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# Global Hydrogen Development - A Technological and Geopolitical Overview

B.E. Lebrouhi<sup>(1,2\*)</sup>, J.J. Djoupo<sup>(1)</sup>, B. Lamrani<sup>(3)</sup>, K. Benabdelaziz<sup>(2)</sup>, T. Kousksou<sup>(1\*)</sup>

<sup>1</sup>Université de Pau et des Pays de L'Adour, E2S UPPA, SIAME, Pau, France

<sup>2</sup>Engineering for Smart and Sustainable Systems Research Center, Mohammadia School of Engineers,  
Mohammed V University in Rabat, Rabat, 11000, Morocco

<sup>3</sup>Université Mohammed V de Rabat, Faculté des Sciences, Laboratoire MANAPSE, B.P. 1014 RP  
Rabat, Maroc

## Abstract:

Hydrogen is an energy carrier that will certainly make an important and decisive contribution to the global energy transition and lead to a significant reduction in greenhouse gas (GHG) emissions over the coming decades. It is estimated that 60 % of GHG emission reductions in the last phase of the energy transition could come from renewables, green hydrogen and electrification based on green energy development. Coordinated efforts by governments, industry and investors, as well as substantial investment in the energy sector, will be required to develop the hydrogen value chain on a global scale. This paper summarizes the technical and technological advances involved in the production, purification, compression, transportation and use of hydrogen. We also describe the roadmaps and strategies that have been developed in recent years in different countries for large-scale hydrogen production.

**Keywords:** Green hydrogen, Geopolitics of energy, Hydrogen production, Fuel cell, Hydrogen storage

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## List of abbreviations

ADEME	French Environment and Energy Management Agency	MCFC	Molten Carbonate Fuel Cell
AEM	Anion Exchange Membrane	METI	Ministry of Economy, Trade, and Industry
AFC	Alkaline Fuel Cell	MNRE	Ministry of New and Renewable Energy
AIST	Agency of Industrial Science and Technology	MOFs	Metal organic frameworks
ANR	National Research Agency	MOST	Ministry of Science and Technology of China
ARENA	The Australian Renewable Energy Agency	MOTIE	Ministry of Trade, Industry and Energy
BCC	Body-centered cubic	NAT	Near ambient temperature
CC	Competence Centers	NEDO	New Energy and Industrial Technology Development Organization
CCS	Carbon Capture and Storage	NHER	National Hydrogen Energy Roadmap
COAG	Council of Australian Governments	NIC	Network innovation and competition
CORFO	Chilean Production Development Corporation	NO <sub>x</sub>	Nitrogen Oxides
CSHFC	Council for a Strategy for Hydrogen and Fuel Cells	NSFC	Natural Science Foundation of China
CSIRO	Commonwealth Scientific and Industrial Research Organisation	O&M	Operating and maintenance
DITR	Department of Industry, Tourism and Resources	OFGEM	Office of Gas and Electricity Markets
DNES	Department of Non-conventional Energy Sources	OLEV	Office for Low Emission Vehicles
DOE	Department Of Energy	PAFC	Phosphoric Acid Fuel Cell
DST	Department of Science and Technology	PAN-H	National Action Plan on Hydrogen and Fuel Cells
EC	European Commission	Pd	Palladium
EHC	Electrochemical hydrogen purification	PEM	Proton exchange membrane
EQHHPP	Euro-Quebec Hydro Hydrogen Pilot Project	PEMFC	Proton Exchange Membrane Fuel Cell
EVs	Electric vehicles	PGMs	Platinum group metals
FCCJ	Fuel Cell Commercialization Conference of Japan	PIIEC	Important Common European Interest Project
FCCSC	Strategic Council for Fuel Cell Commercialization	PNGV	Partnership for a New Generation of Vehicles
FCEV	Fuel Cell Electric Vehicles	PPE	France's multi-year energy plan
FCH-JU	Fuel Cell and Hydrogen Joint Undertaking	PSA	Pressure Swing Adsorption
G20	Group of Twenty	PSS	Porous stainless steel
GDP	Gross Domestic Product	PtG	Power-to-gas
GEF	Global Environmental Facility	PtM	Power-to-Mobility
GHGE	Greenhouse Gas Emissions	PtP	Power-to-power
H <sub>2</sub>	Dihydrogen	R&D	Research and Development
H <sub>2</sub> ME	Hydrogen Mobility Europe	RDFP	R&D Framework Program
		RMB	Chinese renminbi
H <sub>2</sub> SO <sub>4</sub>	sulphuric acid	RTD	Research and technology development
HETF	the Hydrogen Energy Task Force	SOE	Solid oxide electrolyzers
HFSs	Hydrogen Fuel stations	SOFC	Solid Oxide Fuel Cell

MGP	Platinum group metals	SO <sub>x</sub>	Sulfur Oxides
MHAs	Metal hydride alloys	TACHE	Technical Advisory Committee on Hydrogen Energy
HIF	Highly Innovative Fuels	TLO Law	Law Promoting Technology Transfer from Universities to Industry
HRS	hybrid refuelling station	US	United states
HySA	Hydrogen South Africa	UK	United Kingdom
IEA	International Energy Agency	UNDP	United Nations Development Program
KOH	Potassium hydroxide	USA	United states of America
LNG	Liquefied natural gas	USD	United states dollars
LOHC	liquid organic hydrogen	WE-NET	World Energy Network Project

## 1. Introduction

Although hydrogen is a product historically used in the chemical sector, the commitment of a growing number of nations to the energy transition has put it back at the center of attention as an alternative energy vector to fossil fuels [1,2]. All key energy outlook scenarios show that hydrogen and renewable energy resources will be major contributors to the worldwide mitigation of greenhouse gas emissions [3,4]. The evidence is in the growing number of political initiatives to support the development and deployment of green hydrogen production technologies and its use in fuel cells to meet mobility challenges or to provide an alternative to batteries to store intermittent renewable energy production [3,4].

Green hydrogen appears to be a promising and flexible option to accompany this energy transition and mitigate the risks of climate change [5]. It provides the opportunity to decarbonize industry, buildings and transportation as well as to provide flexibility to the electricity grid through fuel cell technology [6,7]. Likewise, the development of hydrogen sector can strengthen the economy by creating thousands of jobs and adding billions of dollars to gross domestic product (GDP), enabling the integration of renewable energy into the power system, reducing dependency on imported fossil fuels, and lowering the carbon footprint [8–10].

In the literature, studies on hydrogen production and storage have received increasing attention during the last twenty years. The variation of yearly published works in Scopus database is plotted in Fig.1. These data are generated using “hydrogen energy production and storage” as keywords in Scopus Website. It can be seen clearly in this figure that the number of published papers is increased from 10 papers in 1990 to more than 680 papers in 2021. The number of

published papers during this period is about 5600 papers. About 17 % of these papers are coming from the United States followed by china with 16.5 % and Germany with 8.2 % (Fig.2). This result can be also translated by the amount of research and development projects on hydrogen and the adopted energy strategies in each country.

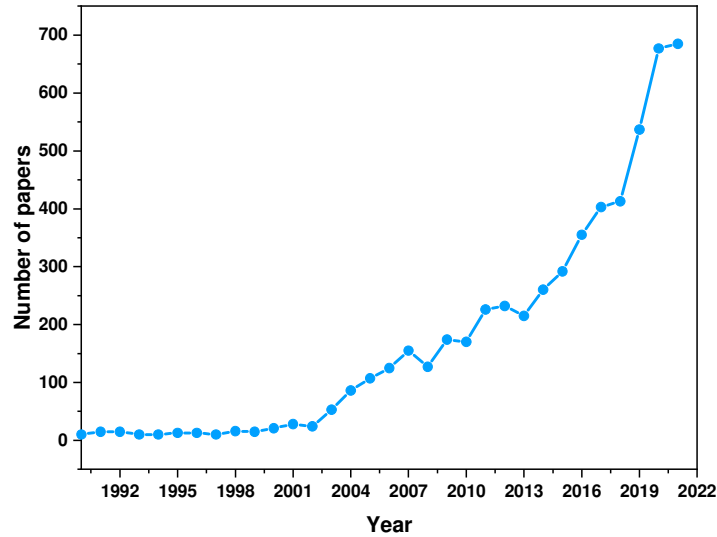


Fig. 1 Yearly variation of published works from Scopus database “Used keywords: hydrogen production and storage”.

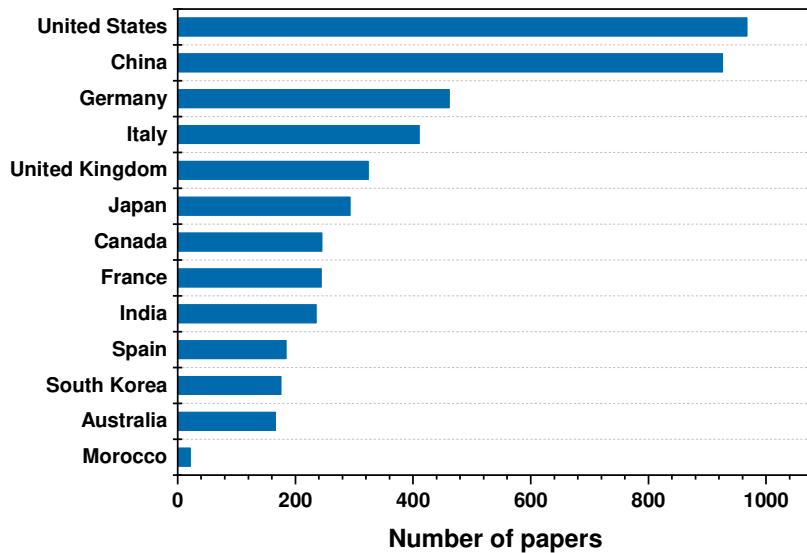


Fig. 2 Published papers per country from Scopus database “Used keywords: hydrogen production and storage”.

These published papers during the last thirty years can be classified into research papers, review papers, conference papers, book chapters and other type of documents. Research papers represent about 60 % of the total published papers, 22 % are in the form of conference papers, 9 .6 % of review papers and 8.4 % of other type of papers such as short surveys and notes.

Nowadays, several countries around the world have established national strategies to accelerate the development of the green hydrogen value chain. Consequently, this will undoubtedly reshape the global geopolitical map and redefine the structure of a new global energy market [11–14]. In this paper, the technical and technological advances involved in the production, purification, compression, storage, transportation and use of hydrogen are discussed in Section 2. Thus, the strategies & roadmaps that have been developed in recent years in different countries for large-scale hydrogen development are extensively reviewed in section 3. In section 4, a detailed analysis on the hydrogen integration in different countries worldwide is presented. The main conclusions and perspectives are highlighted in section 5.

## **2. Hydrogen energy**

To understand the current hydrogen revolution, it is important to recall some fundamental scientific and technical aspects regarding hydrogen.

### **2.1. Some specifications of hydrogen**

Hydrogen is abundantly available in nature in its association with oxygen (water) and to a lesser extent in its association with carbon –in plant and animal tissue and in fossil fuels such as methane [15,16]. It is the energy carrier with the highest energy density: per kg, it contains 2.2 times more energy than natural gas, 2.75 times more than gasoline and 3 times more than oil. However, it is the lightest gas, which makes it difficult to store. Hydrogen is a dangerous gas as it presents an acute risk of leakage as well as a greater facility to create a deflagration and detonation (see **Fig. 3**).



*Fig. 3 Explosion at a hydrogen station (2019-Norway) [17]*

## **2.2. Hydrogen, green, blue, grey or yellow?**

Today, more than 95% of the hydrogen consumed in the world is extracted from fossil fuels, mainly natural gas, by the action of superheated steam. Metal catalysts are used to facilitate the reactions. This technique, called steam reforming, requires the gas-steam mixture to be heated to a very high temperature: between 700 °C and 1,000 °C. This technique emits 10 kg of CO<sub>2</sub> for every 1 kg of H<sub>2</sub> produced [18]. The challenge of eliminating these emissions is important, because the production of 900,000 tonnes of hydrogen used in France leads to the emission of 9 million tonnes of CO<sub>2</sub>. Steam reforming is currently the most economical process for producing hydrogen. However, its cost, estimated at €1.5/kg, is three times higher than that of natural gas [19,20]. Its production cost is highly influenced by the so-called carbon tax. Hydrogen produced from fossil fuels with high greenhouse gas emissions is distinguished by its grey colour. One possibility to decarbonize grey hydrogen is to capture the carbon dioxide emitted during the steam reforming process [21–23]. This CO<sub>2</sub> can then be used as a raw material in certain industries. The decarbonized hydrogen then becomes "blue". Today, this technology is at the experimental stage, and only a few pilot projects have been launched around the world.

It is important to recall that a number of industries in the world produce hydrogen even though it is not the desired product of their production process [24]. The hydrogen co-produced in these



industries is sometimes used as an energy resource within the process itself or in adjacent industrial processes. The co-produced hydrogen can also be recovered as heat, or even rejected in the atmosphere, because there are no other economically interesting opportunities available locally [25]. Such hydrogen can play a role in the energy transition and help mitigate the carbon footprint of the industrial sector. The carbon intensity of this hydrogen will obviously depend on the industrial process from which it comes.

Green hydrogen is produced by electrolysis of water, which involves splitting the latter into dioxygen (O<sub>2</sub>) and dihydrogen (H<sub>2</sub>) using an electric current [26]. The equipment used for this operation is called an electrolyser. If the electricity used is exclusively of renewable origin (produced for example by solar, wind or hydroelectric installations), this hydrogen will be "clean" and qualified as "green" [22,27]. If it is produced by a significant proportion of nuclear electricity (as in France), it will be labelled yellow [28]. In this article, we will only discuss green hydrogen produced from renewable systems such as solar and wind power. Such systems produce hydrogen through water electrolysis systems.

### 2.3. Green hydrogen uses

Green hydrogen has many uses:

- It can substitute grey hydrogen in high emission industrial sectors (refineries, ammonia production, etc.), thus achieving economies of scale and quickly reaching the profitability of green hydrogen, as these sectors usually operate with long-term and significant contracts (**Power-to-industry**).
- The purified green hydrogen can be injected into existing natural gas networks, which will reduce natural gas consumption and emissions in the heating sector of buildings (**Power-to-gas**). The rate of hydrogen injection into the natural gas network varies greatly from country to country, without any valid scientific or technical reason being given [29] (see **Table. 1**). Power-to-gas can also connect electricity, gas and heat networks (market coupling).

*Table 1: Hydrogen injection limit into the natural gas network in % [29]*

Country	UK	Belgium	Switzerland	France	Germany	Netherlands
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% H <sub>2</sub>	0	0	4	6	10	12
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- Green hydrogen can play an important role in managing the balance between electricity production and consumption on an inter-seasonal basis, particularly in cases of significant growth in the share of renewables and a decline in thermal power plants. Indeed, while the balance within a day can probably be ensured by means of other mechanisms (such as load shedding and adjustment of electricity consumption), the latter do not make it possible to manage inter-seasonal imbalances (in particular, the current need for heating in winter causes an increased need for electricity compared to the rest of the year). To avoid the use of thermal power plants for such peak needs, one option would be to produce hydrogen by electrolysis during the summer months and store it until it is used during peak periods (**Power-to-power**).
- The development of hydrogen-powered electric vehicles based on fuel cells will diversify the range of electromobility and substitute fossil fuels (**Power-to-mobility**).
- Green hydrogen offers new opportunities for self-consumption of local energy, especially for areas not connected to the electricity grid.

The green hydrogen value chain consists of several stages: production, compression, storage and transport.

#### 2.4. Green hydrogen production

The main element for the production of green hydrogen from excess renewable electricity is the electrolyser. When integrated into an electricity grid, electrolysers have a dual function as both a hydrogen generation system and as a grid balancing device, operating mainly during periods of excess grid electricity [28,30]. Electrolysis systems need to be extremely resistant to power fluctuations and rapid start-up and shut down, while having limited performance losses [31,32].

Three types of electrolysers are currently in use:

- Alkaline water electrolyser using an aqueous solution of sulphuric acid (H<sub>2</sub>SO<sub>4</sub>) or potassium hydroxide (KOH) [33]. It has benefited from a long experience resulting in a reliable and competitive technology. It generally operates at temperatures between 293 K and 373 K. Alkaline electrolysis has some major merits due to the use of non-noble electrodes and its long-term stability. However, the principal disadvantages associated with alkaline electrolysers reside in the corrosive electrolyte, the permeation of gases and the slow dynamics [34,35].
- Polymer electrolyte membrane also known as proton exchange membrane (PEM), typically operates at temperatures range within 333 K-363 K, while ceramic and polymers are used as a gas separator [36,37]. PEMs have the advantage of high efficiency, rapid response times to the fluctuation of renewable energy sources, ability to operate at high pressure, simple zero-gap cell, modular system design, high current density capabilities, and the production of high-purity hydrogen [38]. The main lifetime limiting factors of PEM under such conditions are usually found to be membrane thinning [39], poisoning of the membrane or cathode electrocatalyst due to metal dissolution and redeposition, or loss of performance due to the degradation of the anode electrocatalyst [40,41].
- Solid oxide electrolysers (SOE) generally operate at temperature above 773 K, while using O<sup>2</sup>- conductors and the solid electrolytes fulfil the role of gas separator [42,43]. High temperature electrolysis permits the use of a lower voltage than alkaline or PEM technologies and a high current density.

The solid form of the electrolyte in SOE and PEM ensures a much more compact configuration and operation at different pressures. Thus, the solid nature of the electrolyte improves the dynamic potential of SOEs and PEMs, where variable power load reaction can be faster than liquid alkaline electrolysers with slower diffusion [34]. Otherwise, the SOEs's high operating temperature is the most beneficial aspect relative against lower temperature electrolysis. An extensive market survey of water electrolysis technology is performed in Ref [35], twenty producers of alkaline water electrolysers offering single-stack capacities of up to 6 MW and twelve producers of PEM with three offering stacks on the MW scale identified.

The energy efficiency is therefore, one of the most important factors to compare these technologies. In [44], a detailed analysis of the various expressions of the water electrolysis energy efficiency coefficient for the tree water electrolysis cells operating under NAT conditions is presented. Notwithstanding the greater efficiency, SOEs are still being developed for commercialization, its efficiency close to 100% generates interest in the developments related to the improvement of durability and costs [45]. Despite these efforts, the SOEs remain far from achieving commercialization status [46]. In [47], the state-of-the-art of commercial electrolyzers provided by 9 companies: CETH2/Areva H2Gen, Hydrotechnik, Hydrogenics, ITM Power, McPhy Energy, NEL, Next Hydrogen, PERIC and Siemens has been analyzed. Regarding this study, it can be concluded that the efficiency is between 52% and 62% for alkaline electrolyzers and 57–64% for PEM systems. Another comparative study of the different current technologies was performed in [48]. For alkaline electrolyzers which are more developed and tested, they could be used as large installations for electrical network stabilization or are directly connected to large wind or solar farm systems. In other hand, it is expected that PEM electrolyzers with improved dynamics and gas quality can be used as an intermediate energy buffer in industrial plants or at the residential level. Otherwise, to compete with the previous ones in the medium to long term, the SOE and PEM electrolyzers must overcome reliability barriers [34]. Other technologies such as Anion Exchange Membrane (AEM) are also under development [49,50]. A main advantage of AEM water electrolysis is the substitution of traditional noble metal electrocatalysts with low-cost transition metal catalysts. The following table (Table 2) summarizes the main energy performance indicators for the four presented technologies i.e. Alkaline, PEM, AEM, SOE, and their trends between 2020 and 2050.

Table 2: Indicators of the key performance for four electrolyser technologies between 2020 and 2050 [51]

	2020				2050			
	Alkaline	PEM	AEM	SOEC	Alkaline	PEM	AEM	SOEC
Cell pressure [bar]	< 30	< 70	< 35	< 10	< 70	< 70	< 70	> 20
Efficiency (system) [%]	50-78	50-83	57-69	45-55	< 45	< 45	< 45	< 40
Lifetime [thousand hours]	60	50-80	> 5	< 20	100	100-200	100	80
Capital costs estimate for large stacks (stack only > 1 MW) [USD/kW <sub>el</sub> ]	270	400	-	> 2000	< 100	< 100	< 100	< 200

Capital cost range estimate for the entire system > 10 MW) [USD/kW <sub>el</sub> ]	500-1000	700-1400	-	-	< 200	< 200	< 200	< 300
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Industrial electrolyzers that are designed to produce green hydrogen are also required to meet a number of basic criteria [37]:

- The ability to absorb peak production of excess electricity from renewable sources;
- A wide range of operation;
- Fast response time.

Meanwhile, the progress of recent years shows that water electrolysis is on its way to large-scale flexible energy storage applications [35,52]. The current research in water electrolysis projects is mainly focused on the following objectives:

- Investigate the influence of the operating temperature and pressure on the efficiency [53];
- The development of non-noble-metal electrocatalysts [54,55];
- Enlarge the power modulation range of the electrolyzers ;
- Increase the operating temperature of the electrolyzers [56];
- Reduce the investment cost of technologies [57];

One other parameter, which is frequently neglected in electrolyser analysis, is water. It is a vital element for electrolyzers. It must meet certain criteria, such as conductivity or impurity concentration, etc. [58,59]. Generally: 9 liters ( $\approx 0.009 \text{ m}^3$ ) of water to obtain 1 kg ( $\approx 11.2 \text{ m}^3$ ) of Hydrogen). This demonstrates that the massive production of hydrogen in the coming decades will require a significant consumption of water on a global scale [58,60]. It is important to note that water scarcity is one of the major problems in the world today. This is due to pollution, climate change, overpopulation and inefficient use of resources. To accompany the development of hydrogen in some countries, it is necessary to increase the storage capacity of the flows (dams and local rainwater storage systems for the most part), to develop optimal management strategies for the available stocks, to set up tools for recycling the resource so as to optimize its use and avoid waste; to control water pollution and to develop seawater desalination stations.

## 2.5. Hydrogen purification and compression

### 2.5.1 Hydrogen purification

Today, hydrogen production is mostly dependent on fossil fuels (more than 95%) [61]. Impurities such as CO, CO<sub>2</sub>, O<sub>2</sub>, H<sub>2</sub>O, SO<sub>x</sub>, NO<sub>x</sub> are present in the resultant hydrogen. Therefore, further efficient hydrogen purification steps – process that converts impure hydrogen to ultrapure hydrogen – are mandatory for some practical applications such as fuel cell vehicles and stationary power production to ensure hydrogen purity and meet the fuel quality requirements (specified by ISO 14687–2) [62]. Many hydrogen purification methods are available (i.e. Pressure Swing Adsorption (PSA), Polymer Membrane Diffusion, Cryogenic Separation, Metal Hydride Separation, Solid Polymer Electrolyte cell, Catalytic Purification, Palladium Membrane Diffusion ... etc.), some of these methods have been commercialized, others still under development [63,64]. The operating temperature, pressure, and purification level, and application scale differ between these methods [65]. For instance, Pressure Swing Adsorption and cryogenic processes are the main commercial methods to purify hydrogen for large industrial scale units. The PSA technique is the most effective way to get pure hydrogen [66]. This technique can purify gaseous mixtures containing 60–90 % mole of hydrogen to 99,999 percent purity [67]. Cryogenic Separation process operates at very low temperatures (20.15 K) and it is suited for large industrial facilities, while hydrogen may be stored in liquid form [61]. In this process, the hydrogen purity is approximately 99 %. The inconveniences of this method are highly cooling cost and pre-treatment requirements. However, the product purity from both methods is generally not sufficient for fuel cell applications. So, further purification cycles are mandatory to improve purity.

Membrane-based separation methods (i.e. polymeric membranes, dense metal membranes, porous membranes, and ion-conductive membranes) can be considered as promising methods for delivering high purity hydrogen from gas mixtures. The membrane-based methods have the

advantages of high efficiency, simple operation, low energy consumption, environmentally friendly [68].

Palladium (Pd) membranes have a high-purifying potential and can be utilized at levels exceeding 573 K [69]. Nonetheless, as the self-supporting Pd membranes are thick, producing high purity hydrogen is expensive. Accordingly, thinner Pd-alloy membranes (e.g. copper, cerium, yttrium, silver and gold) [70] and some composite membranes (e.g. Pd/BCC metal composite membrane, and Pd/NaY/PSS composite membrane) [71] are developed and used to minimize the purification production costs [72], and increase the hydrogen permeability [73].

Metal organic frameworks (MOFs) [74] and Metal hydride alloys (MHAs) [75] can also be used for the separation and purification of hydrogen. The MOFs have already been applied for delivering gas and storing food commercially, combining the benefits of high surface area, tuneable porosity, excellent selectivity and flexible structures, which allow for performance adjustment. The metal hydride alloys can be seen as an attractive solution for hydrogen purification but the absorption process generally requires higher temperatures and therefore highly stable materials are needed in this process [65]. Electrochemical hydrogen purification (EHC) is a new and promising technology of purification that can purify hydrogen up to 99.999 % [61]. The EHC has the advantage of low energetic cost, high hydrogen recovery and purity, low temperature of operation and lower operation and maintenance costs. Furthermore, EHC allows for both purification and compression in a single system, and are compatible with small units of purification, which render them well suited for fuel cell vehicles refilling systems [61].

### **2.5.2 Hydrogen compression**

Among the most commonly used fuels, hydrogen has the lowest volumetric energy density (0.01079 MJ/L at atmospheric conditions) [76]. In reality, hydrogen compression is the direct way to overcome this barrier and achieving high energy densities, high storage levels, and enabling hydrogen more widely used as a renewable and sustainable fuel. Many laboratory research activities, ammonia producers, and new hydrogen refuelling stations generally require hydrogen at 70 MPa. Recently, the development and enhancement of hydrogen compression technologies for stationary and automotive applications [77] have been received substantial attention. According to Sdanghi et al. [76], these technologies can be classified into two main

groups: (i) mechanical compression by using reciprocating piston compressors, diaphragm compressors, linear compressors, liquid compressors (i.e. ionic liquid compressors, liquid piston compressors, and liquid rotatory compressor) ; (ii) non-mechanical compression including cryogenic compression, metal hydride compressors, adsorption compressors and electrochemical compressors. The selection among all these technologies is determined by the application, required pressure, and desired operating temperature.

The first category is widely applied in industry in which hydrogen is contained in a closed volume and compression is achieved by reducing this volume using a moving unit. The reciprocating compressors are ideal option for high-pressure applications. Diaphragm compressors are especially utilized in situations requiring low hydrogen flows, while linear compressors are mostly used for aerospace applications and for cooling electronics. Meanwhile, liquid hydrogen compressors appear to be a highly attractive option in development of hydrogen refill stations for automotive applications, as just certain moving system components are needed to compress hydrogen up to 100 MPa. Despite their relative efficiency, these compressors are costly systems given the high investment, maintenance, and repair costs [61]. For instance, a reciprocating compressors have a capital cost of about \$150,000 with relatively high operating and maintenance (O&M) expenses [78].

The second group, which includes non-mechanical compressors, is likewise a viable solution compared to mechanical compressors [79]. Cryogenic compressors are typically used in automotive applications [80], and it combines hydrogen liquefaction and compression, as well as the pros and cons of both storage technologies. This method allows the attainment of high pressures (70 MPa) at extremely low temperatures (between  $-243.15\text{ }^{\circ}\text{C}$  and  $-173.15\text{ }^{\circ}\text{C}$ ), which is required for the development of an effective hydrogen refuelling station [81]. However, despite these advantages, it is worth nothing that cryogenic compressors cannot guarantee a vacuum stability of ten years yet, this can be considered as a major drawback restricting their use [76]. Metal hydride compressors have been proved as a reliable and effective technology for hydrogen compression [82], in which hydrogen is combines with certain metals or alloys and stored at moderate temperature and pressure while ensuring safe hydrogen storage and compression. Thought this technology hydrogen can be compressed up to 20 MPa, and several studies are underway to achieve higher pressures. Metal hydride compressors are perfectly suitable for on-board applications [83], low-pressure hydrogen producers, and for industrial



systems in which heat is produced. Metal hydride compressors are a cost-effective option compared to mechanical compressors, with lower capital, maintenance and operating costs. In general, the capital cost of a metal hydride system compressing a hydrogen from 0.7 MPa to 25 MPa has been estimated at \$150,000 compared to \$170,000 for a mechanical compressor under the same conditions [84]. Furthermore, the O&M costs are around \$1000 for a metal hydride compressor versus \$9000 for a mechanical compressor. Despite these advantages, metal hydride technology suffers from lower efficiency (25% of efficiency rate with 10% of average efficiency).

Hydrogen adsorption compressors appear to be a promising technology for hydrogen compression especially for decentralized hydrogen refuelling station applications [85]. In general, an adsorption compressor that operates in a broad range of temperatures between 77 K and 298 K can compress hydrogen from value higher than 0.1 MPa to 70 MPa. Hydrogen adsorption phenomenon is based on the ability of hydrogen to slightly bind to the surface of highly porous solids such as carbonaceous materials or metal-organic structures. The advantage of this approach is to reduce the pressure necessary for storing a certain amount of hydrogen, which is a serious safety advantage. Nevertheless, the low efficiency of this compressor should be highlighted, due of the limited heat conductivity of the adsorbent material.

Electrochemical hydrogen compressors are another option for hydrogen compression, which can be considered as competitive solution offering very high level of efficiency (typically over 60%) [61] compared to mechanical compressor. They are commonly used to compress hydrogen using selective polymer membranes. This method is costly effective and perfectly suited for low-pressure applications (lower than 10 MPa). For instance, the capital cost of an electrochemical compressor is between \$170/kg/day and 1700/kg/day compared to \$2300/kg/day of a mechanical compressor. Otherwise, the O&M costs per kilogram are lower than \$1/kg for an electrochemical hydrogen compressor versus \$1.75–2.3/kg for mechanical compressor. The operation costs of this technology can be reduced either by the use of low-cost membranes, the optimization of the catalyst, improvement of thermal management, and enhancement of water management [65].

## **2.6. Green hydrogen storage**

Accordingly, three approaches are typically available to store hydrogen; in gaseous, liquid or solid states (see Fig.4), depending on the volumes, pressure and storage duration [86].

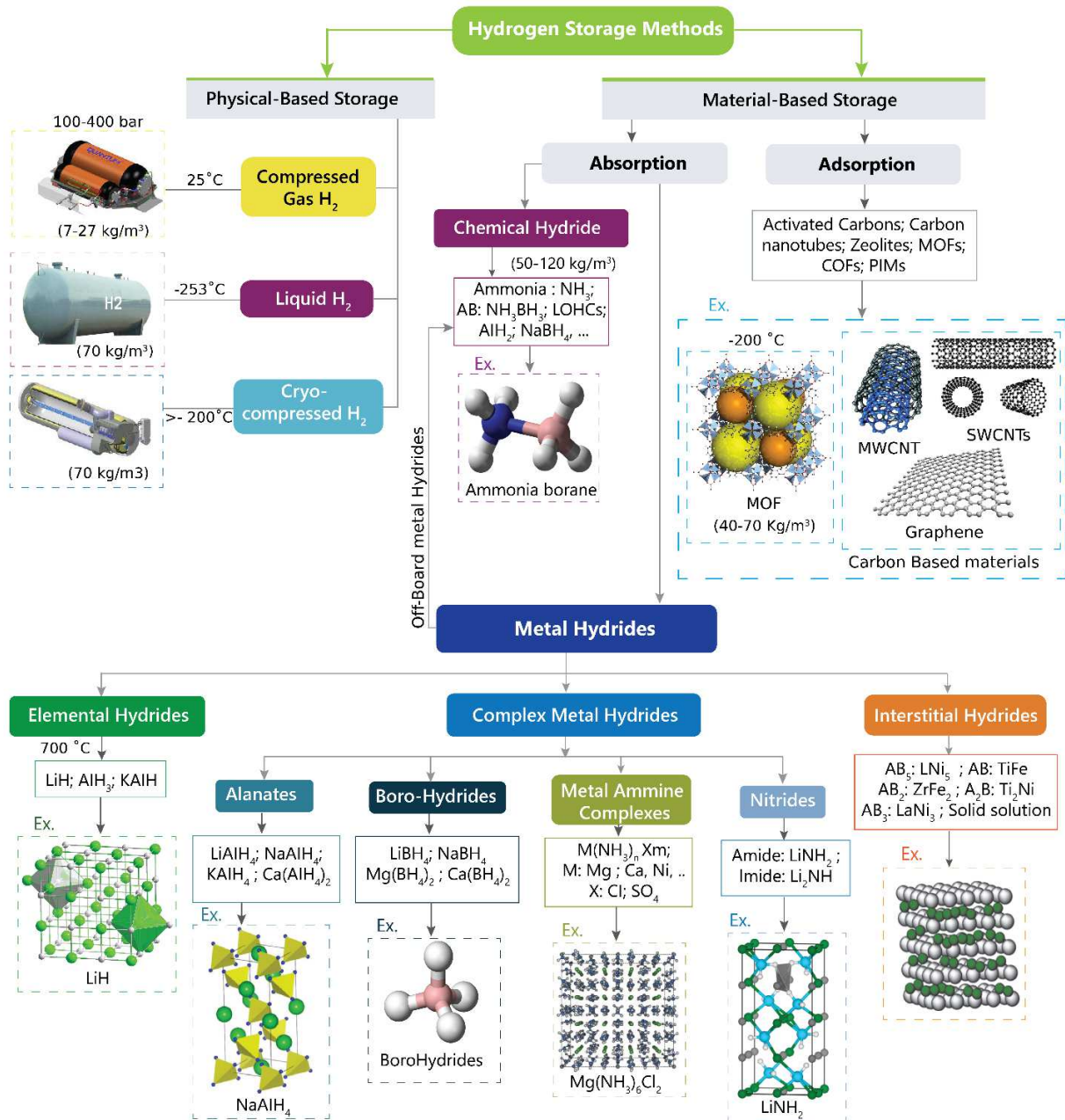


Fig. 4: Hydrogen Storage methods (Based on [87–89])

### 2.6.1. Gaseous-state hydrogen storage

Hydrogen can be compressed and stored as pressurized gas in cylinders, tanks or underground caverns, with a pressure of up to 700 bar in suitable cylinders. Illustratively, for consumers below 50 m<sup>3</sup>/h, it is conditioned in gaseous form in bottles. In fuel cell vehicles for mobility, hydrogen gas is stored at 700 bars. Since the energy density of hydrogen by volume is low, it is necessary to compress it at very high pressure to reduce the size of its storage. The compression of hydrogen represents about 7% of its calorific value to go from 1 to 200 bars and 10% to reach 700 bars. By storing gaseous hydrogen underground, it is often possible to store much larger volumes as well as achieving higher pressures than when doing so aboveground [90–94]. At the end of 2016, there were approximately 672 installed underground storage of natural gases globally, altogether containing about 424 billion cubic metres of working gas [95].

In **Fig. 5**, different types of underground storage, such as gas and oil fields, aquifers, abandoned mines, rock and salt caverns are illustrate [96]. The latter, salt caverns, has been proven to generally be the best solution for hydrogen storage. The beneficial properties include rapid injection and withdrawal rates, low rates of leakage, low risk of contamination of the hydrogen, low construction costs and relatively low cushion gas requirements [97]. Noteworthy, underground storage technologies may, however, not be utilized anywhere since the geological conditions simply does not exist everywhere [98]. Aboveground options for large-scale hydrogen storage are numerous [97], although none of them perfect and most of them requiring further development and refining before being economically viable.

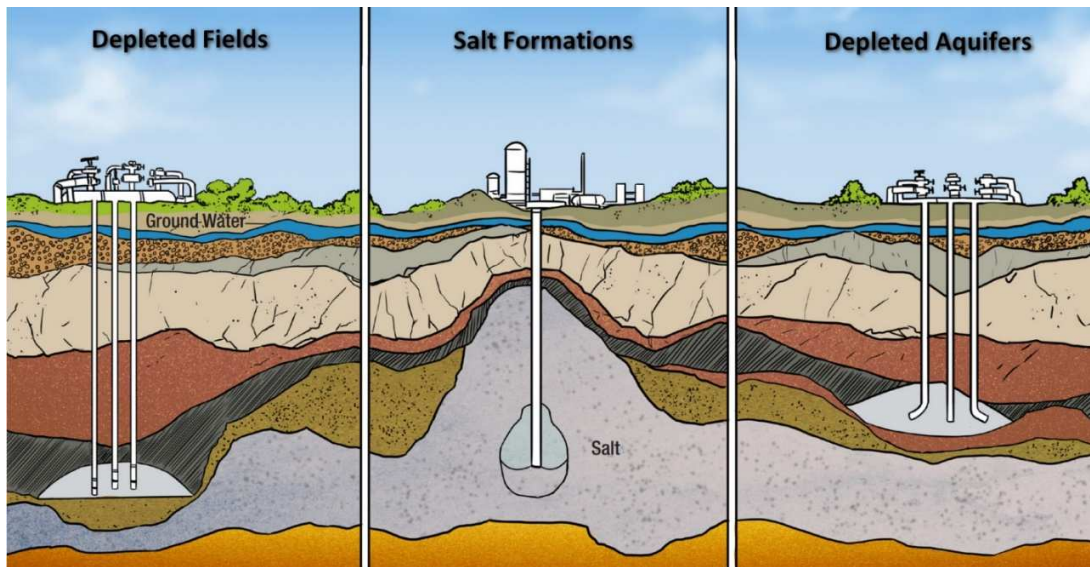


Fig. 5: Different types of underground hydrogen storage [96]

### 2.6.2. Solid-state hydrogen storage

By letting gaseous hydrogen react with a metal in a so-called hydrogenation process, metal hydrides are formed [97]. This enables a high density storage due to the chemical bonds between the metal atoms and the hydrogen one [99]. Storage of hydrogen in solid form is considered as safest mode in which hydrogen combines with materials through physisorption or chemisorption. Hydrogen can be stored and removed from storage by thermal input at atmospheric pressure, thus avoiding the costs of conditioning (compression, liquefaction). However, different hydrogen storage metals can be used, but most of them are somewhat troublesome and need additional production to prove viable [97]. One critical aspect of choosing metal for a metal hydride storage, apart from the storage capacity, is the reversibility of the hydrogenation. In other terms, how strongly hydrogen-metal bonds become. To which temperature the metal hydride must be heated for the bonds to break during the dehydrogenation process is highly necessary for the economically viable storage process and for the general practical handling. Magnesium has been proven to be a good choice of metal for hydrogen storage, as it is widely available at a low cost and has a long-term gravimetric storage capacity reaching up to around 7,6 wt% , and has a high reversibility [100]. On the other hand, hydrides are penalized by their weight and the thermal management required for the adsorption and desorption of hydrogen.

Similar to the metal hydride storage, it is possible to increase storage density by letting the hydrogen bond chemically to chemical hydrogen carriers such as ammonia, methanol, and formic acid [97], which are generally liquids. The liquid state of the hydride generally simplifies transportation as well as the heat and mass transfer of the hydrogenation and dehydrogenation processes [101]. Even the storage itself is in some ways simplified since infrastructure for bulk chemicals (as many of the hydrogen carriers are) is already widely implemented. Methanol and ammonia are two of the most used chemical hydrogen carriers. Methanol has a gravimetric storage capacity of about 12.5 wt.% while the same value for ammonia reaches up to about 17.7 wt.% [97]. Both may be produced by synthesizing natural gas, although newer and more environmentally friendly approaches have also been developed more recently, based on the electrolysis of water.

### **2.6.3. Liquid-state hydrogen storage**

Storing hydrogen as a liquid is another way to increase the density of the substance, as hydrogen in a liquid state weighs about 70 kg/m<sup>3</sup> [102]. This type of storage requires a considerable amount of energy in the cooling process, as hydrogen boils already at -253 °C, as well as a complex vacuum insulated tank. Nevertheless, it is quite well established with a global liquefaction capacity of about 355 tons per day [103]. Liquid hydrogen storage is not economical for long storage times due to the gradual decrease of the volume stored as a result of the boil-off effect [104]. In fact, the storage tank absorbs heat and thus vaporizes the liquid hydrogen, which must be vented to avoid creating overpressure in the tanks. Elsewhere, several research projects are currently under way to improve hydrogen storage technologies.

## **2.7. Hydrogen delivery technologies**

One of the critical contributors to the costs, energy use and emissions associated with hydrogen pathways is the hydrogen transportation [105]. Three main delivery approaches are possible, largely depending on the storage methods, either gaseous, liquid or material-based hydrogen delivery [106]. The delivery method can be chosen based on geographical and market characteristics, such as population density, size of refuelling stations, market penetration of fuel

cell vehicles and so on [107]. For instance, for consumers below 50 m<sup>3</sup>/h, it is conditioned in gaseous form in bottles and transported by semi-trailers (from 3000 to 6000 m<sup>3</sup> of H<sub>2</sub> at 200 bars). When consumption exceeds several tens of thousands of m<sup>3</sup>/h of H<sub>2</sub>, gas companies use hydrogen pipeline networks. The North-western Europe network is the largest in the world with more than 4500 km of pipeline and 50,000 m<sup>3</sup>/h of hydrogen at 100 bars [108]. According to the IEA, pipeline transportation of hydrogen is the most economically advantageous method if distances are less than 1,500 km, except for very small volumes, which can be delivered by truck. For longer distances, and especially for overseas trade, hydrogen could be transported across borders in ships or pipelines. Otherwise, recent studies are performed in this area considering transportation costs, feasible usage, economic cost, environmental drawback and security concerns [109–111]. Several researchers are being focused on hydrogen injection into the natural gas networks and the minimization of the costs [112,113]. Thus, preliminary studies have shown that the transport of a mixture of natural gas and hydrogen is possible through the existing natural gas networks without pipeline modification [112]. It has been highlighted that this can be performed under certain conditions (mainly high production pressures and large enough markets) to be economically feasible over long distances. It is also necessary to know the feasibility of adding hydrogen to the natural gas [114]. The chemical and physical properties of the hydrogen and natural gas differs significantly which influence safety related to gas transport and its utilization as well as on the integrity of the network [115–117]. So, the system, which is actually designed for natural gas, cannot be used for pure hydrogen without care and modifications. Besides, a gas with higher hydrogen content can have an impact on the safety of the transmission–distribution–utilization chain, the durability and the reliability of the gas pipeline and the utilization performances for the end user [118]. Also, safety should be considered regarding transmission, distribution and use of gas. An additional safety risk of using a natural gas system for hydrogen may arise from the fact that the potential leakage rate of hydrogen is much larger than that of natural gas through the same sized leak [119]. However, the main challenges while injecting hydrogen into natural gas network include the adaptation of the current transmission networks of the natural gas to hydrogen transport, and modification of existing pipeline integrity management systems which might cause some economic loss.

## **2.8. Fuel cell technologies**



Electricity can be produced from hydrogen using fuel cells. There are generally four main families of fuel cells, which differ mainly in the type of electrolyte and operating temperature: alkaline cells (Alkaline Fuel Cell (AFC) and Phosphoric Acid Fuel Cell (PAFC)), Proton Exchange Membrane Fuel Cell (PEMFC), Solid Oxide Fuel Cell (SOFC) and Molten Carbonate Fuel Cell (MCFC) [120–124].

Fuel cells operating at low temperatures (<200 °C) use precious metals (platinum) as catalysts at both electrodes. High temperature fuel cells (MCFC and SOFC) can be powered by hydrogen-rich fuels (natural gas, ethanol), tolerate medium purity hydrogen (99.5%) and use special alloys [123,125]. According to fuel cell type and power, the electrical efficiency can reach 50% and more than 90% if heat is recovered, as the reactions in the core of the cell are exothermic. Current research is focused on PEMFC and SOFC fuel cells, whose stationary or on-board applications can supply several markets (transport, cogeneration, etc.) [126,127].

Currently, research is being carried out on the core of the fuel cell [52,128]:

- Increasing the operating temperature of the electrolyte to increase its performance and reduce its cost,
- Reducing the amount of noble metals and/or developing new catalysts,

Integrating the fuel cell into the vehicle also requires optimizing and managing the gas supply, water removal and heat generation.

Electrolysers and fuel cells convert low-carbon/renewable electricity into hydrogen and then into electricity and heat again. In this respect, they are energy converters that separate the production of electricity from its use and provide flexibility to the electricity system. We expect that advances in fuel cell technology can lead to improvements in water electrolysis technologies.

## **2.9. Hydrogen in the transport sector**

Transport represents about 18% of primary energy consumption and 17% of global CO<sub>2</sub> emissions, and is recognized as a challenging sector to decarbonize [129]. Green hydrogen as an energy carrier has many advantages. First, its energy intensity is nearly the same as that of gasoline, while fuel cell electric vehicles generally have better fuel economy than gasoline or

diesel-powered vehicles. Accordingly, 5 kg of hydrogen carried on a vehicle can provide a driving range of up to 500 km. In addition, it can be refueled as quickly as gasoline and diesel. These two advantages make it particularly suitable for long-distance or heavy travel, such as intercity buses and cargo delivery [130,131]. Nevertheless, the transition to hydrogen-based mobility, require the development of hydrogen refuelling stations (HRS) and infrastructure that must be able to meet the demand for hydrogen [132–134]. HRS are similar to petrol stations, the significant difference is that the hydrogen is measured with a mass flow meter and is thereby presented in kg [134]. HRS represent around 70% of the total costs (from 1 to 10 million dollars) of the hydrogen mobility chain [133]. Meanwhile, HRS is a complicated system that requires equipment such as a compressor, dispenser, high-pressure storage tank, water chiller, heat exchanger, and so on [135].

According to Tian et al. [135], HRSs can be classified depending on:

- *Hydrogen production location* (on-site HRSs or off-site HRSs);
- *Hydrogen storage status* (i.e. compressed gaseous hydrogen (CGH<sub>2</sub>) stations or liquid hydrogen (LH<sub>2</sub>) stations);
- *Construction forms* (i.e. stationary HRSs and mobile HRSs);
- *Construction content including independent HRSs and combined HRSs.*

Based on the types of energy sources, HRSs can be divided into electric-hydrogen hybrid stations, oil-hydrogen combined stations and gas-hydrogen combined stations. **Fig.6** summarizes all the HRS categories, which are comprehensively reviewed in [135,136].

In recent work, more attention has been paid to the technological and techno-economic aspects of choosing and selecting HRSs [135]. In addition, security is another vital element that requires greater attention for large-scale HRS deployment [115–117,136]. Public acceptance is another key issue for society. Raising awareness of this new technology can significantly reduce the psychological stress of operating the station, quickly familiarize the user, and contribute to the diffusion of HRS [137].



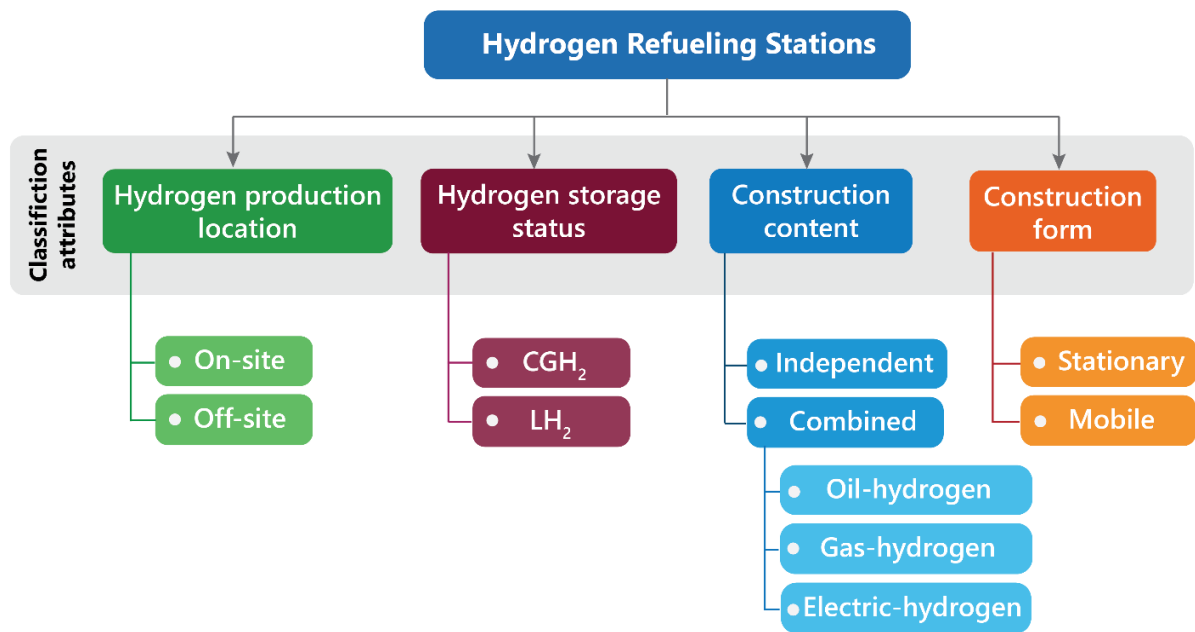


Fig. 6: Classification of HRSs

## 2.10. Hydrogen cost

The high cost of production was a major barrier to the widespread adoption of green or blue hydrogen in the industrial and mobility sectors [138]. The cost of hydrogen production by electrolysis is subject to various estimates according to the sources, varying from 1 €/kg to more than 10 €/kg, according to the assumptions (nature, cost and size of the electrolyser, efficiency and electricity cost) [139,140]. The cost of green hydrogen has recently dropped by 80% between 2002 and 2017 [157] and is expected to continue to drop until mid-century [141] (See Figs 7 and 8). These costs are generally linked to renewable electricity supply and the electrolyser deployment. A low cost of renewable electricity is thus essential for competitive green hydrogen production. Given the temporal variability of the electricity cost, it is in the electrolyser's interest to operate when the electricity cost is low. The duration of use of the electrolyser also has a significant impact on the cost of green hydrogen. It is difficult to simultaneously benefit from a low electricity price and a long annual use of the electrolyser.

Area of use is an additional factor that can affect the cost of green or blue hydrogen. Elsewhere, another factor that impacts the green or blue hydrogen cost is the sector of use (See Fig. 9) [142,143]. As an example, in heavy industries, they traditionally have their hydrogen production

facilities on-site. So, natural gas steam reforming is installed directly on the site, and the cost of hydrogen for these sectors is the production cost. Light industries are more dispersed on territorial scale and do not have on-site production facilities. So, the hydrogen is typically delivered to them by truck, adding logistical costs (often surpass one of production) to the molecule's cost. As a result, prices range from 2 €/kg to more than 10 €/kg [139]. To achieve the decarbonization of these sectors using green hydrogen, it is necessary and if possible to rely on local production systems based on clean energy or a mix of energy adapted to the specific local context [144].

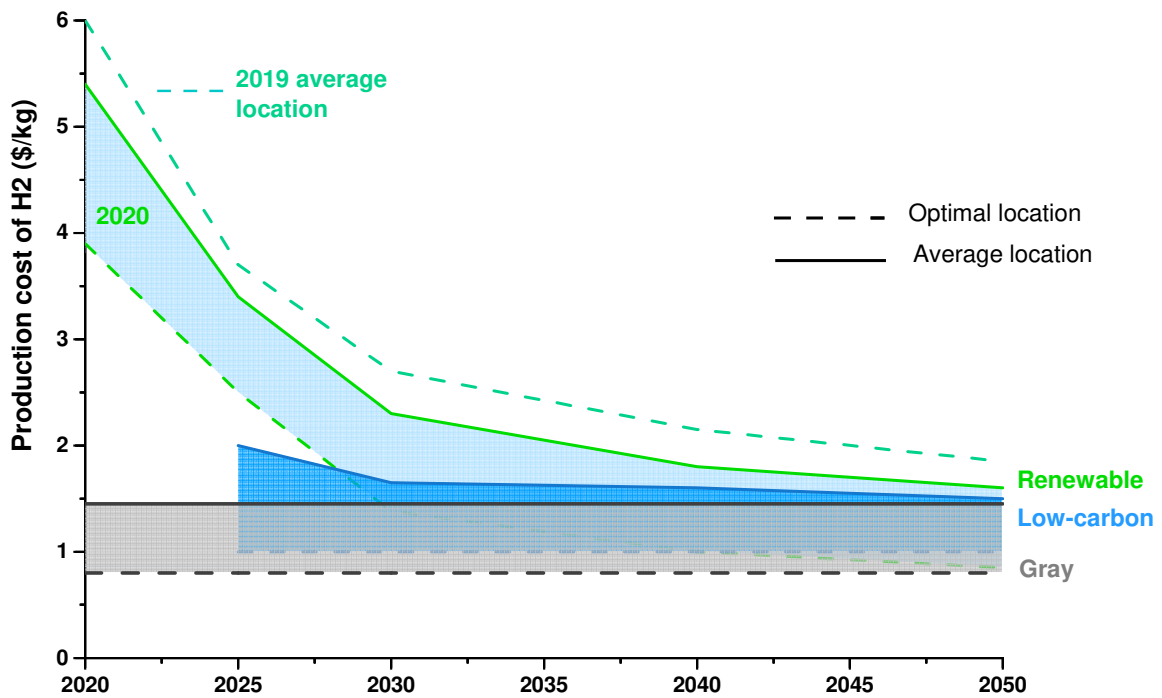
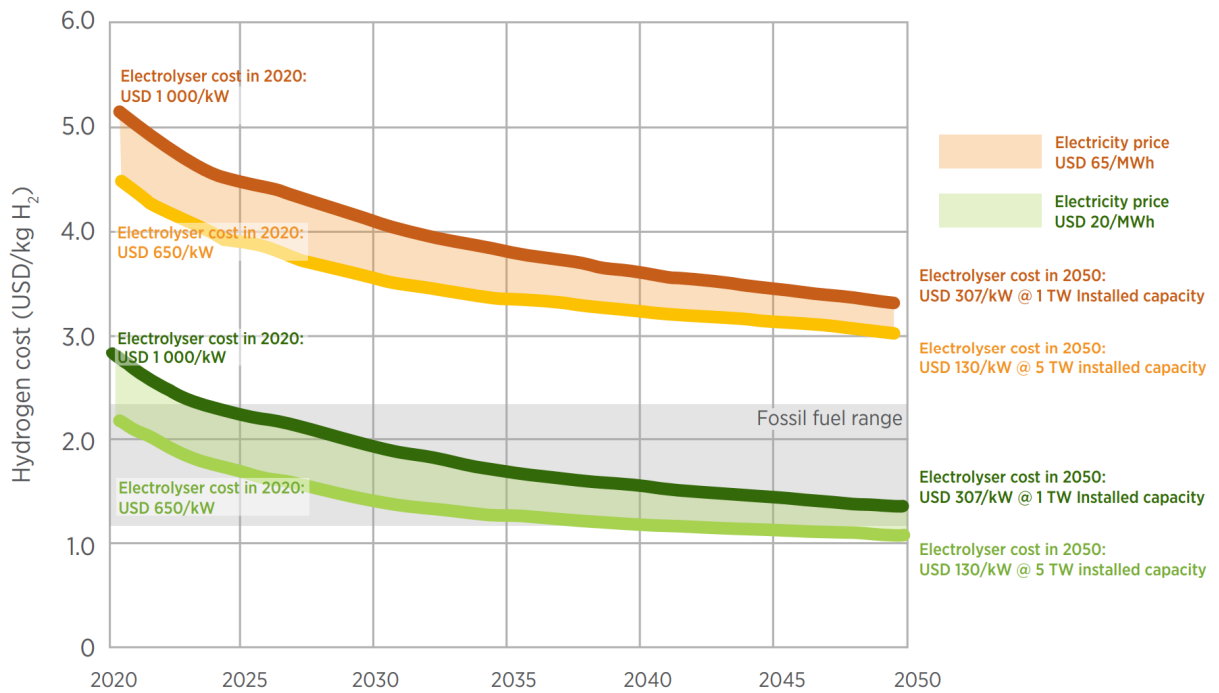
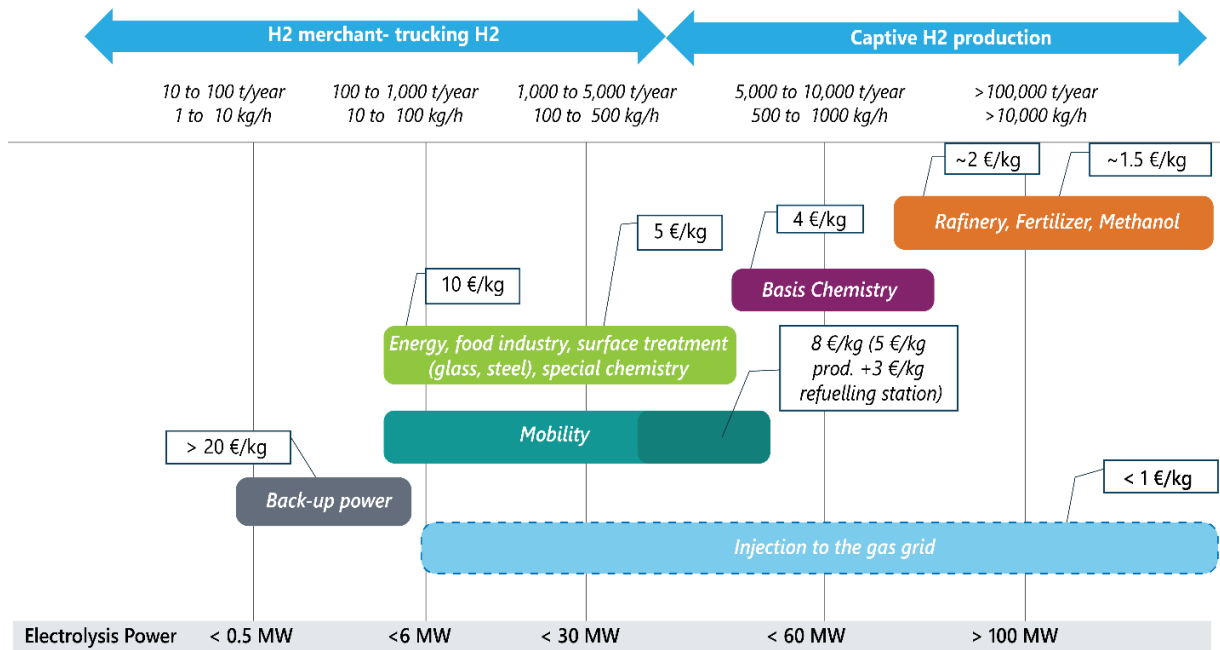


Fig. 7: Hydrogen production costs [141]



**Fig. 8:** Cost of green hydrogen production as a function of electrolyser deployment using an average (USD 65/MWh) and a low (USD 20/MWh) electricity price, constant over the period 2020-2050 [51]



**Fig. 9:** Hydrogen cost per applications (adapted from [145])

### **3. Hydrogen Strategy per Country**

Currently, hydrogen is recognized by many countries around the world as a flexible option capable of creating a new global geopolitical map and reshaping the structure of global energy markets. Many countries around the world have established national strategies to develop the hydrogen value chain. This section reviews the hydrogen roadmaps that have been developed in a few countries around the world such as Australia, Chile, China, Canada, Germany, South Africa, the United Kingdom, Japan, the European Union, France, the United States, South Korea, India and Morocco.

There is no doubt that these countries will play a crucial role in future renewable hydrogen systems thanks to their renewable energy potential, fresh water availability and infrastructure capabilities. However, the outstanding challenge for these countries is to reduce the cost of large-scale green hydrogen production and distribution.

#### **3.1. United States**

With more than 7,500 fuel cell vehicles on the road, the United States has been a leader in fuel cell and hydrogen technologies since 1969 and intends to maintain this leadership by expanding the application areas of these technologies [146]. This commitment is reflected in a series of policy actions, including the publication of the roadmap to a U.S. Hydrogen Economy, which calls for using the potential of hydrogen to strengthen the economy and decarbonize the transportation and industrial sectors [146].

Developing a hydrogen economy in the United States can be beneficial for Uncle Sam's country. Indeed, according to [146], hydrogen offers a unique opportunity to decarbonize the energy system and make it more secure. A competitive hydrogen industry will strengthen the U.S. economic leadership. Furthermore, a hydrogen economy would help to support the country's economy by creating jobs. It is estimated that by 2030, hydrogen would generate around \$140 billion in revenue and create nearly 700,000 jobs. In addition, hydrogen offers an opportunity to decarbonize industry and also transportation through the use of fuel-cell vehicles.

The establishment of a competitive hydrogen sector in the United States is based on the country's resources availability. Indeed, the USA is one of the largest producers of natural gas in the world and has an abundance of renewable resources and low-carbon electricity (hydroelectricity and nuclear power). Using these resources, the country intends to produce electricity at very low cost which would be profitable for the production of green hydrogen [146].

The United States of America (USA) can be called hydrogen technology's pioneer. It is indeed this country that gave its letters of nobility to the fuel cell by integrating it as an energy source in its Apollo 11 space mission launched in 1969 by NASA [146]. Since then, hydrogen technologies, under the political actions of the government, have progressed in this country making the USA one of the world leaders in this field. However, a review of the history of hydrogen policy in the United States reveals a lack of coherence in activities as a result of this country's involvement in the energy sector being formed from the single will of a president rather than from a national or governmental consensus [147]. The different administrations that have succeeded each other have more or less modified or even stopped certain hydrogen initiatives already underway.

As early as 1993, under the Clinton administration, the federal government established an R&D partnership with the "Big 3" U.S. automakers (General Motors, Ford, and DaimlerChrysler) called the Partnership for a New Generation of Vehicles (PNGV), whose objective was to develop new vehicle technologies that would be less polluting and three times more fuel efficient than those existing at that time. Fuel cell technology was one of the PNGV's priority research areas to achieve its goals [148]. However, this program was cancelled under the George W. Bush administration and replaced by another one.

In 2001, President George W. Bush arrived at the White House with a real desire to respond to the challenges of energy security in the USA and climate change through his National Energy Policy [149]. In this report, hydrogen is seen as an alternative energy solution to be developed. In January, the government announced the end of the PNGV and replaced it with the "A freedomCar" program which will be placed under the direction of the Department Of Energy (DOE) [148].

Early in 2002, the DOE published “National Vision of America’s Transition to Hydrogen Economy to 2023 and Beyond”, based on the findings of November 2001 Visioning Conference for the Hydrogen Economy in America attended by 53 business leaders, energy policy makers, university leaders and environmental organizations. This report emphasizes the need for a combined effort by all stakeholders to successfully develop hydrogen in the U.S. [150]. In November 2002, after a workshop on the U.S. hydrogen roadmap, the DOE published the National Hydrogen Energy Roadmap, which explores the potential of hydrogen, its main development challenges, and possible solutions to address them [151]. In 2003, the government launched a fuel cell technology R&D program called the Hydrogen Fuel Initiative to complement the "A freedom CAR" project. In addition to these actions, many R&D programs have been launched within the DOE to develop hydrogen and fuel cell technologies such as the Hydrogen and Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan, the Department of Energy Hydrogen and Fuel Cells Program Plan, etc. [152]. In 2020, the Road Map to a U.S. Hydrogen Economy is published, resulting from the collaboration of many executives and industry experts in the hydrogen sector and which describes the ambitious scenario for hydrogen in the USA. Indeed, the U.S. Hydrogen Economy Roadmap foresees a four-stage scenario for hydrogen development [146]:

- **From 2020 to 2022 "immediate next steps"**: Establishing reliable, technology-neutral decarbonization targets in more states to maintain federal uniformity in the hydrogen advance, since some progressive states in America, such as California, are ahead of the curve on hydrogen mobility. More concretely, it will be a matter of starting the nationwide commercialization of already viable applications such as forklifts and further on, light and heavy-duty vehicles in California. At the end of this phase, the U.S. hydrogen market could reach 12 million tons with approximately 30,000 fuel cell vehicles sold.
- **From 2023 to 2025 "Early scale-up"**: This phase foresees the development of large-scale hydrogen production, thus reducing costs and favouring applications outside of the first advanced states in the sector. The total demand for hydrogen at the end of this phase is expected to be 13 million tons and about 15,000 light, medium and heavy-duty fuel cell vehicles could be sold.

- **From 2026 to 2030 "Diversification":** The goal in this phase is to diversify hydrogen applications beyond the areas adopted by the first advanced states and expand them throughout the federal country. Hydrogen demand would reach 17 million tons with 1.2 million fuel cell vehicles sold and 4300 hydrogen stations throughout the United States. Annual investments by 2030 are estimated at \$8 billion.
- **After 2030 "Widespread Deployment Across the U.S.":** During this phase, hydrogen would be fully distributed across the country, and hydrogen applications would be cost competitive with conventional fuels. By 2050, hydrogen sales might exceed \$750 billion per year, with demand approaching 63 million tons.

More broadly, in order to achieve these objectives, the roadmap identifies nine actions that revolve on the following points [146]: Setting reliable and technology-neutral decarbonization targets; Stimulating market development with the necessary public incentives and infrastructure development support; Support technical research and integrating hydrogen into existing energy regulations.

### 3.2. Australia

Australia is making significant investments in the development of its hydrogen industry. It is depending on the energy sector of decrease GHGE and strengthen its economy. This large country has significant natural resources that will allow it to become a major global exporter in the future [13]. To promote this sector, the government is implementing a number of policy initiatives, such as the financing of R&D projects [153], while establishing partnerships with other countries (Japan, Korea, Singapore, and Taiwan) to support their hydrogen market [13]. For the government, the development of hydrogen sector can strengthen the economy by creating thousands of jobs and contributing more than \$1.7 billion to GDP [154], enabling the integration of renewable energy into the power system, reduce dependency on imported fossil fuels, and reduce its own emissions and the global ones [155].

Meanwhile, Australia's hydrogen sector benefits from an abundant natural resources as well as existing infrastructure to develop [156]; Hydrogen produced from natural gas in Australia has a reputation for being particularly low in impurities, requiring less post-processing to purify it. Likewise, hydrogen can benefit from the vast natural gas infrastructure already in place, such as a 17,000 km long pipeline network for distribution. In addition, the country has large coal

reserves, and the highest average solar radiation, making it one of the top solar energy resources in the world.

Australia's interest in hydrogen dates back to the 1930s when Brisbane Councillor J.F. Kemp suggested the initiative to fuel vehicles with hydrogen from the city's coal gas [153]. Since 1992, research in Australia has been conducted on fuel cell technologies by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). In May 2003, The Hydrogen Economy Challenges and Strategies for Australia Conference was held in Broome city, Western Australia, bringing together experts from around the world [153]. As a result of this conference, a study entitled National Hydrogen Study was published at the request of the Department of Industry, Tourism and Resources (DITR) assesses the role of hydrogen in the energy system and makes recommendations that would set the basis for Australia's participation in a future hydrogen economy [153].

In May 2005, Australia joined the Hydrogen Implementation Agreement of the International Energy Agency [153]. In May 2007, the DITR launched a call for tenders to produce a hydrogen roadmap [153]. In addition to all these actions, the state in collaboration with the Commonwealth is funding hydrogen research studies and demonstration projects [153]. In August 2018, the Renewable Hydrogen Conference was held in Perth city, Western Australia, which presented the vision for renewable hydrogen in Australia's future. Following this conference, the CSIRO published the National Hydrogen Roadmap, which defines a plan for the development of a hydrogen industry in Australia. The roadmap outlines a number of actions across the hydrogen value chain. For instance, it calls for policy measures to stimulate demand for hydrogen, measures to establish specificity standards and incentives for R&D [157].

The year 2019 has seen the adoption of the National Hydrogen Strategy released by the Council of Australian Governments (COAG) Energy Council that sets out an action plan to develop a clean, safe and competitive hydrogen industry [155]. For its objectives, the strategy specifies 57 joint actions, which focus on the national coordination, attracting investment in hydrogen, development of production capacities, regulation and international commitment, innovation and R&D, skills and workforce development, and development of community confidence. The government's actions in favour of hydrogen have multiplied line with its hydrogen strategy, a series of partnerships with countries like Japan, South Korea, China [154]. The Australian Renewable Energy Agency (ARENA) announced in April 2020 the mobilization of \$70 million



to help the rapid deployment of renewable hydrogen in Australia [153]. In April 2021, the Morrison Government announced \$275.5 million to be invested in building the hydrogen industry with the aim to accelerate the establishment of four extra clean hydrogen hubs in regional Australia and to create a clean hydrogen certification system. Alongside this, a project to build the largest solar and wind farm known as the Asian Renewable Energy Hub is taking place in Western Australia. This facility will be used to produce hydrogen to supply, mainly, Asian markets [13].

### **3.3. Canada**

The development of low-carbon hydrogen is a central interest for Canada, which is currently recognized as one of the world's hydrogen pioneers. Canada possesses distinct competitive and comparative advantages that position it to become a world-leading producer, consumer, and exporter of clean hydrogen, as well as diverse hydrogen technology and services [158]: (i) The availability of abundant hydrogen-producing feedstock such as freshwater resources, large scale biomass supply, substantial fossil fuel reserves and high hydroelectric production capacity; (ii) Its innovative leadership and industrial dominance and expertise in fuel cell technology, and carbon capture technology; (iii) Hydrogen-related international cooperation; (iv) Canada's closeness to hydrogen import markets, such as South Korea, Japan, the United States, the United Kingdom, Germany, and the rest of Europe; (v) Infrastructure potential including deep-water ports, extensive pipeline networks, and a growing LNG sector.

In addition, Canada's commitment to expanding the hydrogen industry has been demonstrated through a series of policy measures. In this regard, Natural Resources Canada in collaboration with stakeholder organizations, provincial and territory governments, and indigenous partners have been working in the last three years to establish the Hydrogen Strategy for Canada, which was unveiled in December 2020 [158]. Underpinned by a \$1.5 billion federal investment in a Low-carbon and zero-emission-Fuel Fund to boost the production and use of low-carbon fuels such as hydrogen, this ambitious hydrogen development strategy aims to position Canada as a world leader in hydrogen exports by 2050 by diversifying the future energy mix, generating economic benefits, and achieving net zero emissions. It will involve transitioning from traditional gasoline, diesel, and natural gas fuel sources to zero-emission fuel sources, taking advantage of changing regulatory contexts, and adopting new technology to provide Canadians

with additional zero-emission choices. Furthermore, this strategy will allow Canada to profit from the rising worldwide demand for hydrogen, creating more than 350,000 high-paying employment and establishing a \$50 billion domestic hydrogen sector.

The hydrogen strategy implementation process is divided into three key phases [158]: **Near-Term** (2020–2025); Efforts in this phase will be focused on establishing the groundwork for Canada’s hydrogen sector, including the construction of new hydrogen supply and distribution infrastructure, assisting initial deployment hubs in mature applications as well as supporting Canadian demos in new applications. Additional legislative and regulatory measures will be developed and implemented in order to achieve net-zero carbon emissions by 2050. **Midterm** (2025–2030); the focus will be on the growth and diversification of the hydrogen sector, with the adoption of fuel cell electric vehicles and transit buses projected to begin a rapid expansion phase, as well as larger-scale hydrogen production allowing for natural gas blending. Also, the use of hydrogen in mining projects is expected, and pilot projects evaluating hydrogen as a utility scale energy storage medium will start. **Long-term** (2030–2050); throughout this phase, the emphasis is on increasing the number of new commercial applications backed by supply and distribution infrastructure. New transportation technologies will enter commercial and fast expansion phases, and additional dedicated hydrogen pipelines could be developed.

It is worth noting that strategies for hydrogen integration may range from province to province, and so will the relevant regulations and incentives. For instance, in *Quebec*, production of “green hydrogen” will be prioritized based on the province’s current abundance of hydroelectricity and will operate as part of the province’s wider goal to promote sustainable energy consumption. In *Alberta*, the concentration will be on blue hydrogen production, in which natural gas will be utilized in conjunction with carbon sequestration technology to offset emissions. Consequently, new policies, regulations, and standards will be established in each province to support hydrogen deployment.

The hydrogen strategy considers a range of the end use for hydrogen in Canada, including fuel for transportation and production, heat for the industrial sector and buildings, and feedstock for industrial sectors. Any entity active in these sectors will almost certainly anticipate seizing the opportunity and benefiting from government initiatives incentivizing hydrogen deployment in the coming years.

### 3.4. China

China is becoming the world's largest emitter of GHG due to its extensive usage of coal in power generation [159]. In 1990, its CO<sub>2</sub> rate was less than a quarter of that of developed countries, but over the last two decades, its emissions have risen substantially, accounting for 27% emissions in 2019, considerably exceeding that of developed countries combined [160].

Faced with such a situation, which is not in line with the requirements of the Paris Agreement, the EU urged China, at the EU-China summit in September 2020, to take steps to improve its climate policy. A week later, at the United Nations General Assembly, President Xi Jinping responded favourably by announcing that China would take stronger measures and aim to be carbon neutral by 2060. To attain its objectives, it intends, as stated in its 14th Five-Year Plan, to shift away from coal for power generation and turn more to renewable energy [161].

Despite being the most polluting country, China is investing extensively in renewable energy and is even the world leader. It holds more than a third of the world's solar and wind power capacity, and it is the world leader in biofuels, hydropower, solar water heating, and geothermal heat generation [162]. With its abundant renewable energy and coal resources, it can produce huge amounts of hydrogen and diversify its energy supplies for improved energy security, as it has low reserves of natural gas and oil. Likewise, hydrogen could a great help in achieving the country's climate goals [163]. Furthermore, to grow, China's hydrogen sector benefits from a population that may serve as a significant consumer market for hydrogen applications.

China's interest in hydrogen dates to the 2000s and is particularly evident in fuel cell vehicle applications. Already in May 2004, a workshop on China's vision of the hydrogen economy was held with more than 50 national executives from industry, environmental organizations and research centres in attendance. In January 2005, another workshop was held on China's roadmap to the hydrogen economy, this time with over 90 executives attending. China's vision for its transition to hydrogen was summarized in three phases: technology development phase until 2020, market penetration phase, including transportation and power market by 2050 and after 2050, hydrogen market and economy should be fully realized [164].

In September 2005, Chinese President Hu Jintao visited Canada's leading fuel cell R&D organization, Ballard Power system [164]. The year 2006 saw the launch of the National Medium – and Long-Term Program for Science and Technology Development (2006 2020),

which plans to make China "an innovation-oriented society" by 2020 and a world leader in science and technology by 2050. Hydrogen is one of the seven priority areas on which it intends to focus [165].

China is also setting up funding agencies for R&D projects on hydrogen and its applications, especially fuel cells. Its primary funding agencies are the Ministry of Science and Technology of China (MOST) and the Natural Science Foundation of China (NSFC), both of which have been sponsoring hydrogen storage and fuel cell initiatives since the 2000s [166]. MOST, for instance, has initiated three national basic research programs, each financed by 30 million RMB (Chinese renminbi) through the "973" program. It has also launched a multitude of national high-tech development programs under the "863" program [164].

The Chinese government has also established a variety of demonstration projects. As early as March 2003, China, in collaboration with the Global Environmental Facility (GEF) and the United Nations Development Program (UNDP), launched a fuel cell bus demonstration project, the first phase of which took place between June 2006 and October 2007 and resulted in the deployment of three DaimlerChrysler fuel cell buses in Beijing [167]. In addition, 20 fuel cell vehicles were deployed for the 2008 Beijing Olympics [166].

In 2016, The Action Plan for Energy technology revolution and innovation (2016–2030) was launched by the National Development and Reform Commission of China. This plan put forward three strategic directions for the development of the hydrogen industry and the development of its production, storage and transportation technologies as well as fuel cell technologies [168]. The appearance in 2019, for the first time, of "Hydrogen Energy" in the annual report of the government confirms the government's commitments to promoting charging stations, and other equipment [168]

Notwithstanding these numerous initiatives, there is still no competent policy strategy for hydrogen development. In 2020, relevant policy measures were taken by the government. Also, the National Bureau of Statistics has included hydrogen in its energy statistics since 2020. On April 23, the government issued a notice on the policy improvement of financial subsidies for fuel cell vehicles. Meanwhile, nearly 20 provinces and 30 cities have rolled out their own hydrogen development strategies [168].

While China has made significant progress in the hydrogen industry, it still faces many challenges in establishing a comprehensive hydrogen economy as evidenced by the lack of a systematic comprehensive hydrogen strategy [163]. These challenges include a lack of important advanced hydrogen technologies, competent policy, standards, infrastructure, and people's awareness. Also, geographical distribution problem between demand and resources, as most of the population for demand is located in the east of the country, while the majority of the energy reserves are located in the west and north. This poses a problem for suppliers in terms of distribution. Another challenge for the government is finding space for the construction of hydrogen vehicle charging stations. Indeed, these stations must be built in urban centres, near the population, but Chinese cities are densely populated and there is little space [168].

### **3.5. Japan**

Considered as one of the pioneer countries, Japan is strongly committed to the hydrogen race with the ambition of being the first "hydrogen society". It intends to expand the use of hydrogen in all sectors of its economy since this gas, as an energy carrier, offers the best options for decarbonizing its energy system and enhancing energy security through diversification of its energy sources [13,169].

Historically, Japan has not been a leader in fuel cell technology. Nevertheless, in light of Europe's and the United States' technological advancements, the government introduced a series of laws to improve its technological level. The major goal of all of these laws was to boost R&D in the country by creating a favourable environment for collaboration between companies, universities, and research institutions [147]. In November 1995, Japan promulgated the Science and Technology Basic Law establishing science and technology industries as a priority for development. In 1998, Japan also passed the Law Promoting Technology Transfer from Universities to Industry (TLO Law) to facilitate technology transfer and support collaboration between R&D in universities and industry. In 1999, the government enacted Article 30 of the Law on Special Measures for Industrial Revitalization-a Japanese "Bayh-Dole Law" that allowed inventors to retain the plan outlining Japan's energy mix for the 2030s. The year 2004 saw the passage of the National University Corporation Law which changed the status of universities from a government entity to a special corporation to facilitate their personal involvement in

business. All of these enacted laws had resulted in the establishment of about 200 University-Industry collaborative research centres and 2,000 venture companies by 2013 [147].

In addition to these regulations, the Japanese government is taking a series of actions, including investments in research, to develop its hydrogen industry. Its main funding and support actors for the development of hydrogen technologies are the METI (Ministry of Economy, Trade, and Industry) and NEDO (New Energy and Industrial Technology Development Organization) [170]. The most important projects conducted are the SUNSHINE project launched by the AIST (Agency of Industrial Science and Technology) in 1974, which is the first national hydrogen development program, the MOONLIGHT project that was introduced in 1978 to develop energy conservation technologies, and the R&D Project on Environmental Technology launched in 1989 by METI through AIST. These three projects all placed a high value on the advancement of fuel cell technology [171]. In 1993, the government decided to combine these three projects into a single project called “New SUNSHINE”, to broaden their vision and perspectives and to accelerate their deployment. This New Sunshine in collaboration with NEDO is conducting R&D projects for hydrogen production from renewable energy, especially through its World Energy Network Project (WE-NET) program [147]. This decision was accompanied by the establishment of the Millennium Project in 1999 by METI, to accelerate the development of fuel cell vehicles and cogeneration systems. The Project’s activities can be described as follows: The creation of the Strategic Council for Fuel Cell Commercialization (FCCSC) in December 1999; Establishment of a four-year strategic plan for the development of fuel cells; Creation of the Fuel Cell Commercialization Conference of Japan (FCCJ) in March 2001; Adoption of the Japanese fuel cell roadmap in the same year.

Early in 2000, a strategic plan (2000–2004) for the development and commercialization of fuel cell technologies was established by METI. However, due to difficulties encountered, this program which was supposed to last 4 years ended in 2015 [147]. Elsewhere, natural disasters (earthquakes and tsunami) in Japan in 2011 devastated the country’s economy and environment, resulting in an unprecedented national energy crisis. This crisis, which leads the government to fall back on hydrogen, is behind the country’s desire to be the first "hydrogen society" [147].

In December 2013, METI created the Council for a Strategy for Hydrogen and Fuel Cells (CSHFC) to replace the FCCSC and provide guidance on adopting a policy for a hydrogen society [147]. CSHFC’s guidance led to the inclusion of policy measures for a “hydrogen

society” in the Strategic Energy Plan of April 2014, and the creation of a hydrogen roadmap in June by METI. This roadmap included three phases [147]:

- Phase 1: Expanding the use of fuel cells and hydrogen, as well as the market for residential cogeneration systems, by installing 1.4 million residential fuel cell units by 2020 and 5.3 million by 2030.
- Phase 2: Improvement of the hydrogen value chain (production, storage and transportation) by exploiting abundant imported oil, gas and coal reserves.
- Phase 3: Establishment of a competitive, stable, and totally CO<sub>2</sub>-free energy system.

In December 2017, Japan reaffirmed its commitment to a "hydrogen society" with the release of the National Hydrogen Strategy. This plan aims to achieve hydrogen cost parity with competing fuels [172]. Furthermore, to concretize this strategy, a new roadmap is published in 2019 [173].

Japan is seeking to position itself as an international leader in hydrogen and is convening a G20 Ministerial on hydrogen. It also aims, through the Tokyo 2020 Olympic Games (Postponed to 2021 because of the COVID epidemic), to act as a showcase for a hydrogen-based society. On this occasion, an athletes' village for the Tokyo 2020 Olympic Games as a miniature hydrogen society is built. In addition, the torch flame is powered by hydrogen. Besides, Japanese industrialists are engaging in partnerships with many countries like Australia, Brunei, Saudi Arabia and Norway. In June 2020, Japan received a first shipment of liquid organic hydrogen (LOHC) from Brunei (based on natural gas) [13].

### **3.6. India**

India was an early adopter of hydrogen initiatives, establishing a hydrogen roadmap in 2006, but it is currently falling behind other Asian countries such as China and Japan, as well as European countries. Nevertheless, faced with the urgent need to reduce its reliance on imported oil as well as decarbonize its economy, the Indian government is taking political measures to accelerate the development of its hydrogen sector on a larger scale. Hydrogen has the potential to improve India's energy security. Yet, with the world's second-biggest population behind China, India's growing demand for energy has so far been satisfied by fossil fuels, the majority of which is



imported oil [174]. In 2019, India was the world's third-largest oil importer [175]. Hydrogen is a promising alternative that the government is considering lessening its reliance on oil. Also, hydrogen can serve to reduce of its air pollution. Likewise, India intends to take advantage of the benefits of hydrogen to reduce its GHGE and thus improve its air quality, which is among the worst in the world [175].

To develop its hydrogen economy, India is already exploiting renewable resources such as solar energy and hydroelectricity [176]. Early on, hydrogen piqued the interest of the Indian government, which considered it as a potential replacement for oil. In July 1976, the Department of Science and Technology (DST) established the Hydrogen Energy Task Force (HETF) with the goal of developing a plan of action for the progressive diffusion of hydrogen in India's diverse sectors of energy use [177]. Subsequently, in July 1977, a workshop on hydrogen was held at the DST premises in New Delhi to which over 30 experts from different disciplines and organizations were invited. The workshop gave recommendations for R&D work to be undertaken in the country [177]. In a paper titled Thrust Areas in Engineering Sciences, published in 1983, the DST identified hydrogen as a "thrust area" for its energy R&D [177]. In 1982, the Department of Non-conventional Energy Sources (DNES) was established a committee for hydrogen, the Technical Advisory Committee on Hydrogen Energy (TACHE) [177]. This committee presented measures for the implementation of energy programs and supported numerous hydrogen research actions. In 1985, the DNES supported a National Workshop on Hydrogen Energy where the different hydrogen technologies were discussed [177].

Since 2006, the Ministry of New and Renewable Energy (MNRE), prepares for the Indian government, a roadmap entitled National Hydrogen Energy Roadmap (NHER) which establishes a program for hydrogen development in India [178]. This roadmap included two main initiatives: the "Green Initiative for Future Transport" which planned to introduce one million fuel cell vehicles, and the "Green Initiative for Power" for the generation of about 1,000 MW of electricity based on fuel cell technology [179]. India is also supporting many research, development, and demonstration projects such as two-wheel and three-wheel hydrogen projects and buses [175]. India has invested \$58 million over a three-year period to support hydrogen and fuel cell projects at numerous institutes [179]. More recently, in November 2020, Prime Minister Narendra Modi announced the launch of a hydrogen mission, the National Hydrogen Mission.



### 3.7. South Korea

South Korea is one of the pioneering and leading countries in hydrogen. Indeed, it is by a South Korean company, Hyundai, that the world's first fuel cell vehicle was produced in 2013, and the largest fuel cell manufacturing plant in the world (POSCO Energy) is also South Korean [180]. Moreover, to develop a favourable ecosystem for the growth of the hydrogen industry, the government presented in January 2019, its Roadmap for a Hydrogen Economy which sets out a long-term plan for the development of the hydrogen economy. This roadmap calls for a 5% share of hydrogen in national energy consumption, the creation of 420,000 new jobs and the reduction of GHGE.

South Korea's decision to invest in its hydrogen industry is justified by economic and environmental considerations [181]. Accordingly, South Korea's aging population, which has the world's lowest fertility rate, is slowing the country's economic growth. To address this issue, the government is investing in potential emerging technologies such as hydrogen to strengthen the country's economy and make it more competitive. Hydrogen is expected to bring 43 trillion won (U.S. \$38.B) to the economy and generate 420,000 jobs by 2040. Otherwise, hydrogen would also bring more energy security to the country and reduce energy imports. Indeed, South Korea imports a very large part of its fossil fuels (most of its energy mix) from foreign countries. The nuclear sector is also subject to imports due to a lack of uranium resources. In addition, South Korea is one of the world's most polluting countries (emitting 624 million tons of CO<sub>2</sub> in 2018). This pollution has a negative impact on the population's level of living, with life expectancy anticipated to reduce by 1.4 years in the near future. Developing widespread usage of hydrogen applications would thus be extremely beneficial to the population by reducing GHG.

The national vision of a hydrogen economy in South Korea really started in 2005 with the publication of the Masterplan for the Realization of Hydrogen and New Renewable Energy Economy by MOTIE (Ministry of Trade, Industry and Energy) [182]. Since then, many policy actions have been taken by the South Korean government to improve its economy and reduce its carbon footprint. Already in 2003, a hydrogen R&D centre was established at the Korea Energy Research Institute, through the Ministry of Science and Technology [183]. South Korea was the first country to promote green growth in 2009 through its "Green Growth" to provide a policy framework for green growth in the short and long term [184]. Subsequently, many other actions

are carried out by MOTIE [182]. For instance, MOTIE announced a budget of 2.6 trillion won (approximately USD 22 billion) in 2018 for establishing a public-private H<sub>2</sub> auto industry ecosystem [180].

To foster a hydrogen economy, the government adopted the National Roadmap for Hydrogen Technology Development in 2019. This roadmap's action plans primarily concern the transportation, industrial, and building sectors [185]:

- **Transportation:** South Korea plans to raise domestic hydrogen fuel cell vehicle production to 35,000 units by 2022, 100,000 units by 2025, with 40,000 units for export. The roadmap calls for subsidies and R&D investments to attain this goal. By 2040, the South Korean plan intends for the manufacturing of 80,000 taxis, 40,000 hydrogen buses, and 30,000 trucks. Thus, R&D efforts for hydrogen utilization in trains, planes, drones, and ships are also planned. The roadmap also prioritizes the expansion of hydrogen charging stations. It intends to expand from 34 stations to 310 by 2022 and 1200 by 2040 [181].
- **Hydrogen power generation and supply:** the country plans to expand its fuel cell power generation from 307.6 MW to 15 GW by 2040, of which 7 GW will be for export. The implementation of the roadmap is expected to increase hydrogen demand from 130,000 tons in 2019 to 5.36 million tons per year by 2040. For now, South Korea is focusing on hydrogen production from liquefied natural gas, but it plans to import green hydrogen by 2030 [181].

In January 2020, the National Assembly of Korea passed the Hydrogen Economy Promotion and Hydrogen Safety Management Law establishing a legal framework for government support of hydrogen and safety standards for facilities. Meanwhile, in response to the COVID-19 crisis, the South Korean government launches the "Green New Deal" in 2020 to accelerate the decarbonization of the country's economy [186]. Apart from government initiatives, private industrialists are also taking hydrogen-related initiatives, such as Hyundai, which announced in 2018 its "FCEV Vision 2030," that also calls for an investment of (6.7 billion U.S. dollars) in infrastructure and R&D, with the goal of producing 700,000 fuel cell systems per year by 2030 [181].

### 3.8. United Kingdom

United Kingdom is likewise a significant pioneer in the hydrogen sector and is committed to carbon neutrality by 2050. In June 2019, the UK became the first major global economy to pass rules to stop its global warming impact by 2050, which push the UK to introduce several policy measures to bring all GHG emissions in different sectors to net zero by 2050. Transport, industry, and R&D are the key strategic elements underpinning the UK energy policy measures. Also, the government is deeply concerned with the development of hydrogen despite the various policy measures taken by the government are not specific to hydrogen, but they have allowed some hydrogen projects to see the light of day.

In 2013, the H2Mobility consortium was set up to investigate the potential for hydrogen as a fuel for Ultra Low Carbon Vehicles in the UK [187]. In August 2017, OLEV (Office for Low Emission Vehicles) launched the Hydrogen Transport Program to fund hydrogen station developments and fuel cell vehicle projects through open competitions. The first phase of this initiative received £8.8 million to a project that would build new hydrogen refuelling stations in Derby, Birmingham, and London [188]. Following that, the government announced a £2 million competition for public or private fleet companies to buy or lease fuel cell vehicles [189].

In 2017, the Industrial Strategy white paper was issued, and it is identified four long-term challenges for the UK economy's transformation, including artificial intelligence and the data revolution, the transition to clean growth, tomorrow's mobility, and finally the future of an aging society [190]. Shortly thereafter, the Clean Growth Strategy was released. Priorities outlined in this study include decarbonizing the transportation sector, decreasing emissions from the household and commercial sectors, and making this a realistic future solution [187]. This study recognizes the value of developing clean fuels such as hydrogen for transport, industry and home heating. Around £130 million has been invested in R&D to develop Carbon Capture and Storage (CCS) technologies and pilot projects, in the UK and in international countries such as Mexico, South Africa and Indonesia [191]. In early 2020, the UK government announced £90 million for low-carbon technology adoption. Of this, £28 million has been allocated to hydrogen production projects through hydrogen procurement competitions [187]. Moreover, the UK government launched the Industrial Decarbonization Challenge, a £170 million challenge to allow the large-

scale deployment of low carbon technology by mid-2020 and to promote the achievement of the Clean Growth Challenges [187].

Otherwise, the government finances low-carbon efforts and hydrogen projects through OFGEM, an official government agency and National Independent. In 2019, for instance, the gas network innovation and competition (NIC) prize launched by OFGEM were awarded to a project that aimed to demonstrate whether existing gas networks are 100% suitable for hydrogen transport [187]. Furthermore, OFGEM granted up to £58 million to 5 projects in the NIC 2020 competition, two of which were hydrogen projects. One of the projects is the H100 Fife (SGN), which intends to build the first network for the production, storage, and transport of green hydrogen generated by wind energy to heat 300 houses. It has received £18 million from OFGEM and a further £6.9 million from the Scottish Government. The second project is the HyNTS FutureGrid which aims to build a hydrogen plant from old gas installations to test the behaviour of hydrogen in existing gas networks. This latter project was awarded £9.07 million [192]. A further project, the HyDeploy was supported by the OFGME by £6.7 million to demonstrate the injection of hydrogen into the private natural gas network of the University of Keele [187]. This project, along with the one deployed by ENGIE in France, is one of the first in Europe to inject up to 20% (by volume) of hydrogen into a gas network [193].

In March 2021, the UK Government confirmed its commitment to fund battery and hydrogen technology development by committing more than £30 million [194]. Notwithstanding all these initiatives and policies, there is still a lack of enough subsidies and effective governmental actions to encourage hydrogen production and end use. According to Edwards et al. [187], the UK government should: Develop a cross-departmental hydrogen strategy within government, accelerate the implementation of carbon reduction policy measures, especially in the aviation and heating sectors, assess the risks faced by hydrogen technology pioneers, provide financial support for hydrogen production, transportation, and injection into the grid, reduce cost and increase hydrogen competitiveness, and so on. Numerous industries and organizations have published papers, outlining the various opportunities and scenarios for the hydrogen fuel cell, and pushing the UK government to develop a hydrogen deployment strategy [195]. These incentives have prompted a framework for the UK government to get involved in the hydrogen industry, with the national strategy expected to be announced later in 2021.

### 3.9. European Union

The European Union, like its member countries, has made hydrogen one of the pillars of its energy and climate policy. It considers this gas as an ideal option to meet its targets for 2050: carbon neutrality as outlined by the Paris Climate Agreement and clean energy supply as stated by the European Green Deal [196]. For the EC (European Commission), hydrogen has many advantages [197]: It is the best way for large-scale decarbonization of the transport, industry and building sectors. In addition, hydrogen could play an important role in the transition towards renewable energies while also ensuring flexibility in energy transfer between sectors. Furthermore, hydrogen would help to reduce the EU's reliance on fossil fuels, strengthen the value chain, and help to create jobs for almost one million people [198].

The European Union's interest in hydrogen was already evident in the early 1980s through the funding of R&D projects. The EQHHPP (Euro-Quebec Hydro Hydrogen Pilot Project) demonstration project, which had a total budget of 59 million Canadian dollars, was one of the principal projects funded by the European Commission in collaboration with the Quebec government (38 million ECU). It attempted to convince people of the viability of converting Quebec's hydroelectricity into hydrogen by electrolysis, as well as advancing hydrogen technology related to aeronautics, transportation, electricity/heat cogeneration, and injection into natural gas networks [199]. Since the 2000s, the EU's initiatives in favour of the hydrogen growth have taken on a larger scale, with 300 million Euros funded under the R&D Framework Program (RDFP) to hydrogen and fuel cell research projects [198].

Early in 2004, the European Commission established the "European Hydrogen and Fuel Cell Platform" to support the development of more cost-effective hydrogen and fuel cell applications, as well as to improve hydrogen infrastructure [200]. In 2008, the EC created Europe's largest hydrogen research and technology development and demonstration (RTD) support organization, the Fuel Cell and Hydrogen Joint Undertaking (FCH-JU) with the goal of accelerating the deployment of hydrogen and fuel cell technologies. Based on private and public collaborations, the FCH-JU is composed of three members: European Commission, Hydrogen Europe Research, and Hydrogen Europe. Stakeholders in this program include public authorities, research community centres and industrial partners [197].

In 2008, the first FCH-JU program was launched with the objective of supporting research and technology development projects. It was endowed with a budget of 947 million Euros, half of which is provided by the European Community through the FP7 program and the other half are obtained by private funds, in the form of individual donations from some industrialists [198]. The second program FCH-2-JU is included in the program "Horizon 2020" (2014–2020) and had as main objectives [201]: Improving the efficiency and reducing the costs of green hydrogen production and transportation fuel cell technologies; Promoting the efficient use of critical feedstocks such as platinum; Demonstrating on a large scale the ability of hydrogen to harness renewable energy and support its integration into the energy system; Using hydrogen storage for grid balancing

Among the numerous initiatives taken out by the FCH-JU is the announcement, in September 2015, of a large project for hydrogen mobility in Europe, the Hydrogen Mobility Europe (H2ME). This project received 170 million Euros in funding, 67 million of which came from the FCH-JU, and its first phase was completed in 2020 with the deployment of 630 hydrogen fuel cell electric vehicles in 10 countries and the installation of 37 new hydrogen recharging stations in 8 nations. Overall, 14.5 million kilometres were driven and 147 tons of hydrogen was distributed through 68,000 refills. In total, 14.5 million kilometres was driven, and 147 tons of hydrogen were distributed through 68,000 refills [202]. Furthermore, the EU is establishing Horizon Europe, a research and innovation program, to encourage scientific initiatives in Europe until 2027. It is endowed with 95.5 billion Euro [203]. In addition, in February 2021 the EC proposed to set up 10 new European partnerships under the program "Clean Hydrogen for Europe" and to invest 10 billion Euros to accompany the energy transition [204].

Elsewhere, the European Hydrogen Strategy, unveiled on July 8, 2020, aims to deploy hydrogen and fuel cell solutions in Europe over 3 phases [197,198]:

- *Phase 1* (from 2020 to 2024): Which will focus on the production (about 1 million tons) of green hydrogen (6 GW) by electrolyzers. This hydrogen will be used mainly for the chemical industry and heavy mobility activities.
- *Phase 2* (2025–2030): This phase will be marked by an increase in electrolyser production to 40 GW. The focus this time will be on "new machineries" (i.e. steel and

maritime applications), hydrogen refuelling stations, energy storage, local hydrogen networks and heat production for buildings.

- *Phase 3* (2030–2050): Which will consist of large-scale electricity production, a quarter of which will be used to produce hydrogen.

To reach its objectives, the EU plans, through the European Clean Hydrogen Alliance, to invest the sum of 100 billion Euros between 2020 and 2030 to finance hydrogen production projects using electrolyzers as well as storage and distribution projects [205]. And another 300 billion are planned to ensure the production of electricity by solar and wind energy [198]. It is worth mentioning that international cooperation is also a key component of the EU strategy. Collaboration among neighbouring countries in Western Europe and North Africa, as well as with international actors, for the development of international hydrogen standards [198]

### **3.10. France**

France is also a key pioneer in the hydrogen sector and one of the most advanced countries in the hydrogen race; it considers this sector as a crucial pillar in the country's energy transition. This active commitment comes from the country's goal to reduce the GHG emissions since the Paris Climate Agreement (from 310 Mt in 2015 to about 90 Mt in 2050). However, the ultimate objectives pursued by the French government in the development of its hydrogen sector are to bring more flexibility to the electrical network through the power-to-hydrogen technology [206], and especially to move towards carbon neutrality by reducing the use of fossil fuels [207]. Today, a very large part of hydrogen production is provided by fossil fuels. The government is aiming for at least 10% of its hydrogen production to come from renewable resources by 2023, and between 20 and 40% by 2028.

Already in 2015, all of the qualities were gathered to provide a favourable environment for the development of its hydrogen: A research particularly at the forefront in this field (compared to the progress of other industrialized countries); Voluntary plans of major groups and global leaders (for e.g. Air Liquide, Engie, Michelin, Areva, Total) to develop the sector; A manifestation of interest from Small and medium enterprises and start-ups, as well as from local authorities [208]. Likewise, the government funding R&D projects, most notably through the



National Action Plan on Hydrogen and Fuel Cells (PAN-H) program, which was started in 2008. The government is also setting up, in 2018, the National Hydrogen Plan which has three objectives [198]: Decarbonated hydrogen production for industrial applications; Hydrogen mobility and grid flexibility; Decarbonization of the transport system.

To meet these targets, the plan calls for the construction of at least 26 H<sub>2</sub> charging stations and 380 fuel cell electric vehicles (FCEV) [209]. Other objectives are jointly managed with other energy programs (French Multi-Year Energy Plan and Energy Climate Law). These consist of developing 400 service stations, and 200,000 FCEV. Accordingly, 100 million Euros is invested for the development of service stations. The national hydrogen plan also includes having a 10% share of decarbonated hydrogen in the industrial sector by 2023, and between 20 and 40% by 2028. Furthermore, it entails the identification and development of storage capacity for renewable energies using electrolysers, the establishment of safety and risk prevention regulations, and supporting development projects, mainly through ADEME (Agency for Environment and Energy Management).

All of the government's measures have considerably contributed to France's substantial lead in the hydrogen industry, hence why the country has decided to move to a larger scale by prioritizing green hydrogen. Launched in September 2020, the Recovery Plan Strategy will run from 2021 to 2030 and will benefit from an investment fund of 7 billion Euros. Indeed, this strategy will be implemented over three axes [198,210]:

- **Decarbonizing the hydrogen industry through the emergence of the electrolysis technology:** France aims to increase the production of decarbonated hydrogen using electrolysis technologies, which it is already relatively progressed in, as a first step in its strategy to develop its hydrogen industry. The objective is to reach a production capacity of 6.5 GW of carbon-free hydrogen by electrolysis in 2030. France also intends to use this low- or zero-carbon hydrogen to decarbonize its industry. The plan is to replace the hydrogen utilized by industry (especially refining and chemicals), which is currently primarily produced from fossil fuels, with decarbonized hydrogen. To achieve this, France has a large network of nuclear and hydroelectric energy sources, as well as considerable technological expertise. Meanwhile, the actions carried out to implement the strategy's first axis are mostly in the form of calls for expressions of interest and large-scale requests for projects. An important initiative is the development, in collaboration with Germany, of the Important



Common European Interest Project (PIIEC) on hydrogen, with a French budget of 1.5 billion Euros, the main goal of which is to assist R&D and industrialization of electrolyzers. In addition, France is leading cooperation agreements at the European level for the production of electrolyzers. The French company Air Liquide and the German company Siemens Energy have agreed to collaborate on the production of electrolyzers on a large scale. Furthermore, Lhyphé develops green hydrogen production sites from a wind farm.

- **Developing heavy mobility with decarbonated hydrogen:** Transportation, a major emitter of GHG, is the second most significant sector in France's national recovery strategy, particularly heavy mobility. The objective is to convert existing passenger and freight transport systems (buses, trains, etc.) to hydrogen technologies and to consider the development of hydrogen-powered ships and aircraft. The strategy aims to conserve more than 6 million tons (Mt) of CO<sub>2</sub> by 2030. To do this, France announces project calls, the most important of which are the "Technology Bricks and Demonstrators" that aims to support development work on components or systems related to the production and transport of hydrogen or its uses in the field of transport, and demonstrator projects. This program has a funding of 350 million Euros until 2023. The second is the "Territorial Hydrogen Hubs" which is managed by ADEME and seeks to the deployment of territorial ecosystems. This program will be endowed with 273 million Euros by 2023.
- **Supporting hydrogen research, innovation, and skill development:** The main goal is to support hydrogen R&D efforts, technological innovation, and the development of tools and/or training courses tailored to the specificities of hydrogen in order to increase relevant skills in this field. For this last axis, the strategy launches a call for expressions of interest for a priority research program "Hydrogen Applications", operated by the ANR (National Research Agency) to support research and prepare the future generation of hydrogen technologies (batteries, tanks, materials, electrolyzers)", a program with a budget of 65 million Euros [198].

### 3.11. Germany

one of the largest hydrogen vehicles and infrastructure demonstration projects in Europe and the world [211]. In addition, the Federal Government, in cooperation with 27 other European nations

and the European Commission, is adopting a hydrogen initiative and intends to promote hydrogen technologies [212].

Due to the coronavirus disease 2019 (COVID-19) pandemic, new measures have been taken to strengthen green hydrogen projects. And the year 2020 has seen the adoption of the National Hydrogen Strategy. Through this program, Germany intends to establish a favourable framework for the development of the hydrogen industry along the entire production chain and to encourage relevant innovations and investments. The following are the main objectives to achieve: Making hydrogen an economically viable solution, establishing a local market for hydrogen technologies in Germany allowing for imports, making hydrogen an alternative form of energy, making hydrogen a sustainable feedstock for the industrial sector, improving transportation and distribution infrastructure for hydrogen, boosting scientific research and forming specialties [212]. Parallel to the strategy's adoption, the federal government is forming a Committee of State Secretaries for Hydrogen, composed of relevant ministries, that will be in charge of supervising and continually adjusting the strategy's measures.

In broad terms, this strategy places a strong emphasis on the transportation, industry, building sectors, and research; For transport sector, the strategy provides for 3.6 billion Euros in subsidies for the purchase of electricity and climate-friendly vehicles, 4.5 billion for the development of electric fuels and for the supply of the building sector [198]. The state also earmarks 50 million Euros for the development of hybrid aircraft and ships (powered by electricity and hydrogen) [198]. **For the industry sector**, various instruments for the transition from fossil hydrogen to green hydrogen have been envisaged. There are also initiatives that encourage the use of hydrogen in manufacturing and the reduction of carbon emissions in the material industry. The goal of these initiatives is to push industry to engage in hydrogen solutions [198]. In the **building sector**, an incentive program for energy efficiency has already been in existence since 2016, and investment for the period 2020–2024 would remain at EUR 700 million.

Elsewhere, research is a key component of this strategy. As for measures, the policy calls for 310 million Euros under the "Energy and Climate Fund" between 2020 and 2023 for scientific research targeted green hydrogen, as well as another 200 million during this period to assist research for the development of hydrogen technology [198,212].

German companies and research centres are pioneers in hydrogen technology. In order to maintain its leading position, Germany is facilitating research through investment funds and training specialists in this field all over the world. The federal government is also planning to create new research institutes and training centres of excellence.

The Ministry of Economic Affairs and Energy launched the Energy Transition Research and Innovation platform in 2015. Within the context of this platform, the Kopernikus project is one of the major German energy transition research efforts [213], which contain four pillars, each with its own goal: *EUSURE* is attempting to develop the future electricity grid; *P2X* will explore the conversion of CO<sub>2</sub>, water, and electricity from renewable sources into gases, fuels, chemicals, and polymers; *SynErgie* to investigate how energy-intensive industrial processes may be made more adaptable to the availability of renewable energy sources; Finally, *Ariadne* is described as a collaborative learning process between science and society that examines how policy measures function, from particular sectors to the larger picture [198].

### **3.12. Chile**

Chile also has the potential to become a major global hydrogen exporter owing to its abundant solar and wind energy resources, and also its wide range of water sources, from the arid, mineral-rich north to the water-rich south [214]. This is the government's ambition, as outlined in the Chilean Ministry of Energy's National Strategy for Green Hydrogen, which was unveiled in November 2020. This ambition is accompanied by a series of initiatives taken by the government, including the promotion of hydrogen applications and the establishment of international partnerships.

Chile is committed to reduce its GHGE in order to help slow down the global climate change [215]. Green hydrogen allows for this, as well as the diversification of the energy mix and creation of new jobs for the population [13]. Towards this aim, the country has unique potential that would accelerate the development of the green hydrogen industry. Indeed, Chile has one of the world's best solar resources, with over 3,000 hours of sunshine per year and less than two millimetres of precipitation per year in areas such as the Atacama Desert [13]. It is worth noting that the installed PV capacity in the Atacama Desert has increased substantially in recent years,

reducing the cost of available electricity and offering the green hydrogen industry a competitive advantage [13].

In 2016, the Chilean Production Development Corporation (CORFO) established the Solar Energy Program in order to identify economic potential for the exploitation of the Atacama and Antofagasta regions [216]. In 2018, the Ministry of Energy launched the Chilean National Long Term Energy Policy, which recognized hydrogen as an innovative technology [216]. Furthermore, the government's political involvement in hydrogen is most clearly demonstrated by the adoption of the National Green Hydrogen Strategy [215].

This strategy includes three main goals [215]: Developing 5 GW of electrolysis capacity by 2025; Producing the world's cheapest hydrogen by 2030; Positioning the Chile among the top three exporters of hydrogen fuel by 2040. More precisely, the strategy aims for accelerating R&D, providing financial support for projects, accelerating the regulatory procedure, and implementing economic and quantitative incentives, such as carbon pricing, to make hydrogen more competitive with fuels [215]. It also attempts at land-use planning and the establishment of production hubs, improvement of transportation infrastructure, and finding hydrogen buyers in foreign countries. These targets are supported by suggested initiatives such as allocating USD50 million to pilot projects and boosting hydrogen-based end-user applications.

This strategy has resulted in a few actions. For instance, in April 2021, the Chilean government is issuing calls for proposals for hydrogen projects that will receive funding [217]. Elsewhere, the Magallanes Regional Commission approved the Haru Oni green hydrogen project coordinated by Highly Innovative Fuels (HIF) in July 2021. The development of a hydrogen fuel generating plant in Magallanes is the focus of this project [218].

### **3.13. South Africa**

South Africa's hydrogen sector is beginning to expand, owing to the availability of abundant natural resources and a series of government policy initiatives aimed at seizing hydrogen opportunities to enhance the country's economy and make it a global exporter of green hydrogen. The development of a hydrogen economy in South Africa will significantly contribute to the improvement of its population's standard of living by strengthening the economy and lowering emissions.

In fact, South Africa, which is the world's 14<sup>th</sup> highest emitter of GHG [219], needs to lower its carbon footprint, which is primarily due to its reliance on coal as a primary energy source [220]. In this way, hydrogen can play a key role by decarbonizing its energy system and providing greater security. The hydrogen industry could also generate employment, develop human capital, position South Africa to make a significant contribution to the global climate situation, and enable it to meet its climate ambitions [220]. Otherwise, fuel cell technologies might be a great benefit to the mining sector, which is a major source of revenue for the country but quite energy intensive [221]. While a significant portion of the population (about 1.3 million households) currently without access to a reliable electricity network, hydrogen and associated technologies can serve to mitigate the problem [221].

The country's natural resources make it ideal for hydrogen development, fuelling the government's ambition of making South Africa a major global exporter of green and cost effective hydrogen [222]. Meanwhile, South Africa has the large coal reserves as well as abundant solar energy. With more than 2500 hours of sunshine per year and a global radiation (from 4 to 6.5 kW/m<sup>2</sup>/day), the country is well-known for being one of the sunniest countries in the world [223]. Also, the country possesses wind resources with speeds ranging from 5 to 10 m/s in many parts. Furthermore, South Africa has a large reserve (80% of the world's reserves) of platinum group metals (PGMs), which are utilized in electrolyzers [220].

South Africa's involvement in hydrogen goes back to 2008, when the Department of Science and Technology (DST) launched the National Hydrogen and Fuel Cell Technologies Research, Development, and Innovation Strategy [224]. This strategy had the following ambitions [220]: Establishing a foundation for hydrogen production, storage technologies and processes; Laying the groundwork for the development of PGM-based technologies; Leveraging existing global knowledge to develop expertise to move beyond existing fuel cell technologies for specific applications to address regional development challenges. More specifically, this strategy was highlighted by the establishment of HySA (Hydrogen South Africa), which stimulates and supports innovation across the entire hydrogen and fuel cell technology value chain in South Africa [224]. Founded by the DST, HySA is a long-term (15 years) program with the missions of developing South African intellectual property, human knowledge and skills, products, components and processes to encourage South Africa's participation in the growing hydrogen and fuel cell markets [224].

In concrete terms, this entails establishing competitive local solutions for hydrogen production from renewable energy, and creating wealth through the production of MGP catalysts, as South Africa intends to secure 25% of the worldwide hydrogen and fuel cell market using MGP catalyst technology. For this purpose, HySA is subdivided into three research centres called Competence Centers (CC): the Hydrogen Catalysis CC, the Hydrogen infrastructure CC and the Hydrogen systems CC [225], each with a unique responsibility. To date, HySA has conducted numerous R&D and demonstration projects. For e.g. a hydrogen forklift and hydrogen fuel station, a hybrid fuel cell golf car, renewable hydrogen production and storage, as well as many other projects that have been completed and more are still to come [224].

Recently, the DST collaborated with Implats (Impala Platinum) to use and strengthen local knowledge in hydrogen and fuel cell product development. In this context, Implats has contributed \$670,000 to the niche project in South Africa [226]. This project entails the use of South African raw materials to investigate new onboard hydrogen storage systems for use in small cars such as forklifts, which will be evaluated by Implats. In August 2020, the DST in collaboration with the Department of Defense deployed 7 hydrogen vehicles to a hospital in the capital to assist the government in the COVID-19 crisis. [227]. In October 2020, DST through HySA launched the "Platinum Valley cluster" project. This project aims to identify project prospects to initiate hydrogen activities in prospective centres and highlight recent advances in the extraction, processing, and recycling of PGMs to assist sustainable development [228].

### **3.14. Morocco**

Thanks to its important assets, both in terms of infrastructure and manufacturing, in addition to its optimal geographical location and electrical interconnections (i.e. its proximity to the European continent, pre-existing energy interconnection infrastructures, gas and port infrastructures well connected to the Atlantic and the Mediterranean), Morocco can become a key player in the production and export of green hydrogen on a global scale [229,230]. The country has highlighted the significant progress of sustainable development and renewable energy, recalling that "Morocco had increased by 2020 the participation of green energy to 42% of the total installed electrical power, while committing to increase it to 52% by 2030" [231].

Recent studies estimate that the country could meet between 2% and 4% of the world's needs for fuels produced from green hydrogen by 2030 [232]. To achieve this goal, a global investment of \$82 billion by 2050 is required. With its ambition to exceed 60% of renewable electricity by 2030 and the establishment of an institutional and sustainable governance model and an exemplary legislative framework through Law 10-95 for the Water Sector, Morocco has the potential to develop large-scale green hydrogen production. However, in order to facilitate the influx of investments and the implementation of PtX projects, the hydrogen sector needs to be structured through the implementation of favourable regulatory, legislative and fiscal measures.

The roadmap that Morocco has recently launched for the development of green hydrogen is based on three key axes: the appropriation of the necessary technologies, the development of the market and demand, and finally the investment and supply sector [233]. Several projects are currently under development with some European countries for hydrogen production [234]. For example, a reference project is conducted by MASEN (Moroccan Agency for Sustainable Energy) and the German Cooperation, which is scheduled to start commercial operation by 2025. This project involves the construction of a hybrid photovoltaic and wind power plant to supply a green hydrogen plant with an electrolysis capacity of around 100 MW. These projects will stimulate employment, promote technological creation and integrate a value chain of industrialists and universities and make Morocco a world leader in this sector.

#### **4. Analysis and discussion**

As we have seen in the first part of this paper, the development of the renewable hydrogen value chain through electrolysis requires the massive development of renewable resources, the creation of Gigafactories to manufacture electrolysers, storage and transportation infrastructure as well as the availability of fresh water [14,235]. These conditions are assessed at each country level to identify its role and its contribution towards the emergence of green hydrogen on a global scale (see **Table 3**).

Based on these criteria, each country can play a specific role regarding the hydrogen value chain [14]:

- i. **Export champions**, these countries (notably Australia, the United States, Morocco, Norway) are well positioned to become major suppliers of renewable hydrogen in the future;
- ii. **Water-constrained producers**, these nations (including China and Saudi Arabia) have vast renewable energy resources but limited fresh water resources, making it difficult for them to become hydrogen export champions;
- iii. **Major importers**, due to low renewables potential and land availability, nations in this group (including Japan, Korea and some part in the EU) will be forced to import renewable hydrogen;
- iv. **Self-sufficient producers**, these countries (Turkey, Spain, Thailand) have the renewable and freshwater resource potential to meet their renewable hydrogen needs by domestic production;
- v. **Infrastructure-constrained producers**, these nations (India, Russia, and South America) have extensive access to renewable resources but are unlikely to be able to construct the necessary infrastructure for renewable energy production, transport, and delivery.

Further factors such as political stability, population density, business environment, and available land are also critical to green hydrogen's emergence [236]. Asia-Pacific and Europe are among the potential areas to develop global green hydrogen trade. For Asia-Pacific, countries like Korea, Japan, China, and Singapore, could become a major demand centre, while New Zealand, Australia, Brunei, and could become suppliers. In addition, countries such as Germany, France, the Netherlands and Belgium could source hydrogen from North Africa, the Middle East and Norway.

Finally, **Table. 3** presents an overview of the archetypical country roles in future renewable hydrogen markets, country's renewable energy potential, budget, projected electrolysis capacity and hydrogen production and consumption objectives in industry and power sectors. It also provides the estimated number of Hydrogen Fuel stations (HFS) to be installed in each country and the number of FCEVs to be available on the road in next few years.

Despite the rapid development of hydrogen energy worldwide, the challenges for the industry are very important. The most promising global market appears to be heavy mobility and industry. Other applications are also emerging: hydrogen storage allows, especially in island environments



or isolated sites, regulation of intermittence and optimization between electricity production and consumption. Injecting hydrogen into the gas network can enable coupling between different energy carriers, thus ensuring additional management flexibility. It is necessary to identify and develop new technologies for the production and storage of green hydrogen and to reduce their costs, optimize the manufacturing processes, make the most technically and economically mature technologies reliable and secure. It will be important to ensure the continued coherence of projects and their synergies to enable green hydrogen to play a central role in the world's energy transition.

Finally, securing industrial players requires support and the reduction of legislative and administrative obstacles, a rapid implementation of regulations to support a hydrogen economy in urban areas, the introduction of tax incentives, and action on standardization.

**Table 3:** Archetypical country roles play in energy in renewable hydrogen markets [14,235]

Country grouped by Archetypical role		Renewable hydrogen potential			BUDGET	Future targets by sector			
		RES endowment	Freshwater availability	Infrastructure potential		Power and industry		Mobility	
						Electrolyser Capacity	GH2 and BH2 production and consumption	Estimated FCEVs	HRS network
Export champions	Australia	++	+	+	275.5 M\$	5 GW by 2025	Produce 1Mt GH2 by 2030 and 18 Mt by 2050, cost below AU\$2/kg	No Specified targets	
	Canada	+			1.5 B\$	No Specified targets	30% of the country's end-use energy by clean H2 by 2050	No Specified targets	
	USA	++	+	+	64 M\$ for R&D	No Specified targets		1M by 2030	1000 by 2030
	Morocco	++	+	+	Not specified	Build 100 MW of GreenH2 plant by 2025	Capture 4 to 8% of the fledgling global P2X market	Not specified	
	Norway	++	+	+	19 M€ for R&D, markets, infrastructure, 1.6 B€ for CCS	No Specified targets		Not specified	
	Chile	++	++	+/-	50 M\$ to pilot projects	5 GW by 2025 25 GW by 2030	Produce 160 Mt of GH2 (by 2040) with cost less than \$1.50/kg	No Specified targets	
Major importers	Japan	-	+	+	3.4 B\$ to accelerate green hydrogen R&D	Not specified	Consumption of 300 kt/yr by 2030 5-10 Mt/yr by 2050 (GH2 +BH2)	21 1200 by 2030	320 by 2025 900 by 2030
	South Korea	-	+	+	38 B\$ by large Korean companies such as (SK,Hyundai Motors and POSCO)	1.5 GW by 2022, 15 GW (7 GW exports, 8 GW domestic) by 2040	Consumption of 1.94 Mt by 2030, 5.26 Mt by 2040 (GH2 +BH2)	2.9 M for domestic market and 3.3 M for export by 2040	310 by 2022 1200 by 2040
	EU	-	+	+	180 to 470 B€ for greenH2, 3 to 18 B€ for blueH2; 24 to 42 B€ for electrolyzers ; 11B€ for CCUS ; 65 B€ for infrastructure	6 GW by 2024 40 GW by 2030	Generate 1Mt GH2 by 2024 and 10Mt GH2 by 2030	No Specified targets	
Water constrained producer	China	++	--	+	2B\$ support to local industries	No Specified targets	500 kt/yr ofH2 by 2025	1 million by 2030	1000 by 2030
	Saudi Arabia	++	--	+	No Specified	No Specified targets	Generate 696 Mt/yrs of clean H2 or 24% of the world's energy needs by 2050	No Specified targets	
fficient	Spain	+	+	+	8.9 B€ (most from	300 to 600 MW	Spain produces 500,000 mt H2/yr.	302 000-	500-890 by

					private sector)	by 2024 4 GW by 2030	Plan to move 25% of this demand to green H2 by 2030	605 000 by 2030	2030
	Thailand	+	+	+					
	Turkey	+	+	+	Not specified				
Infrastructure constrained producer	India	+	+/-	-	689 k€ call for research proposals for H2 and FC	Not specified	80% of India's hydrogen is projected to be GreenH2	Not specified	
	Russia	+	+/-	-	Not specified	Not specified	Export of up to 0.2 Mt/yr of h2 by 2024, 2 Mt/yr of by 2035, and 15 Mt/yr by 2050	Not specified	
hydrogen importers	Italy	++		+	10 B€ investments in technology	5 GW by 2030	2% share of H2 in final energy demand by 2030 and 20% by 2050	432 000- 864 000 by 2030	670-1160 by 2030
	Portugal	++		++	7 B€	2-2.5 GW by 2030 5 GW by 2050	Produce 320 kt H2 by 2030 and 578 kt H2 by 2035	55 000- 111 000 by 2030	100-200 by 2030
	Germany				7 B€ in Germany + 2 B€ for foreign projects	Up to 5 GW by 2030 10 GW by 2035/40	0,42 Mt of GH2 (2030), and 0,85 Mt by 2035/40	510 000 – 1M By 2030	783-1343 by 2030
	France	++			7.2 B€ of which 2B€ from recovery funds	6.5 GW by 2030	Produce clean H2 and prevent -6Mt CO2 emissions by 2030	399 000 - 798 000 by 2030	640-1 100 by 2030
	UK				280 M€ Net Zero H2 Fund to 2024/25	5 GW of low- carbon hydrogen capacity by 2030	42 TWh/yr of low carbon H2 production by 2030	380 000- 760 000 by 2030	620-1 120 by 2030
	Netherlands				70M€ of subsidies €35 million/yr	500 MW by 2025 3-4 GW by 2030	30% to 50% of final energy consumption By H2	111 000- 223 000 by 2030	200-380 by 2030
	South Africa	++			Not specified				

**Legend:** abundant/very high (++), available/high (+), poorly available/constrained (-), scarce/highly constrained (--)

**Notes:** HRS: Hydrogen refuelling station; GH2: Green Hydrogen; BH2: Blue Hydrogen; FCEVs: fuel cell vehicle including FC trucks, FC bus, long-haul trucks; RES: Renewable energy sources

## **5. Conclusion**

Hydrogen has become a central element to decarbonize industry and mobility sectors and to reach carbon neutrality by 2050 is crucial. Many challenges need to be met for the production, transport and storage of green hydrogen. In the present work, the technical and technological advances involved in the production, purification, compression, transportation and use of hydrogen are presented and analysed. In addition, the roadmaps and strategies that have been developed in recent years in different countries for large-scale hydrogen production were highlighted. According to the work presented in this paper, the following conclusions have been drawn:

- Green hydrogen will only be competitive thanks to the massive development of renewable energies, the creation of large-scale factories to manufacture electrolyzers and fuel cells and hydrogen refuelling stations for mobility. To achieve this goal, coordinated efforts by governments, industry and investors as well as substantial investments in the sector will be needed;
- Countries with abundant and inexpensive renewable energy sources can produce green hydrogen destined for use in regions with limited renewable energy capacity or higher production costs. However, there are some serious challenges that need to be considered regarding the transportation of hydrogen;
- A transition to all-electricity via hydrogen in the transport, building and industry sectors must be supported by a policy of energy sobriety.

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