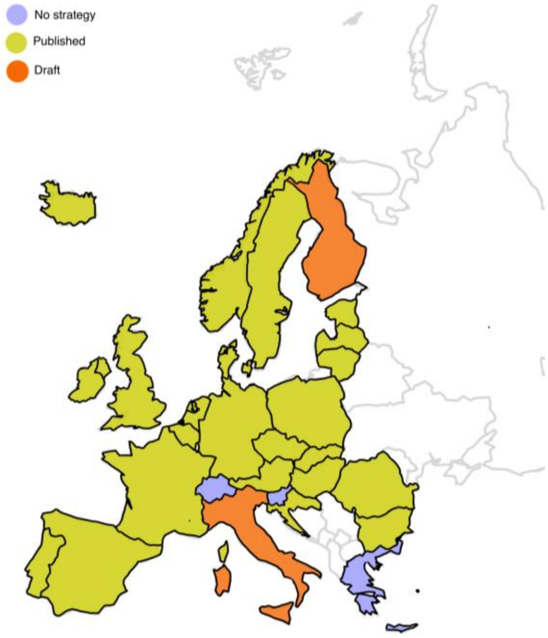
Several European countries have developed national hydrogen strategies that encompass various aspects of the hydrogen value chain. The analysis reveals a clear trend: while all strategies address hydrogen production, initiatives focused on developing hydrogen import and export routes are less common, with only eight countries actively pursuing such efforts. The majority of strategies emphasize ambitions to expand or establish hydrogen distribution and storage networks, along with the application of hydrogen technologies in mobility and industry. In contrast, there is limited emphasis on hydrogen use for heating and energy, with only a few countries incorporating these aspects into their strategies (European Hydrogen Observatory, 2024).

Figure 12- Map of the EU27 Member States showing countries with a published national hydrogen strategy, those with a strategy in draft, and those without a strategy.



Moreover, numerous European countries have integrated quantitative indicators within their national strategies, outlining specific targets and estimates across the hydrogen value chain. This deliberate approach demonstrates a commitment to establishing clear and measurable goals, providing a robust tool for assessing each nation's hydrogen strategy ambitions. By setting these specific targets, countries are advancing their commitment to the development and integration of hydrogen within their energy landscapes (European Hydrogen Observatory, 2024). The following table summarizes the main qualitative measures within the hydrogen value chain for each European country that has published adopted strategies (European Hydrogen Observatory, 2024; IEA, 2023a, 2024).

Country	Key Focus Areas
Austria	Focuses on renewable hydrogen production through electrolysis and biomass and aims to integrate hydrogen into mobility and energy-intensive industries.
Belgium	Aims for all hydrogen to be renewable by 2050 and positions itself as a hub for importing hydrogen via pipelines and shipping.
Bulgaria	Develops pilot projects for renewable hydrogen and emphasizes regulatory frameworks and education in hydrogen technologies.
Croatia	Links hydrogen production to mobility and industry, aiming for sufficient renewable hydrogen by 2030 with infrastructure development focused on demand sites.
Czech Republic	Emphasizes various hydrogen production methods and prioritizes mobility while conducting R&D on hydrogen-powered vehicles.
Denmark	Targets increased electrolysis capacity for renewable hydrogen and emphasizes Power to X technology (PtX) for hard-to-abate sectors.
Estonia	Implements EU-funded projects and focuses on developing hydrogen infrastructure and mobility solutions like refueling stations.
Finland	Advocates for emission-free hydrogen production with a focus on national network development and pilot projects for heavy transport.
France	Aims for 10% of hydrogen from renewables by 2023 and prioritizes hydrogen production from nuclear energy for heavy-duty mobility.
Germany	Focuses on increasing electrolyser capacity and pipeline expansion while prioritizing aviation and shipping applications.
Hungary	Targets low-carbon hydrogen production and the use of natural gas infrastructure for hydrogen storage.
Ireland	Promotes hydrogen production from wind energy and focuses on infrastructure development for transport and industry applications.
Iceland	Targets domestic hydrogen demand of 12 ktpa by 2030, with significant investment needs to support hydrogen for international aviation, projecting tenfold growth by 2040.

Lithuania	Sets a target of 1.3 GW of electrolysis by 2030 and aims to export over 5% of domestic production by 2050, alongside infrastructure development for buses and shipping.
Luxembourg	Develops quotas for sustainable aviation fuels and refueling infrastructure while aiming to decarbonize mobility and industry using hydrogen.
Netherlands	Focuses on bridging price gaps between grey and green hydrogen and coordinates with EU countries for electrolysis development and guarantees of origin.
Norway	Supports hydrogen production through development projects and aims for exports to Europe while promoting zero-emission solutions in various sectors.
Poland	Integrates hydrogen production with local energy sources and focuses on safety in transmission and mobility infrastructure development.
Portugal	Aims to become a green hydrogen exporter through legislative changes and supports hydrogen use in various sectors, including mobility and industry.
Romania	Implements a roadmap with 33 actions targeting decarbonization and aims for 34.4 ktpa of renewable hydrogen production by 2030.
Slovakia	Considers all low-carbon hydrogen production methods and plans for hydrogen refueling stations while focusing on mobility and industrial applications.
Spain	Establishes a regulatory framework for renewable hydrogen production and focuses on mobility infrastructure and financial support for the transition to green hydrogen.
United Kingdom	Aims to increase low-carbon hydrogen production, explore export opportunities, and adapt regulations while supporting various hydrogen applications across sectors.

4. ITALIAN POLICIES AND STRATEGIES FOR HYDROGEN

In 2021, Italy published the guidelines for its national hydrogen strategy, but the final strategy itself is expected to be published on 26 November 2024, as announced by Environment Minister Pichetto during his speech at a conference held in Rome on 30 October 2024 (Davino, 2024).

As the strategy is not yet available, this chapter will primarily analyse Italy's main energy policies - the National Integrated Energy and Climate Plan (NECP) and the first guidelines for the hydrogen strategy. Before looking at these policies, an overview of Italy's main hydrogen projects is given.

4.1 Overview of national current hydrogen projects

Despite the absence of a published hydrogen strategy for Italy, a considerable level of investment has already been made in several projects.

With regard to the production of hydrogen through electrolysis, it is notable that only 10 projects in Italy have progressed beyond the final investment decision (FID) phase, with either operational status or construction underway. The aggregate installed capacity of these projects is approximately 10.5 MW, with an annual production capacity of 1,749 kt of hydrogen. The most ambitious project to have reached the final investment decision stage is designed Enel, which features 4 MW of capacity supported by onshore wind power and is expected to become operational by 2026. The project, situated within the Carlentini Energy Park in Sicily (Bottino, 2021), will employ predominantly alkaline electrolyser technology, with industrial end-users in the vicinity. Among the IPCEI-funded projects is SilverFrog, which is still in the conceptual phase. The project has an announced capacity of 1,000 MW, utilising PEM technology; however, detailed information is still limited.

Two feasibility studies are currently in progress: the Italian Hydrogen Backbone (for further details, see section 4.2.3) and the H2 Valley Puglia. The latter constitutes a branch of the former, with the feasibility studies being conducted by SNAM, Italy's principal gas transmission system operator (TSO).

Additionally, Italy is currently engaged in two hydrogen blending projects in the demonstration phase and two in the conceptualisation stage. The inaugural demonstration project, Contursi Terme, commenced in 2019 and entails the integration of hydrogen into natural gas pipelines at a concentration of 5–10%, with the support of two industrial partners and the direction of SNAM. The second project, "H2 Blending Test at a Compressor Station Designed for Gas Networks," is situated in Florence. It started in 2020 and involves a 10% hydrogen blend, conducted in collaboration with SNAM and Baker Hughes. The two concept-phase projects, also led by SNAM, are anticipated to commence in approximately 2026 and will involve a 2% hydrogen blend, with one located in Apulia and the other in Sicily. To date, no concrete projects have been announced for Underground Gas Storage involving hydrogen in Italy.

In addition to the projects already underway, Italy has also shown commitment to hydrogen through its participation in the Important Projects of Common European Interest (IPCEI) initiatives, specifically Hy2Tech and Hy2Use. These initiatives aim to support decarbonization efforts through hydrogen technology, with total funding of €5.4 billion and €5.2 billion, respectively, and include numerous Italian partners.

Further IPCEI initiatives, Hy2Infra and Hy2Move, are currently in the pre-notification phase. These projects are anticipated to receive €1.4 billion in public funds, complemented by €3.6 billion in private investment, with a projected implementation timeline extending to 2030. These IPCEI projects reflect Italy’s strategic vision of integrating hydrogen into its energy transition framework, bolstering infrastructure, and facilitating technological advancements to meet decarbonization goals.

In terms of national funding and support from the PNRR, almost 28.56% of the total PNRR funding, equivalent to around €55.53 billion, is allocated to Mission 2, which focuses on renewables, hydrogen and biomethane. This substantial investment is intended to drive forward key infrastructure and technology projects to support Italy's energy transition.

4.2 Review of the National Integrated Energy and Climate Plan

The Integrated National Energy and Climate Plan is the main framework through which EU Member States set out policies and measures to achieve their energy and climate change objectives. As a national roadmap updated every 5 years, the NECP outlines each country's commitment to reduce greenhouse gas emissions, known as Nationally Determined Contributions (NDCs), in line with the Paris Agreement. The European Union, as a single regional entity, signed the Paris Agreement with common targets and is coordinating with Member States to achieve these collective goals. The EU's most recent commitment, enshrined in the 'Fit for 55' package, is to reduce net emissions by 55% by 2030. Accordingly, NECP reflects each Member State's strategic approach to aligning with the EU's overarching 2030 target and progressing towards net zero by 2050. This planning process is particularly important for countries such as Italy, where to implement a policy government that makes the NECP an essential mechanism for setting national energy and climate priorities.

The NECP has an important role in the development of Italy's hydrogen policy. The most recent update includes specific estimates and targets for hydrogen, making it an essential reference point for defining Italy's hydrogen strategy in the absence of a formal, stand-alone national hydrogen strategy, which has been repeatedly delayed. The last strategic guidelines for hydrogen were published almost four years ago, underlining the importance of the NECP in filling this gap. By detailing Italy's goals and actions, the NECP provides a valuable basis for shaping the country's hydrogen policy, particularly for guiding investment and setting targets in hard-to-penetrate industrial and transport sectors.

According to data from the NECP, Italy's total hydrogen production is projected to reach approximately 719 ktep (kilo tones equivalent of petroleum), divided among various sectors: 330 ktep for the industrial sector, 390 ktep for transport, and 29 ktep for the maritime and aviation sectors. To make the conversion from ktep to tones of hydrogen the following calculations were done: 1 tep corresponds to 11630 kWh; one kilo of H_2 has a calorific power of 33.33 kWh. So, 1 tep = 349 kg of H_2 per year and based on the NECP scenario means that 250.000 t of hydrogen must be produced to follow the targets that Italy has set itself. If a PEM electrolyser is used, its energy consumption varies based on its operational mode and life stage. Initially, the electrolyser's energy demand is approximately 55.0 kWh per kilogram of hydrogen produced. During continuous operation, this energy requirement rises to 56.9 kWh per kilogram of hydrogen. When the electrolyser operates in an intermittent on-off mode, such as when connected to photovoltaic (PV) systems, the energy consumption increases further to 58.8 kWh per kilogram of hydrogen. Based on these values, different scenarios were evaluated to understand how the targeted hydrogen quantity will be reached; the table below shows the hydrogen production from 1 GW of electrolysers and the quantities that will be produce (Table 6).

Table 6- Different scenarios for hydrogen production with 1GW electrolyser, with three different inputs: continuous production, intermitted operation with PV in central and southern Italy (Crespi et al., 2024)

Scenario	Energy consumption	Operating Hours	Annual hydrogen production
Continuous production	56,9 kWh/kg H_2	8760 h	~154.000 t
Intermittent operation with PV in central Italy	58,8 kWh/kg H_2	1400 h	~24.000 t
Intermittent operation with PV in southern Italy	58,8 kWh/kg H_2	1700 h	~29.000 t

Based on these calculations, the Italian target, mentioned in the NCEP, can be achieved using 3 GW of electrolyser capacity that will work at an efficiency of 65%, working for 12 hours a day.

By 2030, at least 42% of the hydrogen used in the industry must come from Renewable Fuels of Non-Biological Origins (RFNBOs), with this percentage rising to 60% by 2035. In the transport sector, at least 1% of energy consumption is expected to be sourced from RFNBOs, considering double-counting as per RED III. The aviation sector must ensure that a minimum of 1.2% of fuel comes from RFNBOs, utilizing stored CO2 and green hydrogen as set out in Regulation (EU) 2023/2405. Similarly, the maritime sector must have 1.2% of energy originating from RFNBOs, following RED III guidelines, with a progressive reduction of emissions through the use of biofuels, biogas, renewable non-biological fuels, and recycled carbon fuels outlined for the period between 2025 and 2050, as indicated in Regulation 2023/1805.

4.2.1 Green Hydrogen VS Blue Hydrogen

According to the Bloomberg NEF (Schelling, 2023) analysis, grey hydrogen costs between \$0.98 and \$2.93 per kilogram, while blue hydrogen ranges between \$1.8 and \$4.7 per kilogram. Green hydrogen, on the other hand, costs between \$4.5 and \$12 per kilogram, depending on the region and technology used. However, projections show that by 2030, in key markets such as Brazil, China, India, Spain and Sweden, green hydrogen could become up to 18% cheaper than grey hydrogen produced in existing plants, due to factors such as increased production capacity and supportive policies.

The hydrogen produced with CCS is cited various times in the NCEP as a low-carbon hydrogen, but the literature disagrees. The analysis by David Schlissel and Anika Juhn shows that blue hydrogen produced through steam methane reforming with CCS could have a realist emission of 2.5% of CH_4 during the process. The carbon intensity of blue hydrogen calculated jumps between 10.5 and 11.4 kilograms of CO2eq/kgH2.

For the blue hydrogen production, the technology that is typically employed is the pre-combustion carbon-capture in the following paragraph will give an overview of CC(U)S technologies and prices.

There are various types of carbon capture that can be divided into 3 categories: pre-combustion carbon capture, post-combustion carbon capture and oxy-fuel combustion system.

Pre-combustion carbon capture separates carbon from fossil fuels before combustion and can be applied in coal gasification plants or gas-fired plants through methane reforming, a typical technique for producing blue hydrogen. Pre-combustion capture technologies can capture a percentage of CO2 ranging from 79% to 95%.

Post-combustion carbon capture consists in removing CO_2 from the fumes downstream of the combustion process. Post-combustion capture can be achieved in different ways, and amine (generally toxic and aromatic amines are potentially carcinogenic compounds) absorption is the only large-scale, industrially validated technology that can be implemented in thermal power generation plants and industrial plants (Olabi et al., 2022). The main critical aspect of this process is the high energy consumption required for solvent regeneration. The literature shows that the uptake rate of amine absorption is between 85% and 90% (Olabi et al., 2022).

Oxy-fuel combustion involves using pure oxygen, which will generate a flux of flue gas consisting mainly of CO_2 and water. Once the water is removed by condensation, a CO_2-rich flow is obtained. The additional energy required for this technology is mainly related to the compressors of the air separation unit. Oxyfuel captures about 79% of the CO_2 produced.

Depending on the technology used, CO_2 capture investment prices can vary considerably. A full cycle of CO_2 separation and storage in existing facilities costs between €124 and €317 per tons of CO_2 according to the IEA.

The cost of capturing CO2 through separation from fuel or combustion flue gases, including solvent regeneration energy consumption, is approximately €90/tCO_2. Adding about €30/tCO2, which will be transported and then stored. However, the transportation and storage costs can vary significantly, depending on factors such as the transport distance, the geological characteristics of the storage site, and the possibility of using shared or pre-existing infrastructure.

The dangers of storage, the expenses of incorporating future generations in risk management, and the costs of site upkeep and monitoring should all be included in the price.

4.2.2 Italian hydrogen backbone

The Italian hydrogen backbone (Figure 13) is an infrastructural project that has the objective to create a national pipeline for hydrogen transportation. This project is part of the South2Corridor (a 3,300 km hydrogen pipeline connecting North Africa, Italy, Austria, and Germany. The EU Commission, with the Delegated Regulation (UE) 2024/1041 of 28 November 2023, the corridor entered the EU list of Projects of Common Interest (PCI) under the new Regulation (EU) 2022/869 on trans-European energy infrastructures (TEN-E). The European Commission designates PCI as an important cross-border infrastructure project that connects the energy systems of EU nations every two years.

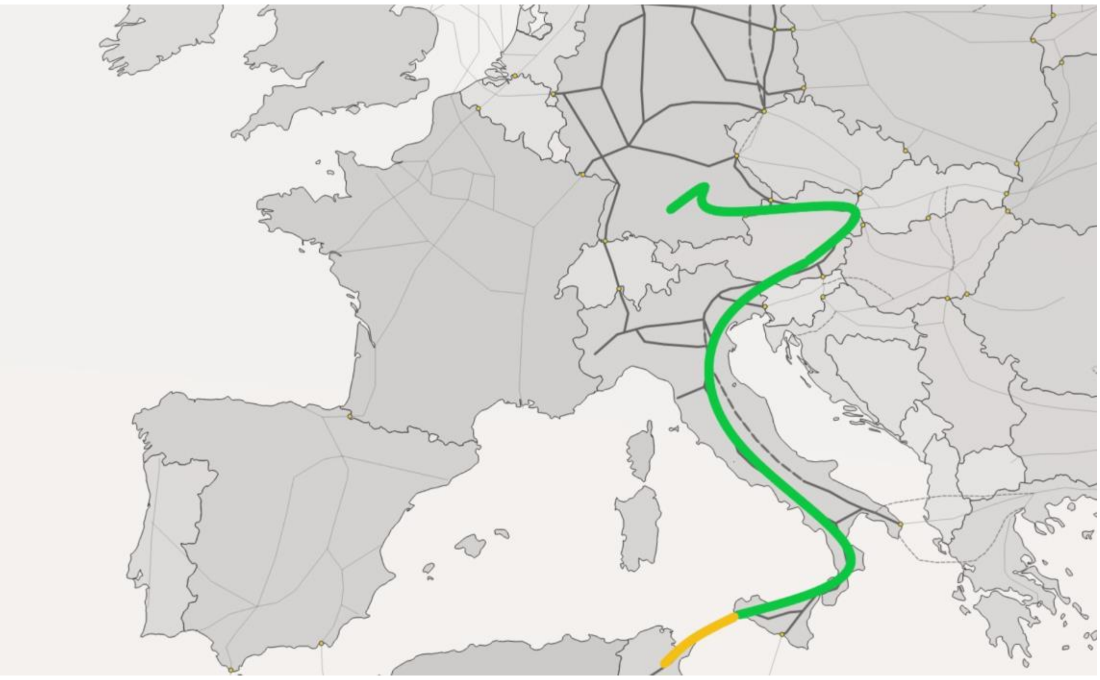


Figure 13- Map of the South2Corridor (Snam, 2023)

The owner and the operator that is working on the infrastructure is Snam the Italian TSO, that on the 30th of October 2024 during a conference on "Italian companies and the challenge of the SouthH2Corridor" showed that the infrastructure development, which will use 60% of existing pipelines and 40% of new ones, will take place in two phases. In the first phase, green hydrogen will be exported from North Africa to central Europe, where consumer markets are more mature than in Italy. In the second phase, connections will be made between the main backbone and the Italian industrial clusters, which will meanwhile be prepared to use hydrogen in their production processes. Then Gaetano Mazzitelli (Chief Commercial & Regulatory Officer Snam) underlined the importance of transport commitments and multi-annual and binding capacity requests which are crucial for starting the construction phase and reaching the FID, particularly from Austria and Germany because carriers (TSO more importantly) cannot take the volume risk.

Since the project is currently in the feasibility study phase, it is essential to carefully consider all potential challenges and benefits. This analysis involves estimating the potential hydrogen production in North Africa. According to insights from the conference, Tunisia and Algeria are expected to be the main exporters of hydrogen to Europe (Bottino, 2024). However, current literature lacks precise estimates of their production capacities (Bayssi et al., 2024). Another significant challenge in establishing the necessary infrastructure is the absence of a developed hydrogen market. Industries that require hydrogen for decarbonization are not yet prepared to integrate and adapt to future technologies (Bottino, 2024; Confindustria, 2024).

4.2.3 Nuclear Hydrogen in Italy

Nuclear energy, in the Italian NECP, is considered a potential contributor to hydrogen production in Italy, particularly for cost-competitive output that aligns with long-term decarbonization goals. A limited share of nuclear capacity, 8 GW, is assumed and two scenarios for electricity needs in 2050 have been considered. In the first scenario, which includes nuclear power, electricity demand would be higher in 2050, as lower electricity production costs would allow greater electrification of sectors and increased production of hydrogen and synthetic fuels. In contrast, in the non-nuclear scenario, offset solutions, including carbon capture technologies, would need to be used to compensate for the increase in total emissions (Figure 14).

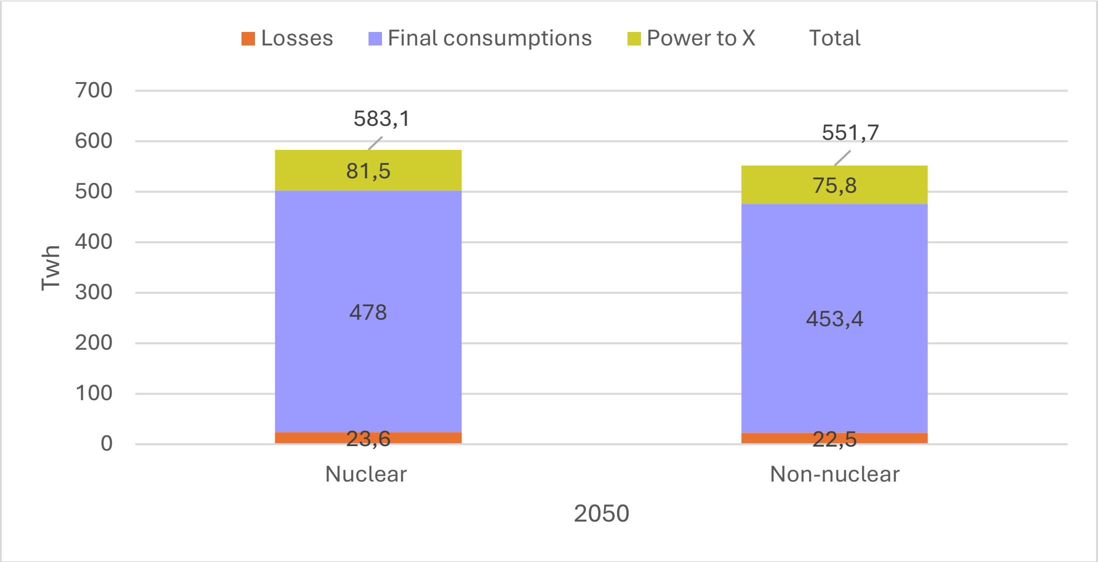


Figure 14- Scenarios of electricity demand in 2050, from the Italian NECP, with and without nuclear energy

Nuclear power has various limits and challenges that have to be overcome if we want to think from a nuclear perspective. Nuclear power does not emit CO_2 directly, but its emissions during its lifecycle are higher than those of renewable resources.

According to the German Environment Agency, nuclear energy emits 3.5 times more CO_2 per kWh than solar power and 13 times more than wind energy (Weber, 2021). The IPCC highlighted that by 2030, the potential for emission reduction from solar and wind energy is four times greater than that from nuclear (Babiker, M. et al., 2022).

Nuclear power is not considered a renewable resource because it relies on uranium, a finite resource. Furthermore, the issue of radioactive waste management poses significant long-term challenges, requiring advanced infrastructure and long-term storage solutions that are yet unresolved (Ewing, 2015).

The recent development of nuclear power plant construction in Europe showed that the time and costs involved in the realisation are prohibitive. In 2022, a plant commissioned in Finland, Olkiluoto 3, a unit of 1600 MW, cost €11 billion and took

17 years of work since the start of the construction, not including planning and approval times. In Normandy, France, the third reactor at Flamanville has been under construction for over 14 years and is still incomplete, with its budget ballooning from an initial £3.3 billion to £12.4 billion. Initially involving Enel as a participant, the plant now aims to begin commercial operations in 2023. The Hinkley Point C project in the UK, initially estimated at £18 billion, has seen its costs surge to £26 billion. This project was made feasible only through government backing, committing taxpayers to buy electricity at £92.50 per MWh (2012 prices, now worth £110), which is more than double the local market price at the time of the 2016 deal. The estimated burden on taxpayers was £37 billion. Although the energy crisis of 2021–22 drove prices up, the market is expected to trend downward, as seen in the UK's latest renewable energy auctions where 93 projects totaling 10.8 GW were awarded at an average price of £41 per MWh (2012 prices), less than half of what British taxpayers will pay for Hinkley for the next 35 years (ECCO, 2022).

Given the current landscape, aiming for hydrogen production through nuclear energy by 2050 doesn't seem practical. The primary reasons are the high costs and long construction timelines associated with nuclear plants, which make it difficult to compete with renewable sources like wind and solar. Additionally, there are still too many uncertainties surrounding next-generation nuclear technologies (Steigerwald et al., 2023). Renewable energy, on the other hand, has proven to be more cost-effective and can be deployed much faster, making it a better option for meeting decarbonization targets. For these reasons, focusing on renewables is a smarter path forward when thinking about hydrogen production in the long term.

5. CONCLUSIONS

5.1 Summary of findings

As announced in previous chapters, hydrogen is a key vector for the global energy transition, with the potential to decarbonise energy-intensive industries sectors where electrification is challenging to implement. This thesis explored its role in renewable hydrogen production, transportation, storage and possible application in the industry and transport sector. Hydrogen is recognized for its potential, but its deployment is still constrained by high costs, infrastructure and efficiency barriers.

At the European level, the policy framework is robust and with clear legislative and non-legislative measures supporting hydrogen development. The European Hydrogen Strategy provides ambitious targets for 2030, including specific goals for renewable hydrogen production and market creation considering hydrogen as a *key building block towards a climate-neutral and zero pollution economy in 2050* (A Hydrogen Strategy for a Climate-Neutral Europe, 2020). National strategies analyzed in the thesis show diverse approaches. Countries like Germany and the Netherlands lead with advanced plans, setting clear production and infrastructure targets. In contrast, nations like Portugal and Mauritania emphasize the role of hydrogen in export markets, leveraging their renewable energy potential. Internationally, regions such as North Africa play a critical role in shaping the global hydrogen market. Projects in Morocco, Egypt, and Mauritania demonstrate how countries with abundant renewable energy resources are positioning themselves as green hydrogen hubs, but with unclear capacity.

The need for technological and infrastructural advancements to support hydrogen's full integration is fundamental. Innovations in electrolysis, carbon capture, and storage are essential to improve efficiency and reduce costs. However, challenges like hydrogen transport, storage losses, and energy-intensive production remain significant barriers to large-scale adoption.

The Italian NECP served as a crucial instrument for aligning national energy and climate goals with the broader European framework. While it identified hydrogen as a cornerstone of the energy transition, it falls short of providing clear operational directives and measurable targets. This underscores the need for more robust national planning and the strategic integration of hydrogen into decarbonization initiatives, especially in industrial applications. The upcoming release of the Italian Hydrogen Strategy, scheduled for November 26th, is expected to address these gaps. This strategy could offer a detailed roadmap, unlocking significant opportunities for Italy to establish itself as a leader in renewable energy and sustainable industry. The hydrogen strategy should do a detailed analysis demand and starting from it analyse the possible offer.

5.2Future Perspectives

To accelerate the hydrogen deployment future efforts should focus on scaling back overly ambitious targets and prioritizing its use in sectors where hydrogen has the highest potential for impact. Michael Liebreich has conducted thorough analyses to guide the prioritization of hydrogen applications, through the “Hydrogen Ladder” (Liebreich, 2021). This ladder ranks hydrogen uses, starting with the top priority where its use is unavoidable due to a lack of alternatives, and moving down to less critical areas where the deployment of hydrogen is uncompetitive. As said in chapter 2 currently, hydrogen is predominantly used in fertilizer production, oil refining, and it also holds high potential for decarbonizing the steel sector, particularly when combined with electric furnaces.

Clean hydrogen should be primarily deployed in these sectors, especially because alternatives are scarce. In power systems, hydrogen’s inefficiencies restrict its role to long-term energy storage, mainly for improving grid resilience during extreme events. In aviation and shipping, hydrogen and its derivatives, such as ammonia, have the potential to decarbonize long-haul shipping and aviation. However, technical challenges, especially hydrogen’s low volumetric energy density, remain. Short-haul aviation is likely to favour battery-electric solutions, while hydrogen-based alternatives may be more appropriate for coastal and river vessels.

For land transportation, hydrogen is generally inefficient and more expensive compared to battery-electric alternatives, which dominate short- and medium-range vehicles. Hydrogen could find its niche in remote rail routes, vintage vehicles using synthetic fuels, and off-road machinery requiring portable energy sources.

Looking ahead, research and development will be essential for addressing these challenges and optimizing hydrogen deployment across various sectors.

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