ACADEMIE DES TECHNOLOGIES
POUR UN PROGRÈS RAISONNÉ CHOISI PARTAGÉ
NATIONAL ACADEMY OF TECHNOLOGIES OF FRANCE
SHARING A REASONED, CHOSEN PROGRESS

中国工程院
CAE
CHINESE ACADEMY OF ENGINEER

HYDROGEN: H_2

FUNDAMENTALS and STRATEGIES IN CHINA and FRANCE/EUROPE FOR DECARBONIZING THE ECONOMY

A COLLABORATION BETWEEN
THE NATIONAL ACADEMY OF TECHNOLOGIES OF FRANCE
AND
THE CHINESE ACADEMY OF ENGINEERING

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A glossary, a list of acronyms and abbreviations, and a table of contents

are to be found at the end of this report.

Considering the objective of a zero-carbon economy the Chinese Academy of Engineering (CAE) and the National Academy of Technologies of France (NATF) have jointly analyzed what could be the role of decarbonized hydrogen in reaching this goal. This report analyzes the entire hydrogen value chain from production to utilization, including technology and innovation, economic and safety issues. Due to the very different situations in France/Europe and in China, the envisioned solutions have been compared together with their roadmaps.

This report is a résumé of their findings. The two Academies hope they will contribute to a better future.

Foreword

Low-carbon hydrogen is an alternative energy source that can be obtained in a variety of ways, and that has a number of uses. As such, it is an ideal vector for decarbonization of the economy by promoting the large-scale development of decarbonized electricity such as renewable energy, nuclear… Furthermore, as it is clean, versatile and efficient, it is an important tool for addressing climate change as well as optimizing energy infrastructure. Low-carbon hydrogen also has applications in electricity production, transportation, household consumption, and industries, where it can support decarbonization efforts in these hard-to-abate sectors.

This understanding of hydrogen's crucial role in decarbonizing economies has strengthened interest in it worldwide. A growing number of countries and regions including France, the European Union and China, have established hydrogen development road maps, on the basis that this resource is an essential component of the Net-Zero Emissions target. The National Academy of Technologies of France (NATF) and the Chinese Academy of Engineering (CAE) have identified the main characteristics of the hydrogen industry and the hydrogen economy. This report describes, as part of a common and jointly defined framework, the French, European and Chinese visions concerning the major challenges of hydrogen development.

By comparing the Chinese, European and French perspectives, this report aims to present a clear overview of the main drivers of hydrogen development, as well as provide some background for the strategies developed by these stakeholders. The report then surveys the current global landscape, the European and Chinese approaches to hydrogen classification and guarantee of origin, and the various technologies related to the production, storage and transportation of hydrogen. Afterwards, the current and future uses of hydrogen in industry, as well as its potential use as an energy carrier, are presented, from both a European and a Chinese perspective. There is also a focus on safety in use for transportation and households. Finally, possible road maps are presented for the production and use of hydrogen in China and in France by 2050.

Both CAE and NATF aim to create a greater understanding about the new hydrogen economy and its role in the ecological transition. We hope to continue this kind of co-operation between our two organizations.

Chinese Academy of Engineering
The President

李晓红

Li XIAOHONG

National Academy of Technologies of France
The President

Denis RANQUE

中国工程院
Chinese Academy of Engineering

The Chinese Academy of Engineering (CAE) is the highest honorary and advisory academic institution in the nation's fields of engineering sciences and technology. It is dedicated to uniting outstanding talents in engineering to lead innovation and development in China. The highest decision-making body in the CAE is the General Assembly, which selects new members every two years through voting. The CAE has nine academic divisions, six special committees and one general administration department.

ACADÉMIE DES TECHNOLOGIES
POUR UN PROGRÈS RAISONNÉ CHOISI PARTAGÉ

Created in 2000, the National Academy of Technologies of France (NATF) is born out of the need to provide our country with an independent and autonomous Academy dedicated to the applications of sciences and technologies, at a time where technologies are taking an increasingly important place in everyone's life. Its motto, *"Sharing a reasoned, chosen progress"* inspires the work of its 350 members. It brings together eminent scientists, recognized personalities from the socio-economic world and of Education. The Academy of Technologies conducts reflections and formulates proposals on issues related to technologies and their interactions with the society. It is committed to promoting technological development at the service of the citizens, the environment and a sustainable well-being.

Executive summary

Europe and China have opted for a net-zero GHG emission policy at the horizon 2050 for Europe and 2060 for China.

How to produce low-carbon hydrogen ?

Decarbonised hydrogen will be produced in Europe, mainly using electrolysis with low carbon electricity (renewable or nuclear). In China, a diversified hydrogen production system is expected, where a clean, low-carbon and low-cost hydrogen production system will be gradually promoted. Up to 2025, the use of industrial by-product hydrogen and renewable hydrogen is encouraged. In the longer term, it will make renewable hydrogen the dominant production route.

Research is going on in both countries and unforeseen game changers, such as plasma technology, might lower the cost of hydrogen production. Exploration and production of natural hydrogen are also starting in various parts of the world, but not particularly in China.

While most EU Member States and China have currently a carbonised electricity mix, priority is given to the utilisation of the growing installed capacity of wind and solar and the progressive phasing out of fossil fuels. However, in the coming decade, the periodic surplus electricity due to the intermittency of renewable electricity will offer only limited opportunities for producing decarbonised hydrogen as the electrolysers' load factor will be insufficient for their optimal amortisation. France is a particular case, having decarbonised electricity (nuclear and hydro), which allows it to promptly develop decarbonised hydrogen production by electrolysis, using a combination of nuclear, hydro and intermittent renewables, while ensuring a high load factor of electrolysers.

In any case, hydrogen trajectories in China and Europe will need very large infrastructure investments for decarbonised electricity (variable energies, such as solar and wind, but also nuclear and hydroelectricity).

The current global landscape and European and Chinese approaches to classification and guarantee of origin of hydrogen (colours…) are presented in the report, along with the various technologies related to the storage and transportation of hydrogen

Emerging technologies such as plasma technology could also reduce future electricity needs for hydrogen production.

Considering the huge amounts of electricity needed for electrolysis and even plasma technologies, steam methane reforming and coal gasification with carbon capture, storage, and utilisation should also be developed.

Some European countries plan to import hydrogen from foreign countries by pipeline or maritime transport. Due to the great potential of solar energy in China, the country does not envisage major imports of hydrogen, except perhaps for regions where solar energy is not sufficiently abundant.

Long-distance transport is a complex issue. Intense development of renewable electricity in various countries in Africa, Asia and South America will contribute to producing green hydrogen, ammonia and methanol, the latter two chemicals being more amenable to transport than hydrogen

Why is low carbon hydrogen needed ?

Decarbonised hydrogen will play an important role in the related policies for both countries, especially in a number of industrial sectors such as ammonia production, refineries, cement and steel industry .
But low carbon hydrogen will also play an important role.as an energy carrier in mobility for heavy road transport, railways and aviation, which is a difficult sector to decarbonise,

(China, implements also a significant development in methanol production for mobility (road, maritime).

Safety issues are a significant concern for public and semi-public use of hydrogen, such as for mobility. It requires international cooperation for standards.

The widespread use of *Power-to-Hydrogen-to-Power a*nd hydrogen seasonal storage for electricity production to compensate for the intermittency of wind and solar is uncertain as this would be very costly but is still envisaged in some European countries.

The energy crisis that began in 2021 and the events in Ukraine in 2022 have caused a surge in natural gas prices in Europe, increasing the cost of hydrogen from methane reforming. Beyond these events, the volatility of prices for natural gas favours alternative options for hydrogen production, such as, of course, electrolysis, albeit the cost of electricity has also surged, but also coal gasification with CCS.

Europe and China are implementing carbon price mechanisms, which will be critical on the long term for the development of decarbonised hydrogen.

Introduction

As of today, the hydrogen molecule H_2 (hydrogen in this report) is needed in many industrial processes (refineries, petrochemicals, ammonia-, fertilizer- and methanol production, etc.). In 2021, for its various purposes, the world produced around 74 M tons of hydrogen. The European Union and China produce around 9 million and 33 million tons, respectively. The industrial uses of hydrogen are numerous and well known, implemented safely and at low cost. It is important to note that most of the hydrogen produced in the world has emitted CO_2 when produced. As the ecological and energy transition aims at decarbonising the economy, decarbonisation of hydrogen production is crucial.

The objectives of decarbonising economies around the world, stimulated by the Paris Agreement (COP 21), have reinforced the interest in hydrogen. Around thirty countries and regions including France, the European Union and China have established hydrogen development road maps, considering that it is an essential component of the Net-Zero emissions target.

The National Academy of Technology of France (NATF) and the Chinese Academy of Engineering (CAE) regularly cooperate on technological subjects of common interest[1]. They undertook in 2021 a round of discussions and exchanges on the role of hydrogen for the decarbonisation of their economies. To this end, they have jointly defined and identified in a common framework the main facets of the hydrogen industry and economy and have described the French, European

1 a) Study for "Joint recommendations for the nuclear energy future" (late 2016 to mid-2017). Participating academies: Chinese Academy of Engineering, National Academy of Technologies of France, French Academy of Sciences.
b) Study on "Nuclear Energy and the Environment" (late 2017 to early 2019). Participating academies: Chinese Academy of Engineering, National Academy of France, French Academy of Sciences.
c) Study on "Tuberculosis and its Public Health Contexts - Comparison Between Offers and Care Pathways in France and China", early 2019 to late 2020 (and ongoing). Participating academies: National Academy of Technologies of France, National Academy of Medecine of France, Chinese Academy of Engineering, Chinese Academy of Medecine.

and Chinese visions concerning the major challenges of hydrogen development. The Chinese Academy of Engineering was supported by the Dalian Institute of Chemical Physics (DICP) and the Chinese Academy of Science.

Each of the major facets of the hydrogen economy is discussed in a separate chapter of this report, all of which are structured in the same way. The first part explains the issues dealt with in the chapter; a second part composed of two subparts presents respectively the Chinese and Franco-European approaches to these issues.

The **first chapter** describes the present global landscape. European and Chinese approaches to classification and guarantee of origin of hydrogen are presented in this chapter. The **second chapter** is devoted to the various technologies related to the production and transport of hydrogen. It takes stock of current and close-to-mature production methods from gaseous or solid hydrocarbons, which emit substantial greenhouse gases (Steam Methane Reforming (SMR) and coal gasification). It presents the alternatives available for decarbonised production (electrolysis using carbon-free electricity or the use of hydrocarbons but with capture and storage of CO_2). Economics is also an issue to be developed in this chapter. Finally, it also presents more innovative processes with a low or medium TRL and describes their state of development and their potential.

The current and future uses of hydrogen in industry, mainly for its chemical properties, are presented in a **third chapter**. The prospects for new uses of hydrogen in industry, for its chemical properties, are also described; this concerns, in particular, the mobilisation of the reducing properties of hydrogen to produce steels. Finally, this chapter provides information on the main French, European and Chinese producers of hydrogen.

The **fourth chapter** is devoted to the prospective use of hydrogen as an energy carrier, which in Europe as in China is the reason for the current hype for hydrogen. The different potential uses are presented: direct combustion, use in stationary or mobile fuel cells to produce electricity. The status of these different technologies and the place they could occupy in the future in Europe and in China are presented. It is also planned to use hydrogen as inter-seasonal energy storage, particularly for electricity production mixes including large shares of intermittent sources. Mobility is one of the major uses of hydrogen able to play a role in the decarbonisation of the economy; it allows the use of carbon-free fuel and a greater autonomy compared to batteries. These different perspectives are presented for Europe and China.

In the **fifth chapter**, the focus is on the technologies required for H_2 production, utilisation, storage and transportation equipment, such as electrolysers, fuel cells, high-pressure tanks, but also on basic components, such as membranes. A description of European and Chinese industrial manufacturers, current and future, is given in this chapter.

The **sixth chapter** looks into safety issues related to the use of hydrogen, in particular, for mobility and households

The **seventh chapter** presents one or more possible road maps for the production and use of hydrogen in France and China by 2050 with an intermediate point in 2030. This chapter aims to quantify the main uses of hydrogen at these horizons, as well as the production methods that will be implemented. This chapter provides approximate data for the two main ways to produce carbon-free hydrogen: 1) electrolysis and 2) the traditional way + CCS .

The information provided includes estimates on the electrical power and energy required for the production by electrolysis, and on the geological storage needs for CO_2 (CCS) according to the production methods envisaged for hydrogen.

This report is intended for public and private organizations already familiar with the hydrogen economy and technologies. By comparing the Chinese, European and French prospects, it aims to better understand the main drivers of hydrogen development, and to provide some background on the strategies developed by the various players.

The overall summary and conclusions of the report are presented in the **Executive Summary** at the beginning of this report, recalling current and future hydrogen policies, safety issues, needed infrastructure investments, possible import of green hydrogen, carbon price mechanisms as well as the communalities and differences between France/Europe and China.

Chapter 1

Current Situation

Role of hydrogen

Hydrogen is an alternative secondary energy source with a wide range of provenances and applications. Its carbon-free property makes it an ideal energy carrier for the clean and efficient replacement of fossil energy and for large-scale renewable energy development. It also provides an option for comprehensive and deep decarbonisation in sectors such as industry, construction, and transportation. While the hydrogen energy industry has a complex supply and production chain, its rapid development is expected to boost economic development. The role of hydrogen is expected to contribute to the three following goals :

Promote energy transitions and ensure energy security

The world's energy demand is mainly covered by three fossil fuel sources, namely oil, coal, and natural gas. In 2020, these three fuels accounted for 31.2%, 27.2 % and 24.7% of the global energy supply system, respectively, with a total of 83.1%.[2] From the perspective of energy security, the reserves of fossil fuels are limited. Once the fossil fuels are exhausted, energy supply will become a major problem. Hydrogen made from renewable energy could become an alternative to fossil fuels.

2 BP World Energy Statistical Yearbook 2021

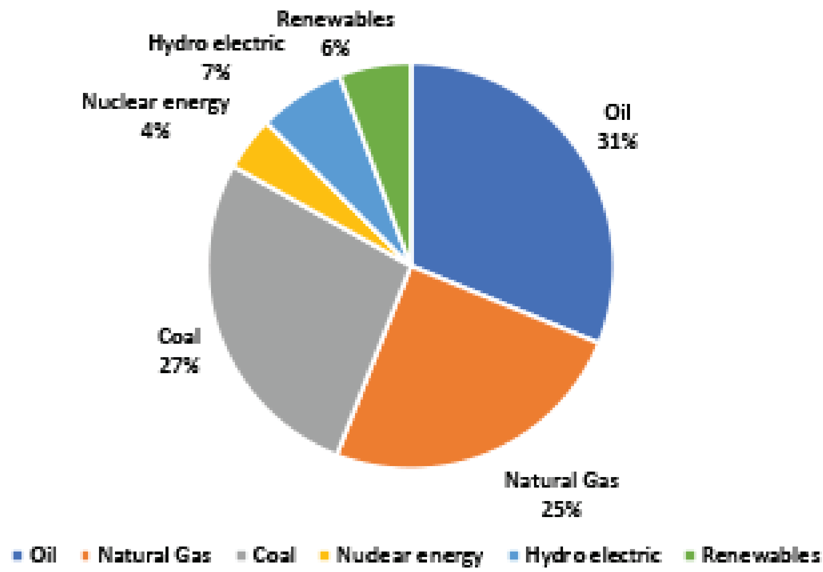


Figure 1 Global energy consumption in 2020

Reduce greenhouse gas and pollutant emissions

The Paris Agreement, signed in 2015 by 196 parties aims to limit global warming to well below 2 °C, preferably to 1.5 °C, compared to pre-industrial levels. To achieve this goal, significant reductions in greenhouse gas emissions across all sectors are required. The use of fossil fuels leads to the emission of CO_2 into the atmosphere, causing the now well-known greenhouse effect. Global CO_2 emissions from the use of fossil fuels either as energy or for other industrial purposes are increasing year by year, and by 2020, they had exceeded 36 billion tons. Hydrogen offers various ways to decarbonise a range of sectors, especially the hard-to-abate ones, such as the chemical, steel, cement, and aluminium sectors.

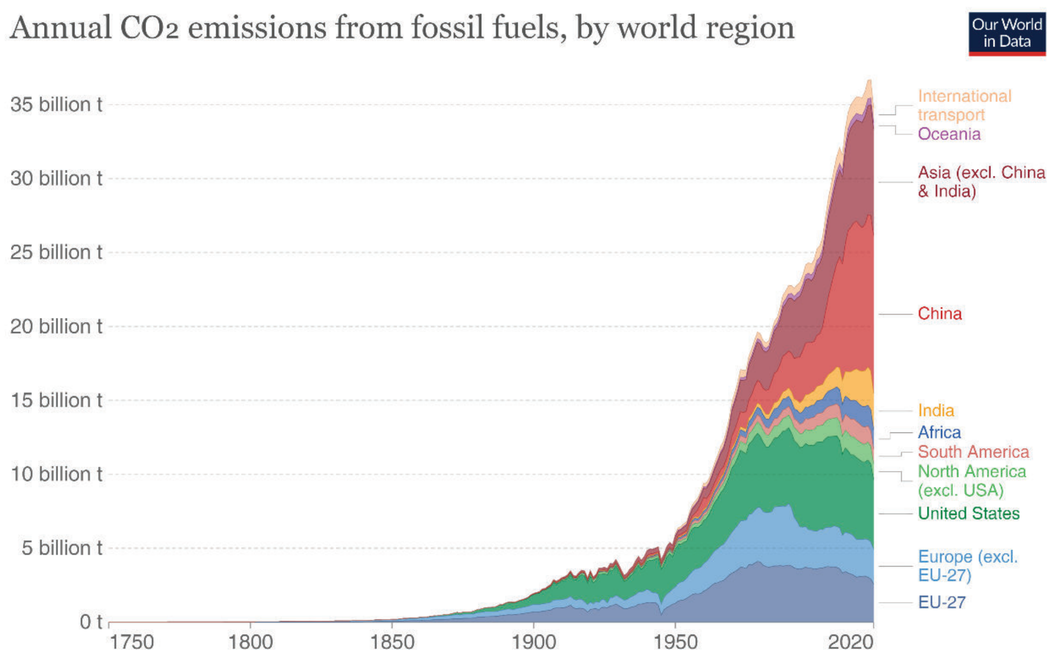


Figure 2 Global fossil energy CO_2 emissions[3]

Stimulate economic growth

Hydrogen can be widely used in energy, transportation, industry, buildings, and other fields. For the petrochemical, steel and other metallurgical industries, among others, hydrogen can be used as a high-efficiency raw material, reducing agent and high-quality heat source, effectively reducing carbon emissions. For transportation, it can be used in fuel cells to reduce the long-distance and high-load transportation dependency on fossil fuel. It can be used as a source of energy for electricity and heating in residential and commercial buildings.

As an emerging industry, the production, storage, transportation, and downstream application of hydrogen involves many areas such as energy, materials, and equipment manufacturing. It can not only effectively drive the transformation and upgrading of traditional industries, but also create a new green and low-carbon industrial chain.

According to the forecast of the International Hydrogen Council, by 2050, the development of hydrogen as a secondary energy source will have created 30 million jobs, avoided 6 billion tons of carbon dioxide emissions, and generated 2.5 trillion US dollars of output value.[4]

3 CO_2 and Greenhouse Gas Emissions - Our World in Data

4 https://hydrogencouncil.com/en/study-hydrogen-scaling-up/

Principal characteristics of the hydrogen industry

Physical properties of hydrogen

Hydrogen is an attractive fuel with more energy per unit mass than natural gas or gasoline. However, hydrogen is also the lightest element with a low volume energy density at standard temperature and pressure. Therefore, for a same amount of energy, a larger volume of gaseous hydrogen needs to be transported than in the case of other fuels. To address this issue, hydrogen can be compressed, liquefied, or converted into higher energy-density hydrogen-based fuels.

Table 1 Physical Properties of hydrogen[5]

Physical property	Unit	Hydrogen	Reference
Density (gaseous) atmospheric pressure	kg/m^3 (0 °C ,1 bar)	0.089	1/10 of natural gas
Density (liquid)	kg/m^3 (°C,1 bar)	70.79	1/6 of LNG
Liquefaction temperature	°C (1 bar)		90 °C lower than LNG
Mass energy density (LHV)	MJ/kg	120.07	Gasoline: 43.45 LNG: 48.63
Gaseous volumetric energy density (AMB, LHV)	MJ/L	0.01	1/3 of natural gas
Liquid volume energy density (AMB, LHV)	MJ/L	8.5	1/3 of LNG
Flame spread speed	cm/s	346	8 times of natural gas
Flammability range in air	vol%	4.0 ~ 75.0	Methane: 5.0 ~ 15.0 Gasoline: 1.4 ~ 7.6
Ignition range	%	4 ~77	wider than natural gas
Autoignition temperature in air	°C	585	Methane: 540 Gasoline: 230 ~ 480
Ignition energy	mJ	0.021	Natural gas: 0.29 mJ Gasoline vapor: 0.24 mJ

History of hydrogen energy technology

The vision of a hydrogen economy was introduced in the 1970s at the time of the first oil crisis. Its aim is to promote the hydrogen value chain to support the energy transition to renewable energy sources. However, in the decades that followed, the development of hydrogen technology stagnated due to cost issues. In 2014, breakthroughs in fuel cell technology in Japan renewed attention towards hydrogen as a secondary energy source. The vision of building a "Hydrogen

5 Feng Xiangfa, "Methanol, Ammonia and New Energy Economy", 2010

Economy" was revived in some countries, as the gradual reduction of primary energy reserves such as oil and coal led to energy shortages. Currently, at the national level, Japan is the most active promoter of hydrogen energy development; in terms of economic sectors, the transportation industry is the "leader" in the application of global hydrogen technology for energy purposes.

Table 2 Development of Hydrogen energy technology

Time	Event	Country	Notes
1783	In 1783 French chemist Antoine Lavoisier discovered that hydrogen combines with oxygen to form water.	France	He named this first element of the periodic system "Hydrogène"
1789	The electrolysis of water to produce hydrogen and oxygen was first discovered.	Netherlands	The industrial synthesis of hydrogen and oxygen through electrolysis was developed in 1888.
1804	The first internal combustion engine powered by hydrogen	Switzerland	
1839	British scientist William Grove realized the principle of fuel cell operation	U.K.	Breakthroughs in fuel cell technology could expand the utilisation of hydrogen energy
1923	British scientist envisioned the use of hydrogen as an energy carrier	U.K.	
1938	The first 240 km hydrogen pipeline, Rhein-Ruhr Pipeline, was operative.	Germany	
1965	The Polymer electrolyte fuel cell (PEFC) was officially used in the U.S. Gemini 5 spacecraft	U.S.	In the same year, General Motors (GM) also starts R&D on fuel cell vehicles.
1968	Alkaline fuel cells were used in the US Apollo spacecraft	U.S.	The United States is the first country to realize the application of hydrogen energy technology
1994	Germany's Daimler launched the first generation of fuel cell vehicles named "NECAR"	Germany	
2009	Panasonic and Toshiba launched the world's first home fuel cell ENE-FARM with energy efficiency over 95%	Japan	In the early 21st century, pure electric vehicles have been developing steadily because they are more economical, while the development of fuel cell vehicles and hydrogen energy technology stagnates. Hydrogen energy was taken seriously again after the breakthrough in fuel cell technology in Japan.
2014	Toyota launched the world's first four-passenger fuel cell car, "Mirai", which has a cruising range of 500 kilometres and takes only 3 minutes to refill hydrogen fuel	Japan	
2015	The world's first hydrogen-based tram was completed by CSR Sifang Company.	China	

2016	Honda released the Clarity Fuel Cell, a 5-passenger hydrogen fuel cell vehicle with a cruising range of up to 750 kilometres, again, same as Toyota, with refilling in 3 minutes, reaching the same standard as conventional power vehicles	Japan	
2016	French company Alstom launched the world's first hydrogen fuel cell passenger train	France	
2018	The HyDeploy hydrogen trial project has been launched with focus on injecting zero-carbon hydrogen into the UK's natural gas network.	U.K.	In 2021, the first project in the UK to blend hydrogen into a natural gas network hailed a success
2018	The hydrogen fuel cell supercar "H2 SPEED" designed by Italian company Pininfarina was unveiled in Geneva	Italy	
2019	Alaka'i Technologies unveiled Skai, the world's first hydrogen fuel cell powered air mobility solution	U.S.	
2020	Construction work of the Netherlands first hydrogen-powered housing project to start towards end of 2020.	Netherlands	The H2@Home project was operational since November 2021 and was expected to be tested through July 2022.

Economical aspects and value chain of hydrogen production

Global hydrogen production in 2020 was 90 million tons, of which 72 million tons (79%) came from dedicated hydrogen production plants. The remaining 21% was from by-product hydrogen, mainly from refineries. In 2020, worldwide demand for pure hydrogen, used for ammonia synthesis and oil refining, was 72 million tons; another 18 million tons of hydrogen was mixed with other gases and used for methanol production and direct reduced iron (DRI) in steelmaking.

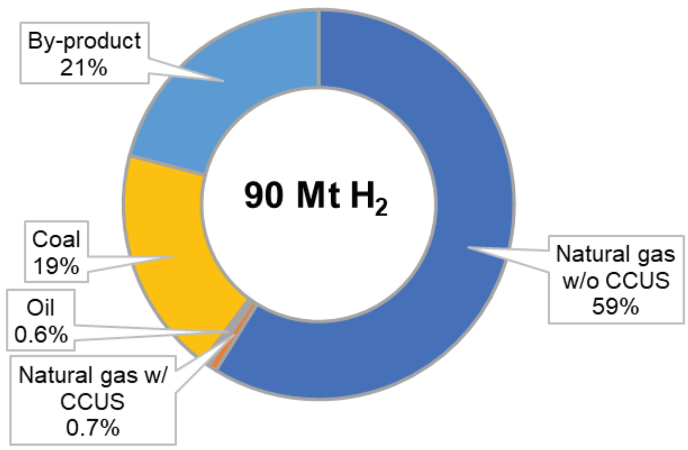


Figure 3 Global hydrogen production in 2020[6]

Natural gas is the main raw material for hydrogen production worldwide, accounting for about 60% of the world's hydrogen production in 2020, and 19% of the production was from coal, which is mainly in China. Hydrogen production from fossil fuels contributed to nearly 900 million tons of CO_2, accounting for 2.5% of global energy and industrial CO_2 emissions. Currently, hydrogen production from fossil fuels is the most economical method in most countries, while low-carbon hydrogen production technologies are much more expensive. However, with the massive scale implementations of renewable electricity and electrolysers, their costs are expected to fall rapidly, which should contribute to a lower production cost for low carbon hydrogen. In addition, the technology improvements for electrolysers and penalties for CO_2 emissions could further narrow the cost gap.

Since 2000, hydrogen demand has grown rapidly, especially in the refining and chemical industry, where it has grown by 50%. Almost all of this demand comes from refining and chemicals. New applications for hydrogen, such as Fuel Cell Electric Vehicles (FCEV) and electricity generation with hydrogen are appearing, but the related hydrogen demand is negligible at this moment. As concerns about climate change have grown around the world, and governments and industry have begun to make strong commitments to reduce carbon emissions, these new applications for hydrogen will be promoted and their introduction accelerated. As a result, hydrogen demand for these applications may surge in the future.

6 IEA, Global Hydrogen Review 2021

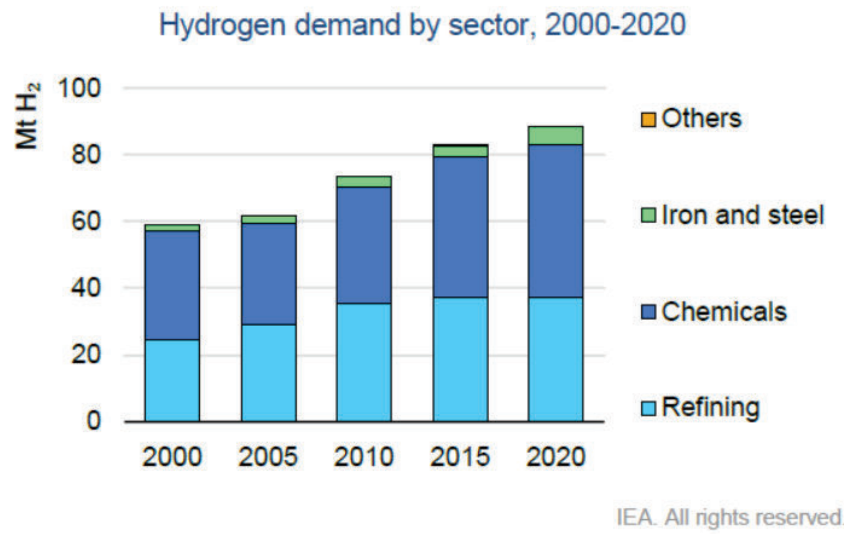


Figure 4 Global hydrogen demand by sector from 2000 to 2020[7]

Hydrogen can be used not only as an energy carrier or industrial feedstock in the form of pure hydrogen, but also in combination with other substances to generate hydrogen-based fuels and feedstocks using hydrogen from any source, such as water electrolysis, biomass, or fossil fuels. It can be used in engines, gas turbines or chemical processes as well as for the synthesis of natural gas, liquid fuel, methanol, ammonia, etc.

China

Current Situation

China is currently the world's largest hydrogen producer and mainly relies on coal gasification and industrial by-products. In recent years, China's hydrogen production has grown rapidly. In 2019, total hydrogen production, including industrial by-product reached 33.4 million tons and among this, the production of high-purity hydrogen was around 12.5 million tons.

7 I EA, Global Hydrogen Review 2021

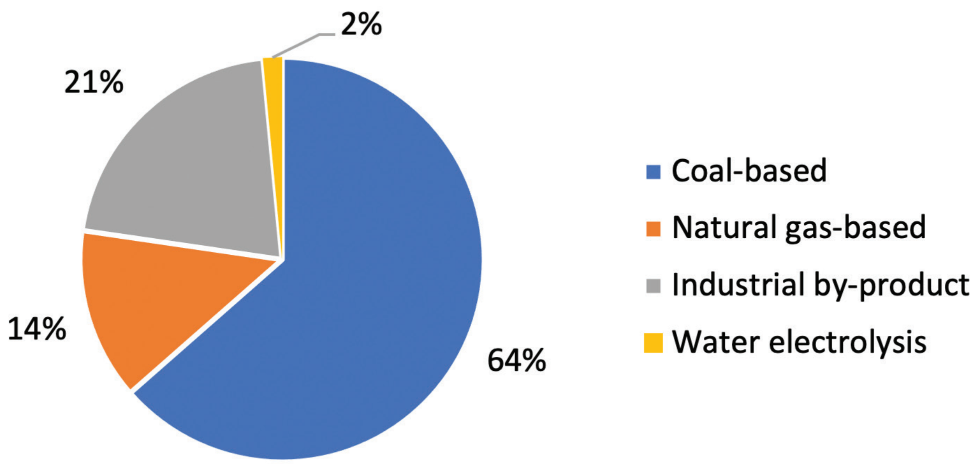


Figure 5 Hydrogen production in China (2019)[8]

Hydrogen is primarily used for industrial purposes. Among the different uses, the largest is as an intermediate raw material to produce ammonia, accounting for 32%, followed by methanol, accounting for 27%.

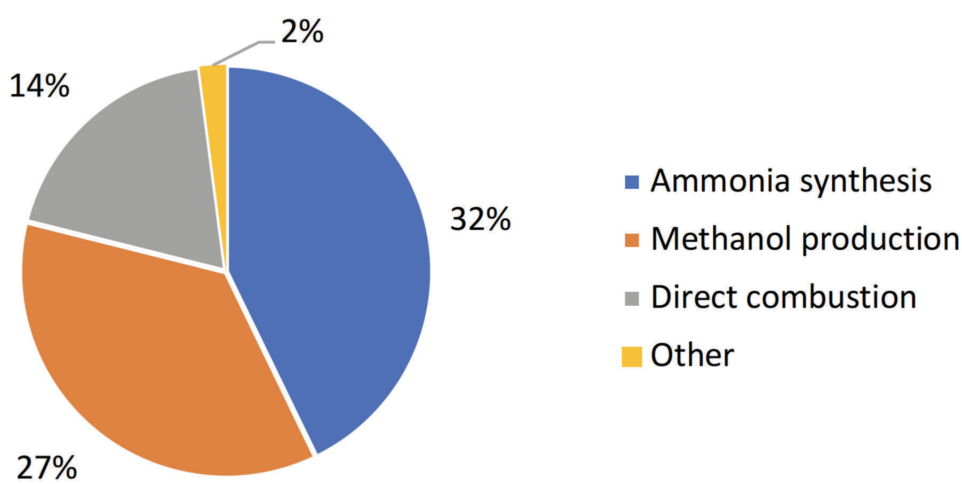


Figure 6 Hydrogen consumption in China (2019)[9]

8 China hydrogen and fuel cell industry handbook (2020), China Hydrogen Alliance.

9 China hydrogen and fuel cell industry handbook (2020), China Hydrogen Alliance.

In 2021, China produced 1790 fuel cell vehicles, which is a 49% increase compared to 2020. By the end of 2021, China has a total of approximately 9000 fuel cell vehicles and has built more than 200 hydrogen refuelling stations. By the end of 2021, five fuel cell vehicle demonstration city clusters have been announced in China, including Beijing-Tianjin-Hebei (led by Beijing), Shanghai (led by Shanghai), Guangdong Province (led by Foshan), Henan Province (led by Zhengzhou), and Hebei Province (led by Zhangjiakou). In these demonstration city clusters, fuel cell vehicles will be promoted with clear targets for the number of hydrogen fuel cell vehicles, the number of refuelling stations and their capacity, as well as the hydrogen production capacity. Research papers such as "China's Hydrogen Energy and Fuel Cell Industry White Paper" and "Energy-saving and New Energy Vehicle Technology Roadmap Version 2.0" have suggested that China will register more than 1 million fuel cell vehicles in use by 2035, becoming an important promoter of vehicles powered by alternative energies.

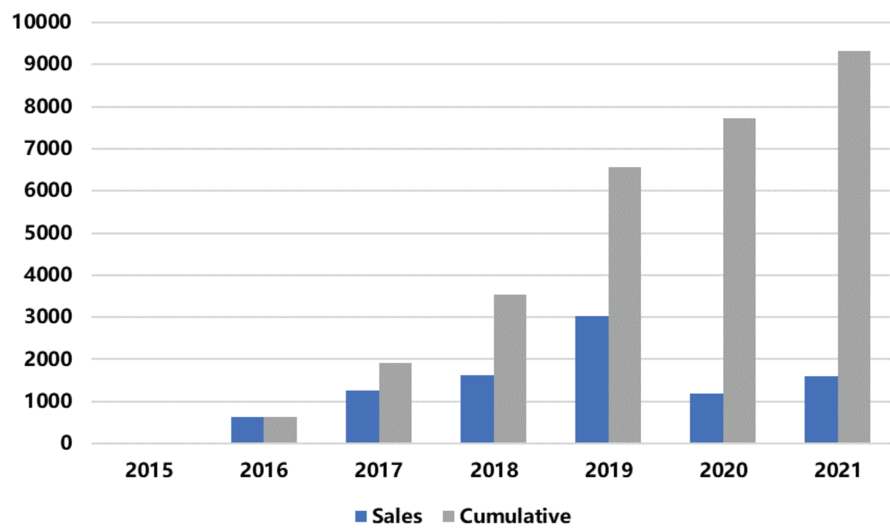


Figure 7 Fuel cell vehicles in China (2015-2021)[10][11]

To promote the development and industrialization of hydrogen technology, from 2018 to 2020, a national R&D plan called for the launch of a key project named "renewable energy and hydrogen energy technology", where the research focus is on hydrogen fuel cell technology.

In 2021, China's Ministry of Science and Technology issued the 2021 annual project application guide for the "14th Five-Year Plan" and the national key R&D plan called "Hydrogen Energy Technology", where, for the first time, hydrogen was proposed as an independent technology programme. As a result, both funding and the number of projects have increased significantly

10 China hydrogen and fuel cell industry handbook (2020), China Hydrogen Alliance.

11 China hydrogen energy industry development report 2022: Launching multi-scenario demonstration of hydrogen energy in transportation, manufacturing, architecture and energy storage, EV100plus & ChinaEV100.

over the previous three years. It is also worth noting that the research areas have extended to hydrogen safety, hydrogen conversion and hydrogen energy for civilian use. In 2022, the number of projects is increasing further and the focus is shifting to the hydrogen supply chain, where the use of ammonia as an energy carrier is also included.

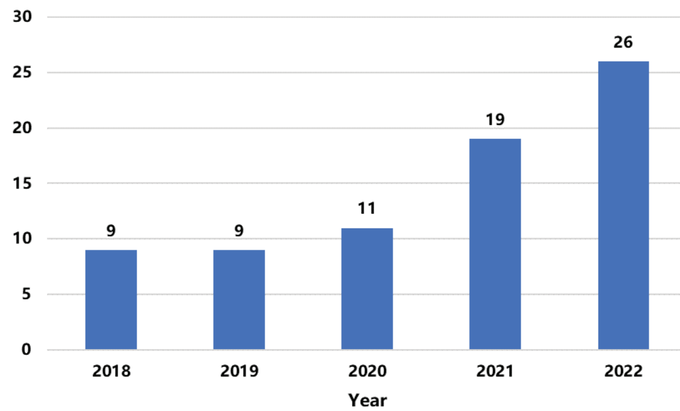


Figure 8 Number of key special projects of "hydrogen energy technology" (2018 – 2022) in China

Environmental Impact of different H_2, Certification

Hydrogen can be produced from different feedstocks through a variety of processes, where the energy conversion efficiency, emissions, as well as the devices, equipment and materials used in these processes are different. Considering that the vision of decarbonisation to combat climate change is the most important driver for the large-scale worldwide deployment of hydrogen, only low-carbon hydrogen production processes will have the potential to decarbonise the energy system. Consequently, it is essential to be aware of the carbon emissions associated with each hydrogen production process.

Various color codes are commonly used to differentiate hydrogen categories according to their provenance, such as green, blue and grey. However, it is important to keep in mind that this classification is sometimes suggestive and that using the same technology with various sources of energy will result in completely different impacts. To clarify the definitions and the quality criteria of hydrogen from different pathways or sources in China, the *Standard and Evaluation of Low-carbon Hydrogen, Clean Hydrogen, and Renewable Hydrogen* (T/CAB 0078-2020), proposed by the China Hydrogen Alliance, was implemented on 29 December 2020. This standard uses the life cycle assessment method to establish the quantitative evaluation system for these three categories and promotes the sustainable development of a hydrogen energy industry chain ~~from the source~~. The standard points out that in terms of carbon emissions per unit of hydrogen, the threshold for *low-carbon hydrogen* is 14.51 $kgCO_2e/kgH_2$, and the threshold for *clean* and for *renewable hydrogen* is 4.9 $kgCO_2e/kgH_2$. Renewable hydrogen also requires hydrogen production energy to be renewable energy, where renewable energy refers to non-fossil energy such as wind-, solar-, hydro-, biomass-, geothermal-, ocean energy, etc.

Criteria	Indicator		
	low-carbon hydrogen	clean hydrogen	renewable hydrogen
Carbon emissions per unit of hydrogen ($kgCO_2kg\ e/kgH_2$)	14.51	4.9	4.9
Renewable energy for hydrogen production*	No	No	Yes

* Renewable energy refers to non-fossil energy such as wind-, solar-, hydro-, biomass-, geothermal-, ocean energy, etc.

The standard benchmarks the Green Hydrogen Certification project implemented in Europe based on the natural gas hydrogen production process, and takes into consideration the dominance of coal-based hydrogen production process in China. Generally, the methodology used in the standard is in line with the Green Hydrogen Certification project, while the thresholds used in the classification are determined by the carbon emissions from coal-based hydrogen production process. The current emissions from coal-based hydrogen production process in China is 29.02 $kgCO_2/kgH_2$, and according to the *National Climate Change Plan (2014-2020)* and *Energy Production and Consumption Revolution Strategy (2016-2030)* of China, the emissions should be reduced by 50% and 65%, respectively, which gives the thresholds of 14.51 and 4.90 $kgCO_2/kgH_2$.

The China Hydrogen Alliance hope that the release and implementation of the standard will help guide the transformation of the high-carbon emission hydrogen production process to the green hydrogen production process, and help to open up the carbon and hydrogen market. However, it should be noted that the China Hydrogen Alliance is an unofficial organization, and the use of this standard is not mandatory.

France/Europe

Current Situation

In 2020, nearly 7 million tons of H_2 was produced and used in the EU, 3.7 million tons for oil refining and 3 million tons for the chemical industry, which are major consumers of hydrogen. Hydrogen is obtained mainly from natural gas (2/3 of total production) and as by-products from the refining and petrochemical sectors (1/3 of total production).

In November 2018, the European Commission set out a vision for net-zero emissions by 2050, followed in March 2020 by the first proposal for a European climate law to be adopted in June 2021. So far, most decarbonisation had focused on power generation, while the net zero target expanded the scope of decarbonisation to include building heating systems, industry, transport and agriculture.

The EU Hydrogen Strategy in July 2020 and the European Clean Hydrogen Alliance in November 2020 are important milestones. These strategies emphasize the use of hydrogen in industry and heavy-duty transportation, as well as its peak adjustment role with regard to renewable energy sources, especially offshore wind in the northwest and photovoltaics in the south. The coalition brings together industry, state and local governments, civil society, and other stakeholders to implement the strategy.

In terms of supply, hydrogen production from water electrolysis using renewable energy is considered to be the main way to produce hydrogen. In the near future, the role of other technologies based on low-carbon hydrogen is to develop the hydrogen market and expand its scale, while the cost of hydrogen production from water electrolysis is expected to gradually decrease. In addition to producing decarbonised hydrogen, the EU sees water electrolysis as a strategic opportunity to export the technology. EU countries currently account for more than 60% of global electrolyser production capacity.

The EU Hydrogen Strategy envisages three phases of hydrogen applications. [12]

Table 3 Three stages of European hydrogen energy strategy

Stage	Target
Phase 1 (until 2024)	Focus on scaling up, with a medium-term target of 6GW of renewable hydrogen electrolysis to inspire new uses in areas such as heavy-duty transportation
Phase 2 (2025-2030)	Hydrogen becomes a fixed part of the integrated energy system, renewable hydrogen becomes competitive, and hydrogen has new applications in metallurgy and shipping
Phase 3 (after 2030)	Renewable hydrogen technologies should mature and be deployed at scale to cover all hard-to-decarbonise sectors

In December 2020, the European Commission adopted a proposal to amend EU rules on Trans-European Energy Networks (TEN-E Regulation), ending support for natural gas pipelines and replacing them with hydrogen networks. Hydrogen networks are EU-compliant infrastruc-

12 hydrogen_strategy.pdf (europa.eu)

ture projects of mutual interest. The proposal covers dedicated hydrogen transport in relation to cross-border energy networks, new facilities for large-scale electrolyser projects and re-use of legacy facilities.

The EU has made progress in hydrogen application technologies. The European Fuel Cell and Hydrogen Joint Organization (FCH-JU) plays an important role in its programme, supporting research, innovation, and demonstration. More than 140 MW of electrolyser units dedicated to hydrogen production have been installed, accounting for more than 40% of global capacity. Strong signals from the government's strategy are driving more deployments of hydrogen energy. Of the 20 GW of electrolytic hydrogen production in the pipeline, more than 1 GW is already under construction or has committed funds. While current project plans may fall short of EU targets, the number of projects is growing rapidly, and the gap is narrowing. However, neither the current projects nor the EU target may be able to meet the EU's 2050 net-zero commitment due to insufficient electrolyser capacity.

In terms of transport, by the end of 2020, there were about 2,200 fuel cell vehicles, mainly passenger cars, and about 165 hydrogen refuelling stations in operation in EU countries. Germany has the largest number, but the Czech Republic, France, the Netherlands, Portugal, and Spain all have FCEV targets. If realized, there will be around 415,000 FCEVs by 2030.

In July 2021, as part of the REFHYNE project,[13] the industrial sector, in particular ITM and Shell, put a 10 MW PEM electrolyser into operation at the site of the German Rhineland refinery. In steelmaking, Thyssenkrupp has demonstrated the partial replacement of pulverized coal with hydrogen in one blast furnace and is working to expand the practice to other blast furnaces. The H2FUTURE project in Linz, Austria, has added hydrogen produced by a 6 MW PEM electrolyser to the coke oven gas pipeline feeding the steel plant since 2019.[14] The HYBRIT project, the first attempt to produce steel using pure hydrogen DRI, is currently in the pilot stage (4.5 MW electrolysis capacity) but is expected to start demonstrations ahead of schedule in 2025.[15] Also in the steel manufacturing industry, the world's largest SOEC electrolyser (0.72MW, manufactured by Sunfire) is used in the GrinHy2.0 project.[16]

In the chemical sector, Fertiberia and Iberdrola in Spain are building the world's largest green ammonia demonstration project (20 MW), which was expected to be operational by the end of 2021. Denmark's GreenLab Skive is building a 12 MW methanol production demonstration

13 REFHYNE – Clean Refinery Hydrogen for Europe

14 H2FUTURE PROJECT - https://www.h2future-project.eu/Startseite
- https://www.h2future-project.eu/(h2future-project.eu)

15 https://www.hybritdevelopment.se/Hybrit https://www.hybritdevelopment.se/(hybritdevelopment.se)

16 https://www.green-industrial-hydrogen.com/

project to start operations in 2022. However, these projects will fall short of the announced 2030 commitment targets.

The first steps have already begun in developing a dedicated infrastructure for hydrogen for delivery to end users. Europe has more than 1,600 kilometres of hydrogen pipelines, most of which belong to and are used by industrial producers and users, but large-scale deployment of low-carbon hydrogen will require additional transportation and distribution systems. As a result, a consortium of gas network operators has launched a European Hydrogen Backbone (EHB) initiative in 2020. Spanning 21 countries (including non-EU countries such as Switzerland and the UK), the EHB envisions 39,700 km of pipelines by 2040, of which 69% will be repurposed natural gas networks and 31% new hydrogen pipelines. In November 2018, for the first time on record, 12 km of an existing natural gas pipeline, was converted into a hydrogen pipeline with a capacity of 4 thousand tons of hydrogen per year and put into commercial service in Gasunie, the Netherlands.[17] In June 2021, Gasunie also announced that it had been asked by the State Secretary for Energy and Climate to develop a national hydrogen transport infrastructure development plan until 2027, of which 85% would be to retrofit natural gas pipelines. In September 2021, the Dutch government announced a €750 million investment (as part of a broader €6.8 billion package of climate measures) to convert the existing gas network into hydrogen transmission infrastructure. In addition, the gas transmission system operator's latest ten-year European network development plan roughly estimates that by 2030, 1,100 kilometres of gas pipelines could be retrofitted, but the final investment decision has yet to confirm the safety of these projects. Some EU countries are also conducting mixed-transport experiments, including France, Germany, the Netherlands, and Portugal. In May 2021, the German government announced 62 large-scale hydrogen projects[18], of which pipeline transportation has been selected for further evaluation by the Important Project of European Common Interest (IPCEI), with up to 8 billion euros of financial support. The National Strategy for the Development of low-carbon Hydrogen in France[19] states:

17 https://www.gasunie.nl/en/news/gasunie-hydrogen-pipeline-from-dow-to-yara-brought-into-operationGasunie https://www.gasunie.nl/en/news/gasunie-hydrogen-pipeline-from-dow-to-yara-brought-into-operationhydrogen pipeline from Dow to Yara brought into operation › https://www.gasunie.nl/en/news/gasunie-hydrogen-pipeline-from-dow-to-yara-brought-into-operationGasuniehttps://www.gasunie.nl/en/news/gasunie-hydrogen-pipeline-from-dow-to-yara-brought-into-operation

18 BMVI and https://www.now-gmbh.de/en/news/pressreleases/bmvi-and-bmwi-launch-62-large-scale-hydrogen-projects/ BMWi https://www.now-gmbh.de/en/news/pressreleases/bmvi-and-bmwi-launch-62-large-scale-hydrogen-projects/ launch 62 large-scale hydrogen projects - NOW GmbH (now-gmbh.de)

19 https://www.entreprises.gouv.fr/fr/strategies-d-acceleration/strategie-nationale-pour-developpement-de-l-hydrogene-decarbone-france
https://www.entreprises.gouv.fr/fr/strategies-d-acceleration/strategie-nationale-pour-developpement-de-l-hydrogene-decarbone-france

"With a view to decarbonising the French industry, carbon-free hydrogen [from water electrolysis] is one of the solutions adopted. The development of this type of hydrogen production allows tackling several issues:

- *From an environmental point of view, hydrogen is a response to the decarbonisation of industry and transport,*
- *From an economic point of view, hydrogen makes it possible to create new sectors and, therefore, new jobs,*
- *The use of carbon-free hydrogen responds to France's wishes to reduce its dependence on imported energies.*
- *Carbon-free hydrogen would also allow France to consolidate its technological independence.*
- *As part of the recovery plan, a budget of 2 billion euros has already been allocated to the development of carbon-free hydrogen. In total, funding of € 7 billion in public support is planned until 2030."*

Furthermore, the strategy states that the impact of hydrogen on greenhouse gas emissions could be important, with a potential reduction to 53 million tons of CO_2 emitted per year in 2030 compared to 80 million tons emitted per year today. This is about 16% of the reduction needed compared to the reference scenario (temperature rise below two degrees).[20]

By 2050, the hydrogen industry could theoretically represent a turnover of 40 billion euros and more than 150,000 jobs[21]. But to achieve this vision, France must change scale and make the necessary investments. A study estimates the overall investment at €8 bn by 2028 in equipment, infrastructure, scaling up of production facilities and R&D if the costs of hydrogen technologies can be reduced rapidly[22]. Ideally, €650 million per year should be spent for R&D over the next 10 years.

Potentially, hydrogen could represent 20% of the energy demand in France by 2050, with a production of 4 to 6 million tons of H_2 per year. As an energy carrier it could be used to decarbonise end uses in several sectors (industry, transport, buildings) and to accompany the development of renewable energies (RE). In 2050, hydrogen should meet 10% of the needs of industry and one-third of those of the building industry. It could also find applications after transformation into ammonia and/or methanol.

20 https://www.economie.gouv.fr/presentation-strategie-nationale-developpement-hydrogene-decarbone-france#

21 Plan de déploiement de l'hydrogène pour la transition énergétique, Nov. 2017

22 https://energies.airliquide.com/air-liquide-and-12-partners-publish-prospective-study-role-carbon-free-hydrogen-energy-transition
https://energies.airliquide.com/air-liquide-and-12-partners-publish-prospective-study-role-carbon-free-hydrogen-energy-transition

The plan also comprises the development of a domestic fuel cell production for heavy- and light-duty vehicles[23]. The company Hycco, which is the first manufacturer of hydrogen fuel cell components in France, was created in Albi (South-West of France). A first production line is about to be launched. Franc's Plastic Omnium and Germany's ElringKlinger have created a joint venture dedicated to the manufacture of fuel cells: EKPO. Hydrogène de France (HDF), a small company based in Gironde, announced in December its intention to build the world's first high-powered fuel cell mass production plant to compensate for the intermittency of renewable energy.

Daimler Truck and Total Energies have just joined forces in hydrogen road transport to decarbonise the road freight transport within the European Union by developing a sector and an ecosystem of heavy goods vehicles running on hydrogen via fuel cells and electric engines[24].

RTE[25], the French TSO (electricity) considers the future potential of hydrogen (not including hydrogen for power generation) at 43 TWh (~1.07 Mt of H_2) in the reference scenario and 130 TWh (~3.25 Mt H_2) in the hydrogen+ scenario with hydrogen utilisation for example in the steel industry, but also for transportation and aviation. If hydrogen for hypothetical power generation for electricity supply stability (compensation for intermittency of renewable energy) were included, which could become a necessity if additional nuclear power plants were to be closed and, as a consequence, the part of renewable energies would radically increase, hydrogen demand could rise substantially, requiring considerable additional electrolyser capacity for the necessary additional production of hydrogen.

In terms of research and pilot installations, almost all the described new approaches to produce low carbon hydrogen are studied in the French academic laboratories, start-up and large companies have also dedicated teams. All the large pilots are associating them. The EPIC is in charge of the industrial security and INERIS[26] is also involved. The ecosystem is federated in France Hydrogène.[27]

Environmental impact of different H_2, Certification

In December 2021, the European Commission published its legislative ***Package on Hydrogen and Decarbonised Markets.*** The "Package" proposes new rules aiming to develop a hydrogen

23 Integrated National Energy and Climate Plan for France, March 2020, page 65

24 https://www.actu-environnement.com/media/pdf/publireportages/environnement-et-technique/hors-serie-hydrogene-2021.pdf

25 https://assets.rte-france.com/prod/public/2021-10/BP2050_rapport-complet_chapitre9_hydrogene-couplages.pdf

26 https://www.ineris.fr

27 www.france-hydrogene.org

market in the EU. The new rules bring much awaited legal clarity to the concepts and role of blue and green hydrogen within the EU's energy regulatory framework for the climate transition.

In effect, the Commission's legislative Package is intended to promote the use of blue hydrogen until at least 2030 provided that it achieves the same decarbonisation as green hydrogen (i.e. 70% GHG reduction).

The Legislative Package on Hydrogen and Decarbonised Markets

The Package is yet another piece of the "***Fit for 55***" Agenda to achieve the EU's climate neutrality by 2050 and includes three legislative proposals: (i) a proposal for a recast of the EU Regulation on the Internal Markets for Renewable and Natural Gases and for Hydrogen ("***Proposed Gas and Hydrogen Regulation***"); (ii) a proposal for an EU Directive on Common Rules for the Internal Markets in Renewable and Natural Gases and in Hydrogen ("***Proposed Gas and Hydrogen Directive***"); and (iii) a proposal for an EU Regulation on Methane Emissions Reduction in the Energy Sector ("***Proposed Methane Regulation***").

In line with the ***EU Hydrogen Strategy***, the Package aims to facilitate the uptake of renewable and low-carbon gases, including hydrogen, in the EU's energy infrastructure. The legislative proposals create a dedicated hydrogen infrastructure and adapt the gas market regulatory framework to remove barriers to the entry of hydrogen with the aim of promoting the utilisation of hydrogen in areas where electrification is not an option, such as energy-intensive industries and heavy-duty transport.

Both green and blue hydrogen categories would benefit from this proposed advantageous regulatory framework provided they comply with the proposed definitions and requirements. However, they would continue to be impacted differently under other parts of the EU's climate and energy rules, such as the ***Renewable Energies Directive*** ("RED II") and the ***proposal for a Regulation on a Carbon Border Adjustment Mechanism*** ("Proposed CBAM Regulation") and the Regulation on the Establishment of a Framework to Facilitate Sustainable Investment ("Taxonomy Regulation").

Renewable and Low-Carbon Hydrogen

The EU's current energy regulatory framework fails to define renewable (aka[28] "green") and low-carbon (aka "blue") hydrogen. This legal uncertainty has hampered the role-out of green and blue hydrogen markets and infrastructure in the EU. To correct this, the Package introduces new legal definitions of renewable and low-carbon hydrogen that the Commission will be em-

28 aka: "also known as"

powered to detail by adopting specific calculation methodologies and threshold determinations in delegated acts.

The Proposed Gas and Hydrogen Directive includes definitions of renewable and low-carbon hydrogen that are in line with those of the proposal to amend the Renewable Energies Directive II ("***Proposed Directive to Amend RED II***").

Renewable hydrogen is defined by reference to the definition of the Proposed Directive to Amend RED II, as hydrogen that (i) derives its energy content from renewable sources other than biomass; and (ii) achieves a 70% GHG emission reduction compared to fossil fuels.

Low-carbon hydrogen is defined as hydrogen with an energy content that is derived from non-renewable sources, and that meets a GHG emission reduction threshold of 70% compared to fossil-based hydrogen.

This means that the EU's rules for the maximum greenhouse gas emission intensity of renewable ("green") and low-carbon ("blue") will be broadly similar, since the Gas and Hydrogen Directive sets the same decarbonisation impact criteria for both (*i.e.* 70% GHG reduction). The reduction threshold for renewable and low-carbon hydrogen will likely be calculated using a "well-to-gate" approach, that is, taking into account the CO_2 emissions from exploration to the production process, including transportation until the production process. However, the Commission has yet to establish the exact calculation and determination methodologies for green and blue hydrogen (see below).

Thus, the proposed main difference between renewable and low-carbon hydrogen would be the production process of the hydrogen and, in particular, the source of the energy that is used to make the hydrogen (*e.g.* in an electrolyser). In effect, the aim of this approach is to allow low-carbon hydrogen to play a role in decarbonisation and facilitate the energy transition until 2030. The amended RED II would continue to promote green hydrogen, and various EU legislation, such as the Proposed CBAM Regulation, would likely impact blue and green hydrogen differently. However, both blue and green hydrogen meeting the proposed definitions would benefit from the Package's proposed dedicated hydrogen infrastructure and market outlined below at least until 2030.

In the Parliament's view, "low-carbon" includes so-called "blue" hydrogen, which is made from fossil gas in combination with carbon capture and storage (CCS) technology to store the associated CO_2 emissions underground. Although the report makes no explicit mention of nuclear, it is understood that the "low-carbon" definition also encompasses "yellow" hydrogen made from nuclear power.

The expectation is that by 2030 the EU will introduce a stricter GHG reduction threshold for the definition of low-carbon ("blue") hydrogen. This threshold could be similar to that set under the ***draft technical screening criteria for gas investments*** under the Taxonomy Regulation, but that remains to be seen.

Certification of Low-Carbon Hydrogen

Both renewable and low-carbon hydrogen would have to be certified:

Renewable hydrogen would have to be certified in accordance with the Proposed Directive to Amend RED II, which requires the Commission to adopt delegated legislation that establishes the methodology for the certification.

Low-carbon hydrogen would have to be certified in accordance with a methodology that the Commission must adopt as a delegated act under the Proposed Gas and Hydrogen Directive. To avoid duplication, the Package requires that the methodology does not take into account the capture of carbon dioxide which has already received credit for avoided emissions under other legislation, such as the Emissions Trading System Directive. The certification requirements will require companies that produce low-carbon hydrogen to provide extensive information about their processes and include related information in an EU database.

The Package also allows the Commission to recognize a voluntary national or international scheme that sets standards for the production of low-carbon hydrogen as equal to the Commission's own methodology (*e.g.* the CertifHy scheme). Hence, if an operator provides compliance with a recognized scheme, this will serve to satisfy the certification requirement for low-carbon hydrogen.

The Package applies these certification requirements equally to imported and EU-produced blue and green hydrogen, which may be related to recent efforts by certain Member States to scale up production of hydrogen both inside and outside the EU. For instance, in December 2021 ***the Commission approved the German State aid scheme H2Global*** that also supports the production of green hydrogen in non-EU countries for its export to, and sale in, the EU.

Certification of origin

Although certification of origin is very important, there is no official certification adopted by the EU.

An example of what has been done by a European association is given below:

The CertifHy GO certification system developed by the Fuel Cells and Hydrogen Joint Undertaking - FCH JU benefits from European support, but is not yet a standard. It is presented as an example. It identifies three types of hydrogen: grey hydrogen from hydrocarbons without CO_2 capture, blue hydrogen from non-renewable sources but with a low CO_2 impact (60% reduction in CO_2 emissions compared to methane reforming), green hydrogen whose production respects the CO_2 ceiling of blue hydrogen and is derived from renewable energies. The latter is typically hydrogen from electrolysis if a significant part of the electricity is of renewable origin. This classification has the merit to exist and to be a first step towards certifications of origin, but it is flawed on different points: the allowed CO_2 emissions which remain significant with green hydrogen, the limit between green and blue, the fact that it does not take into account hydrogen having other sources than those mentioned above and finally the fact that it does not take into account the routing of the hydrogen to its point of use and more globally a complete life cycle analysis. Emissions of green hydrogen: the production of green hydrogen, as well as blue hydrogen, can emit - and in practice will emit since blends are allowed - 40% of the CO_2 that would have been emitted by steam-reforming production (SMR) without CO_2 capture. Taking into account the conversion efficiency and the respective calorific values, it is shown that, per unit of energy contained, green hydrogen emits 65% of the CO_2 that would be emitted by natural gas. Blue/green: if one were to stick to an impact-based definition in terms of GHG emissions, hydrogen from electrolysis from nuclear electricity should be considered green. But nuclear power is not qualified as renewable, and electrolysis using this technology produces blue, not green, hydrogen. And some non-governmental associations are even advocating that this qualification be removed and that it be considered grey. This is a subject that can have substantial commercial consequences. Moreover, it is surprising that the term blue hydrogen is widely used when CO_2 capture, transport, use and storage (Carbon Capture Utilisation and Storage: CCUS) is still in a research and pilot phase (excluding storage in depleted oil or gas wells). In practice, there is currently no real blue hydrogen, except if it is produced by nuclear electricity.

This brief summary highlights, if it is still necessary, that the classification of the impact of human activities using as sole gauges "renewable", which excludes nuclear energy (which does not emit CO_2), and "greenhouse gas emitters", are not the only relevant ones. Electrolysers and fuel cells contain nonrenewable metals, and the life cycle analysis of a product must be systematically carried out from A to Z. Some economic or political players may find it advantageous to have sectors classified as virtuous or not. It is relatively easy to simplify the vision of a process to achieve partisan objectives. It is much more complex to do a complete and comprehensive life cycle analysis. For example, the environmental cost of hydrogen that is produced, trucked, liquefied and transported by ship, then regasified, compressed and trucked again (the Australian-Japanese project) is not the same as the environmental cost of just producing it. The National Academy of Technologies of France would like the classification of the different types of hydrogen to be based exclusively on an analysis of the CO_2 emitted during the life cycle and up to the point of distribution.

Chapter 2

Hydrogen Production Storage and Transport

Issues and context

This chapter takes stock of current and close to mature production methods from gaseous, liquid or solid hydrocarbons, which emit greenhouse gases (Steam Methane Reforming (SMR) and coal gasification). It also presents the alternatives available for decarbonised production (electrolysis using low-carbon electricity or the use of hydrocarbons but with capture and storage of CO_2). The energy required by the various technologies will be compared. Economics is also an issue which is addressed in this chapter. Finally, it presents more innovative processes with a lower TRL and describes their state of development. The possibilities and the costs of long-distance transportation are key to the development of a global H_2 market and therefore will be part of this chapter.

This report also compares:

- current H_2 production modes that are used in China and France/Europe,
- the expected future share of production for 2030 and 2050 in each mode ;
- ongoing research projects and existing pilots to improve the already existing solutions and develop new ones ;
- the industrial/public ecosystems around the research on H_2 production processes;
- the transport modes, on land and transoceanic.

Current technologies

Current mature technologies for H_2 production

Ninety-six percent of the world's hydrogen is produced by reforming hydrocarbons or by coal gasification with CO_2 emissions, which, in most cases, are not captured.

Reforming: SMR wet method

Forty-nine percent of world production is by Steam Methane Reforming (SMR).

The main hydrogen production processes used today are wet reforming (SMR), which requires an external energy input, and autothermal reforming (ATR), which uses the energy from the second of the two subsequent reactions within the reforming process according to the following reactions:

$CH_4 + H_2O \leftrightarrow CO + 3\ H_2$ endothermic reaction, at high temperature (840 to 920 °C), moderate pressure (20-30 bar) and in the presence of a catalyst (Ni);

$CO + H_2O \leftrightarrow CO_2 + H_2$ exothermic reaction in the presence of water is the WGSR (*Water Gas Shift Reaction*);

The overall yield is 72 to 82%. Half of the hydrogen is derived from methane and half from water. Ten kilograms of CO_2 is emitted per kg of H_2, and the energy contained in the produced hydrogen is about 2/3 of the energy needed for the reactions. 5.2 kWh is needed to manufacture 1 kg of H_2.

SMR facilities are typically large, with about 100 tons per day of hydrogen for the larger ones worldwide and up to 600 tons for the largest in the United States and Asia.

Oxidation of petroleum fractions

Twenty-nine percent of the world's production is achieved by partial oxidation of petroleum fractions.

This process is suitable for heavy oil fractions.

The principle is the same as steam reforming of methane to form synthesis gas but the oxidation of the hydrocarbon is done by dioxygen instead of water.

The reaction is exothermic, at high temperature (900 to 1,000 °C), higher pressure (20-60 bars) and generally without catalyst.

This process is used to provide synthetic gas with an H_2/CO ratio specific for petrochemicals in the absence of light hydrocarbons, or to destroy heavy hydrocarbon residues with low valorisation potential.

Coal gasification

> *Eighteen percent of the world's production is made by "carbo-reduction of water" by coal (i.e. coal gasification). This ratio reaches 60% for China.*

It is the reaction between incandescent coal and water to produce gas from water:

$$C + H_2O \leftrightarrow CO + H_2$$

Followed by: $CO + H_2O \leftrightarrow CO_2 + H_2$, i.e. the WGSR (Water Gas Shift Reaction)

Almost 100% of the hydrogen produced comes from water with the result that the CO_2 emitted per kg of hydrogen is much higher than that of the SMR process.

China is not the only country where H_2 is produced from coal. In Australia, a major project for the production of hydrogen by coal gasification using lignite has been launched to export this hydrogen to Japan (see page: 25)

Reforming or coal gasification with CO_2 capture and storage

In order to reduce the GHG impacts of the current production of hydrogen from hydrocarbons or coal, large projects combining the production of hydrogen from carbon-based energies with CO_2 capture and storage are ongoing or projected. The resulting H_2 is sometimes called blue hydrogen to indicate that it emits little CO_2 during the complete manufacturing cycle. The cost of CO_2 capture is in the order of €10-20 per ton of CO_2 (€100-200 per ton of hydrogen); the cost of capture is, therefore, lower than the trading value of emission permits on the EU-ETS market and is a cost-effective operation.

CO_2 capture processes are proven technologies in the industry. They are efficient, although they can probably be improved. The main challenges to pass from grey to blue H_2 is mainly in terms of CO_2 storage. Worldwide the CO_2 storage projects are mainly Enhance Oil Recovery projects and since the oil production in Europe is low and decreasing, the market is missing. Real CO_2 subsurface storage in depleted O&G fields or in aquifers as is practised in Norway is exceptional.

These projects are encouraged by natural gas producers. Their technical and financial feasibility depends on the proximity of storage capacities and their operating costs. The technologies of gas underground storage are mature and well known by the major gas operating companies.

However onshore, in Europe where the population density is high and the public reluctant to accept new underground storages, the possibilities to develop such a storage in the vicinity of the CO_2 emitting industrial sites are rather low. The public authorities are testing the feasibility of CO_2 transport to Norway where offshore storage will be possible [reference 29 and 30].

If the hydrogen economy develops on a large scale, this type of opportunity can play a role in the hydrogen market and change the balance. It will be in favour of large facilities near major CO_2 transport hubs.

For the development of the hydrogen sector, as for the continuity of other industries, we will probably not be able to ignore CO_2 capture. Various examples show that several countries and private companies are seriously investing in research to develop the production of blue hydrogen[29,30] which needs CO_2 storage. Blue H_2 is, indeed, at least on paper, potentially cheaper than green H_2 and for the countries where EOR is ongoing and where a large CO_2 market exists, it should be considered a realistic possibility.

Production by steam reforming of biomethane

This mature solution requires the biogas to be treated to remove the sulphur and carbon monoxide that poison the catalysts that are used in the reforming process. These treatments are already in place for the transformation of the biogas produced in the digesters into biomethane that can be injected into the network.

Water electrolysis

Currently, the main process available to produce decarbonised hydrogen in industrial quantities is the electrolysis of water, provided that the electricity itself is decarbonised. Three main processes coexist:

- electrolysis of water with the addition of an alkaline solution (usually KOH) to improve the conductivity of the medium at low temperature and pressure (about 30 bar). The efficiency is a little over 70%;
- electrolysis with proton exchange membrane (polymer-electrolyte membrane or proton-electrolyte membrane PEM). The concept of Polymer membranes can be used in electrolysers as well as in fuel cells (FCs). Expectations are high concerning this technology.

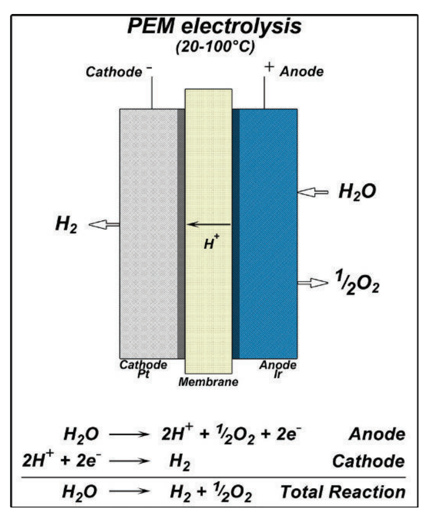


Figure 9 - Principle of a PEM electrolyser
@Davidlfritz - Wikipedia

29 https://www.equinor.com/en/news/2020-05-northern-lights.html

30 https://www.horisontenergi.no/carbon-storage/

The efficiency achieved is 60% and the aim is to exceed 70%. For the time being, alkaline electrolysers have lower investment costs than PEM. However, The market will ultimately decide between alkaline and PEM solutions;

- high temperature electrolysis (Protonic ceramic fuel cells (PCFC) or Solid oxide electrolysis cells (SOEC)), which require high temperatures and are therefore not very flexible. However, they may have a better efficiency if heat can be recovered and valorised. Some of these electrolysers could be coupled with waste heat sources, but also with cogeneration nuclear reactors or concentrated solar power plants: developments in this area are long-term.

Hydrogen Transport and Storage

Transport of hydrogen is a major issue. Indeed, depending on its cost and efficiency, including safety, the solutions will determine whether hydrogen can be produced where it is consumed or where the production can be economically decarbonised. Hydrogen may be produced far from the final user, depending on the adaptation of volume, transport and storage. Obviously, its production by electricity via water electrolysis is easier to be done on the site where it is needed/consumed than for other processes needing complex installations, at least in small quantities.

At present, hydrogen is transported in tanks by truck or railways. Dedicated pipelines exist in certain areas of the world where the H_2 market is large, namely in the USA (>2,500 km) and northern Europe. For instance, in Belgium, there are more than 600 km of H_2 pipelines. These pipelines may be extended to long-distance as is the case for methane. Work is ongoing to create an H_2 pipeline grid at the European level. For one part it will reuse existing methane pipelines but, new sections will also have to be laid. The impact of such pipeline grids on the potential scenario of market penetration will be discussed in the following sections.

The direct use of the old steel pipes for H_2 is an issue since hydrogen embrittles the steel and can facilitate the propagation of defects. Hydrogen may be blended with methane if the final user wants this type of blend. If the percentage of H_2 remains low, the methane transport and distribution grids are suitable and pilots have tested this solution in Germany, France (Grhyd[31]) and the UK (Hydeploy[32]) (among others)

These various modes of transport are linked to the available storage facilities, in tanks on the surface or in larger underground cavities. The storage in salt cavities is the most adapted technique, as they have a very low permeability, but storage in aquifers does also exist, especially for the blend H_2/CH_4. Today various countries, including France, have pilots to test the management of H_2 underground storage in the new context of an increasing H_2 market. When the H_2 storage

31 https://grhyd.fr

32 https://hydeploy.co.uk/about/news/first-uk-trial-of-hydrogen-blended-gas-hailed-a-success/

is mainly considered as a security in case of delivery failure, it will be very rarely solicited. If the charge and discharge of H_2 are done on a daily basis, there are uncertainties about the possibility of rock deformation. Another point to be solved is that of the cushion gas in the H_2 storage facilities, representing a large percentage of the total gas content.

However, a global market can only emerge if the transport of H_2 from one continent to another is possible. For natural gas, this transport is done by pipeline and by boat, the LNG transport representing 52% of the global gas transport[33].

Today, undersea H_2 pipelines do not exist, and unfortunately liquefied hydrogen is much more difficult to handle than liquefied natural gas. The temperature of H_2 liquefaction is near 0 K (-273 °C) and the reaction is exothermic resulting in a huge loss of energy. Other alternatives are tested, especially using organic liquid carrier beds.

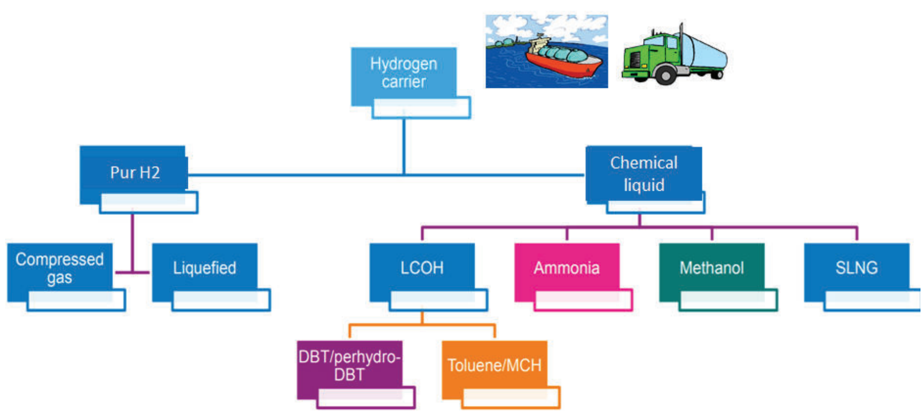


Figure 10: Transport as liquefied ammonia or methanol is for instance another means of shipping hydrogen. Other solutions are under study and tests.

33 bp-stats-review-2021-full-report.pdf

Ammonia as a hydrogen carrier: production, transport, storage

Consideration is being given to converting hydrogen into ammonia (NH_3), which is easier to use than hydrogen and can be an alternative energy carrier.

At room temperature and atmospheric pressure, ammonia is gaseous, but liquefies at - 33 °C. It can be stored and transported in a liquid state at ambient temperature but under pressure or at -33 °C and normal atmospheric pressure. Its main use today is in the production of nitrogen fertilizers. The United States operates 5 000 km of dedicated ammonia pipeline. Its energy content is relatively high (6.5 KWh/kg or 3 KWh/l). It is produced by the Haber-Bosch process from nitrogen and hydrogen and can therefore be decarbonised if the hydrogen is produced in a decarbonised manner. It can be considered as a hydrogen storage system. It is then dissociated into $N_2 + 3H_2$ between 400 °C and 800 °C using catalysts. It can also be used as a fuel in combustion engines, turbines (such as the X15 rocket engine in the 1960s, combined with oxygen), and proton ceramic fuel cells. It can be mixed with hydrogen to improve burner performance and gas turbine efficiency. In February 2020, the Royal Society published a report on this subject[1]. Japanese universities are very active. Despite the security problems, this topic seems promising.

1 https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia,

Methanol as a hydrogen carrier: production, transport, storage

Methanol is yet another solution as an energy carrier for hydrogen. The ratio of hydrogen over total mass is slightly less favourable than with ammonia (-30%) but at room temperature and atmospheric pressure methanol is a liquid and presents much less security hazards.

Methanol issues will be further developed in chapter 4. Currently, the major impediment is that it is mainly produced from hydrocarbons. Different options are explored to produce methanol by combining low-carbon hydrogen with captured CO_2, or by co-electrolysis of water and CO_2, but these solutions have yet to reach industrial scales and economic efficiency.

While its energy content is about half that of gasoline (4.3 kWh/l), methanol is still a liquid fuel and can benefit from all the current facilities inherited from our hydrocarbon economies for transportation, storage and distribution. China devotes strong efforts on methanol, developing vehicles (cars, trucks and boats) able to burn it directly, unblended. Obviously, the size of gas tanks needs to be doubled for the same vehicle range, which impairs methanol for certain applications. France imports methanol for its hydrogen production in Kourou, European space port in French Guiana.

An interesting example of a global project of production and transport of hydrogen is one implying the Australian government and the Japanese firm Kawasaki Heavy Industries. Australia has large quantities of lignite in the Latrobe Valley. The project consists of using lignite for coal gasification. The hydrogen will then be transported by truck to the Australian port of Hastings and then by a hydrogen tanker to Kobe in Japan. The approximately $400 million pilot project is being funded by the Australian government and the State of Victoria for the facilities and by Japan for the ship. The project started in 2019. If it expands, it is planned to achieve capture and storage of the CO_2 emitted (CCS). The developers of the project consider that the Gippsland

Basin lignite deposit in the Latrobe Valley has the capacity to store CO_2, a fact which is confirmed by the Global CCS Institute. The hydrogen produced must be transported to a liquefaction plant at the port of Hastings and then transported to Japan. The economic balance of the project has not been demonstrated, but the Australian government, the State of Victoria and Kawasaki have chosen to take this risk. The first delivery took place in January 2022[34].

Another major project is led by Chiyoda, the hydrogen produced by steam reforming in Brunei is transported by boat using an organic medium (toluene hydrogenated into methylcyclohexane) in Japan[35].

Hydrogen economy and business models

There is no shortage of publications proposing economic models or cost estimates for a hydrogen sector, with sometimes contradictory conclusions. Cost calculation methods may reveal incompatibilities in the conditions of use of the technologies, primary data may be unclear (old sources or poorly supported prospective sources), etc. There is often a melange of today's cost and expectations, more or less optimistic, depending on the authors.

The purpose of this section is to identify established sources for economic data, or failing that, to propose order-of-magnitude comparisons for evaluating options. The ambition is not to achieve the rigour of real economic models, but to identify the cost determinants of the main uses considered and their margins of evolution.

Hydrogen production costs

Cost of production by gasification or reforming

Gasification and reforming are established technology streams, with relatively little cost detail provided by industry. Most of the references put forward production costs for reforming in the order of €1.5 to €2 / kg of hydrogen.

The usual production method, steam methane reforming requires about 3.5 kg of CH_4 to produce a kilogramme of hydrogen (both raw material and energy source). In addition, methanol pyrolysis is an energy-efficient method.

34 https://www.reuters.com/business/environment/worlds-first-hydrogen-tanker-ship-test-cargo-australia-japan-2022-01-20/

35 https://www.chiyodacorp.com/en/service/spera-hydrogen/

The price of natural gas varies greatly depending on the country, producer or importer, and the conditions under which it is transported by pipeline or LNG tanker: the IEA in its report on hydrogen expects US$ 3 to US$ 11 per million BTU (British Thermal Unit), i.e. from US$ 12 to US$ 37/MWh. This represents a raw material and energy cost for reforming of between US$ 0.65 and US$ 2/kg hydrogen. To this must be added the costs of amortization and operation of the installations.

The energy crisis that began in 2021 and the events in Ukraine in 2022 have caused a surge of the already high natural gas prices in Europe. Considering a long-lasting 30% mean increase of NG prices, costs for hydrogen from methane reforming would rise by at least US$ 0.5/kg; if NG were to rise further durably, up to USD 100/kg, SMR hydrogen costs might double, up to US$ 6/kg. This allows for competitive costs for low carbon hydrogen from electrolysis, on the condition of low *market price* for electricity *on the grid* – which in many countries *can* also *be impacted by gas price*s.

Beyond these events, the volatility of prices for natural gas favours all the other options for hydrogen production, such as for instance coal gasification, which allows for slightly lower costs due to a cheaper and very abundant raw material: coal. However, gasification leads to much higher carbon emissions and requires the management of solids (coal and ash), which is more demanding to handle than gas.

Carbon capture could reduce emissions from gasification or reforming by up to 90%, at an extra cost of 50% on investment and 10% on fuel, which would add ~US$ 0.5/kg to the price of hydrogen: capture becomes profitable if the cost of CO_2 (emission certificates) is above ~US$ 60 per ton and even less in the case of gasification. However, this assessment only takes into account the extra cost of CO_2 capture: it does not say anything about the possible costs of storing or reusing it, which can be substantial (€100 to €250 per tonne of CO_2 captured and stored)[36].

In a nutshell

- Production costs: US$ 1.5 to US$ 2/kg of hydrogen, US$3 to US$ 4.5/kg with capture and storage.
- Energy need: about 5.2 kWh/ kg of H2
- Mature installations (except transport, storage or use of CO2).
- Main determinants for the evolution of costs:
  - gas (or coal) price,
  - cost per tonne of CO_2, either tax or CCS.

36 Data provided by Total

Cost of production by electrolysis

The production cost for the three available technologies (alkaline, PEM and SOEC) is conditioned by the cost of the electric kWh, the efficiency and load factor of the electrolyser and the plant amortization and lifetime.

According to the following table (Buttler et al. 2018), the electricity consumption of alkaline and PEM technologies is 55 to 70kWh/kg H_2 produced, and 41 to 43kWh/kg for high-temperature technologies (**which require a heat source, often considered as waste heat and therefore not accounted for**).

	AEL	PEMEL	SOEL
Operation parameters			
Cell temperature (°C)	60–90	50–80	700–900
Typical pressure (bar)	10–30	20–50	1–15
Current density (A/cm^2)	0.25–0.45	1.0–2.0	0.3–1.0
Flexibility			
Load flexibility (% of nominal load)	20–100	0–100	−100/+100
Cold start-up time	1–2 h	5–10 min	hours
Warm start-up time	1–5 min	< 10 s	15 min
Efficiency			
Nominal stack efficiency (LHV)	63–71%	60–68%	100%[a]
...specific energy consumption (kWh/Nm^3)	4.2–4.8	4.4–5.0	3
Nominal system[b] efficiency (LHV)	51–60%	46–60%	76–81%
...specific energy consumption (kWh/Nm^3)	5.0–5.9	5.0–6.5	3.7–3.9
Available capacity			
Max. nominal power per stack (MW)	6	2	< 0.01
H_2 production per stack (Nm^3/h)	1400	400	< 10
Cell area (m^2)	< 3.6	< 0.13	< 0.06
Durability			
Life time (kh)	55–120	60–100	(8–20)[c]
Efficiency degradation (%/a)	0.25–1.5	0.5–2.5	3–50
Economic parameter			
Investment costs (€/kW)	800–1500	1400–2100	(> 2000)[c]
Maintenance costs (% of investment costs per year)	2–3	3–5	n.a.

[a] Operating at thermoneutral voltage.
[b] Including auxiliaries and heat supply (SOEL).
[c] High uncertainty due to pre-commercial status of SOEL.

Table 4 – Synthesis of electrolysis production yields and costs - ref. Buttler et al (2018).

The favourable value of 55kWh/kg H_2 for electrolysers is generally accepted.

This production efficiency must be coupled with the price of electricity, both current and future, to obtain an order of magnitude of the cost of hydrogen. The mean wholesale price of electricity in France has varied between €30/MWh and €60/MWh over the past ten years.

According to IEA (projected cost of generating electricity 2020 report), the levelised cost of electricity (LCOE) range from \$30/MWh to \$100/MWh for the main generation technologies. However, LCOE is a measure that does not reflect the value delivered to the system, as it does not take into account the transmission/distribution of electricity and other system costs, including taxes.

Coal or natural gas without CCS should not be considered in the production of electricity for electrolysis, giving higher carbon emission than gasification or methane reforming process: electricity mixes emitting far less than 185g CO_2/kWh is required for producing hydrogen by electrolysis with a CO_2 footprint significantly reduced compared to the reforming process.

Buttler A. et al. 2018[37], quote a capital cost of €800 to €1,500/kW of installed power for alkaline electrolysis and €1,400 to €2,100/kW for PEM, and more hypothetical costs for SOEC which is still not industrially mature. It is considered an average of US\$ 1,000/kW as the actual costs in 2021.

It is assumed a 100,000 hours life expectancy for the electrolytic installation, which is a rather favourable value for both alkali and PEM systems. Their lifetime can be expanded by a refurbishing of the "stacks" that constitute the heart of the system, for a fraction of the initial investment.

The impact of this investment on the production price depends on the total quantity of hydrogen produced, i.e. the operating time of the installation or its load factor.

The amount of hydrogen produced will depend on the availability of low-carbon electricity. Very few countries in the world can display electric mixes far below 185 g CO_2/kWh. As an alternative, some countries consider using dedicated variable renewable generators to feed the electrolysers, which requires coping with the intermittency impact on the electrolysers' load factors. This impact may be mitigated by selecting areas in the world offering high load factors for variable renewable sources.

Taking into account the amount of hydrogen produced during the lifetime of the installation, amortization and operating costs of the electrolysers, the levelized cost of the electrolysers (with a 7% discount rate) depends on the effective load factors driven by the electricity supply:

Electrolyse load factor	25%	40%	70%
Electrolyser contribution	\$3/kgH_2	\$1.9/kgH_2	\$1.1/kgH_2

37 See supra ref.

The target price is expected to be competitive even if the current values are much higher (see the values below). Combining the contributions of the electricity cost and of the electrolysers' capital cost, the overall hydrogen cost varies between:

- 2.7US$/kg$H_2$ assuming an electrolysers' load factor of 70% and $30/MWh for the electricity
- And 5.1 US$/kg$H_2$ assuming an electrolysers' load factor of 40% and $60/MWh for the electricity

The above simple illustration is consistent with the evaluation provided by the IEA in its report "The Future of hydrogen, 2019".

The amortization of the electrolyser is of significant importance only at low charge rates and/or low electricity prices.

Readers have to be aware that these numbers are, for a large part, just expectations. Today's cost of Clean H_2 is higher and fast reduction is expected due to the research effort in the domain and market size effects.

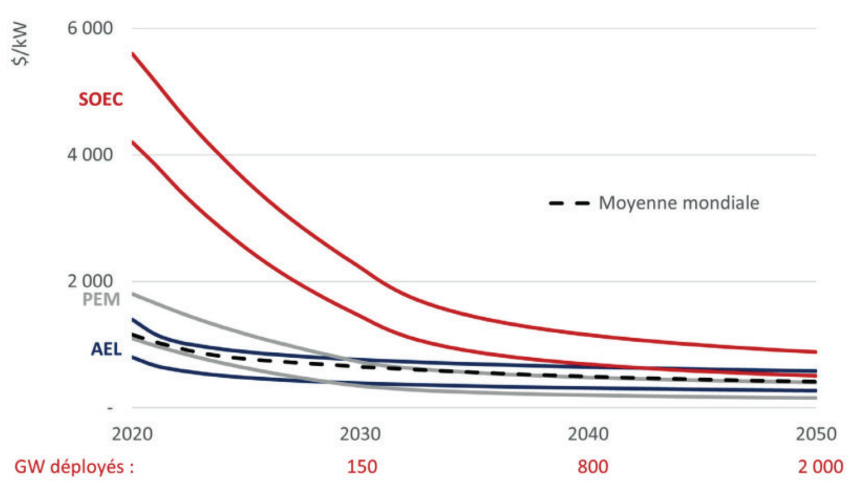


Figure 3. Fourchettes de coûts des électrolyseurs, 2020-2050

Source : AIE, 2019 pour les coûts de l'année de base

Figure 11: Range of electrolyser costs, 2020-2050

Source: IEA 2019 for the baseline year costs

In a nutshell:

- Expected costs: US$ 2.7 to US$ 5.1 of hydrogen per kilogram when the electricity cost varies from 30 to $60/MWh and the electrolysers' load factor from 40% to 70%. I.e. a division by at least two with respect to the current prices
- Energy need: from 40 to 55kWh/kg of H_2
- mature (alkaline), maturing (PEM), industrially prospective (SOEC) facilities;
- main determinants of cost evolution:
  - price of electricity,
  - electrolysers' load factor.

According to *Future cost and performance of water electrolysis*, 2017, which seeks to establish the margins of progress for the electrolysis industry, the figures used above are rather at the limits of the present state of the art, still far from being generalized. Alkaline and PEM technologies will compete over the next decade, depending on their price and other characteristics (e.g. flexibility); SOEC is not expected to be massively introduced before 2030. The expected progress relates more to the investment costs and lifetime of electrolysers than to efficiency, which is expected to improve only slightly for as long as SOEC is not widely deployed on an industrial scale.

Innovative Ways to produce carbon-free H_2

Future production technologies

While the economic potential for electrolysis and fuel cells can still be improved, these technologies are, to a large extent, already mature and the energy needed to break the water molecule is a physical constraint. There are, however, other innovative ways of producing low carbon or carbon-free hydrogen and these are mainly based on new technologies that are still in need of research and development. The TRL is low for some of them but already around 6 or 7 for some others.

Emerging breakthrough technologies such as plasma technology for the production of hydrogen from methane without generating CO_2, anoxic pyrolysis of CH_4, work on microbial hydrogen generation, photosynthesis, biomimicry, or the exploration for native hydrogen such as that found accidentally in Mali represent still very limited fields of activities in many countries, including France. Nevertheless, research and development is continuing and encouraging results are being obtained.

It should be noted that the plasma technologies make it possible to crack hydrocarbons more generally; the input may be other than methane. In California, the energy company SGH_2 uses solid waste as source material (https://www.intelligentliving.co/gasification-plant-waste-green-hydrogen/). Other countries doing R&D in this area include Canada and Russia.

Some of the emerging technologies mentioned above are described in the following paragraphs.

Methane pyrolysis (plasma technologies)

The principle is simple: CH_4 + temperature => H_2 + carbon black. French laboratories host leaders in this technology. The Sophia Antipolis research centre (Persee project) is working on low-temperature plasma processes (around 1,100 °C) to directly separate methane into carbon black and hydrogen. The first commercial-scale facility using this technique is currently commissioned by Monolith in Nebraska and will produce green hydrogen for fertilizer and carbon black markets[38].

From an energy balance point of view, this reaction is much less expensive than steam reforming and water decomposition (38 - 62 kJ/mol of hydrogen produced and 285 kJ/mol of hydrogen produced, respectively). This solution, therefore, has a much higher potential (it would require ¼ of the energy needed for electrolysis) than the others for a massive and inexpensive production of hydrogen. In addition, carbon black has various industrial uses. The CO_2 balance is potentially excellent since it would allow the replacement of two operations currently emitting CO_2 (the production of hydrogen by steam reforming and the production of carbon black from hydrocarbons in furnaces) by a non-emitting process. The cost might be between €0.5 and €1 of electricity per kg of hydrogen. To this must be added the consumption of methane, which represents between €0.8 and €1/kg H_2. The greatest uncertainty weighs on the cost of the installations, their efficiency, and their lifespan.

Mwave

Microwave technologies are also under development (see for instance Sakowin in France) that could be more efficient for H_2 production and at the same time modulable[39]. The final announced H_2 price is today between \$2 and \$4/kg, which is competitive compared to SRM + CCS.

In a nutshell

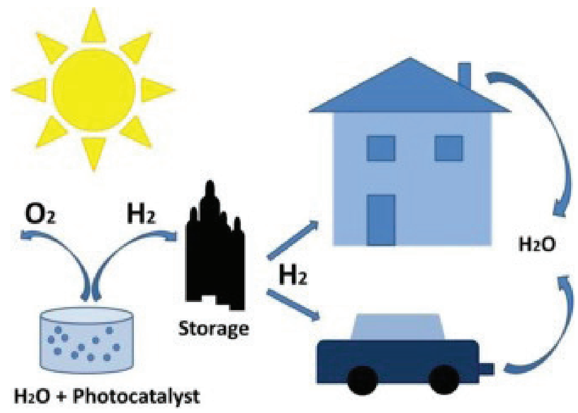
- costs: potentially US$ 2 to US$ 3/kg of hydrogen for plasma technology, to be defined for the other routes;
- TRL between 5 and 7;
- Energy need: about 4.7 kWh/kg of H2, which, on paper, is the more efficient way to produce H_2
- main determinants of the evolution of costs:
- price of electricity or gas depending on the heat source used,
- amortisation of the installations (load factor).

38 https://monolith-corp.com/methane-pyrolysis

39 https://sakowin.com

Photosynthesis / Photocatalytic pure water splitting

Direct photocatalytic electrolysis of water is a scientific reality, Research goal is focused on the realisation of efficient and reliable roof panels . Such a breakthrough makes it possible to move towards more energy self-sufficient homes, with the stored hydrogen then being used at night.



Aleksandar Vaneski
Researchgate

Hydrogen from syngas

The pyrolysis of dry biomass generates a syngas that contains, among other things, hydrogen and methane, but instead of concentrating methane in a second phase, as in the biogas process, hydrogen is concentrated. This second phase can be performed by catalysis or microbial activity. Pilots exist with wood, wet organic waste (such as tyres and demolition wastes), the announced cost of H_2 is currently around 6 to 8 €/kg but the TRL is still intermediate.

Production by bacterial or biological activity

If a good part of the bacteria in the subsoil consume hydrogen, hydrogenases, some of them can generate hydrogen if they have another source of energy, which can be biomass or the sun. The possibilities of producing hydrogen from these enzymes had been explored as early as 2003 by BRGM and other laboratories have continued the research. The CEA currently has patents on the production of hydrogen from

Algae-based bioreactors have the potential to generate hydrogen, possibly by neutralizing CO_2.

Production by oxidation (biomimicry)

The principle is close to what nature does, one oxidises iron in the ferrous state (Fe_2+) which releases hydrogen by passing to the ferric state (Fe_3+). Research is being conducted, in France mainly in Grenoble, on catalysts to lower the temperature at which this reaction is effective (Brunet, 2019). Magnetite is a by-product of this reaction and its market value, especially for filters, improves the economy of the system.

Overall, the above-mentioned various technologies, the list of which is not exhaustive, can enable hydrogen to be integrated into the energy mix of regions while meeting certain waste treatment needs (steel mills, dairy farms, and forests for the last three technologies mentioned).

Natural hydrogen

Natural hydrogen mainly comes from the water/rock interaction and is thus constantly regenerated by the water circulation in the subsurface.

With respect to natural hydrogen, exploration and extraction techniques are well known to the gas or geothermal industry and, therefore, the TRL is high, near 9 and the price of hydrogen at the wellhead could be equivalent to that of methane. Potentially it could become cheaper than the H_2 extracted from methane, which is currently the cheapest source. However, as all the resources of natural H_2 will not be present all over the earth, the economic value of these discoveries will be related to their accessibility (depth of the reservoir, porosity) and the long-distance transport of hydrogen. However, in cases of local use, the cost of exploiting this resource can be rather low.

When hydrogen accumulations were accidentally discovered when drilling for hydrocarbons (Kansas/US, Amadeus Basin/Australia) and water (Mali), attitudes shifted to considering that there might be a real potential for discovering exploitable naturally occurring hydrogen resources. The deposit in Mali, at a depth of 110 m, is indeed being continuously exploited since about 8 years with a stable yield of about 1200 m^3 per day (at 4 bar), suggesting continuous recharging from a deeper level (Prinzhofer et al. 2018). The legislation for exploring and exploiting natural hydrogen is starting to be framed in various countries. Mali, USA and part of Australia, among others, already have such legislation and exploration and permitting are ongoing (Moretti et al. 2021). South Australia is currently the leading area of this sort of exploration with more than 20 exploration licenses already taken. Since hydrogen is often found blended with He, another strategic gas, this exploration is quickly growing and many companies have been created for that purpose, such as in the USA (Mountain desert, Beam) in Australia (Gold H_2, Buru, H_2ex) but also in France (45-8), Spain (Helios), the UK (H_2AU) and in Switzerland (HYNAT).

Conclusion

Overall, the above-mentioned various technologies, the list of which is not exhaustive, can enable hydrogen to be integrated into the energy mix of regions while meeting certain waste treatment needs (steel mills, dairy farms, forests for the last three technologies (before natural hydrogen) mentioned).

China

In China, a diversified hydrogen production system is expected, where a clean, low-carbon and low-cost hydrogen production system will be gradually promoted. Currently, the H_2 production comes mostly from coal gasification (>60%), and among the remainders, about 14% comes from Steam Methane Reforming (SMR) and 21% comes from industrial processes such as oil refining, coke oven gas, chlorine alkali offgas etc. Only about 2% comes from water electrolysis, which is the most potential route for green hydrogen production in the future when electricity will mainly come from renewable sources.

According to the *Medium- and long-term planning for the hydrogen energy industry (2021-2035)*, the production of hydrogen in China should be based on the resources available. For example, the use of industrial by-product hydrogen should be given a higher priority in places where such resources are available. It is also encouraged to demonstrate the production of hydrogen from renewable energy in places which are rich in wind, solar, hydropower, and other renewable energy resources. The CCUS technology is widely regarded as an effective means and solution to address the challenges of climate change and achieve carbon neutrality and thus has attracted broad interest. However, the large-scale promotion and application of CCUS technology still face great technical and economic challenges in China. According to the *Roadmap for carbon capture, utilisation and storage technology development in China (2019)*[40], it is anticipated that the commercial scale industrialization of CCUS technology may take place after 2035, becoming an important supporting technology for low-carbon hydrogen production from fossil fuels whenever other options are limited. In the short term (before 2030), continuous R&D, as well as the large-scale demonstration of the CCUS technology, will be promoted in China.

H_2 Production by Water electrolysis

In terms of industrialization, alkaline water electrolysis is the most mature electrolysis technology and has been applied to some large-scale projects.

- In Nov 2020, a research team from the Dalian Institute of Chemical Physics (DICP) of the Chinese Academy of Sciences and their collaborators industrialized the Liquid Solar Fuel Production Demonstration Project in Lanzhou, Gansu. 21,000 Nm^3/h[41] alkaline water electrolysers powered by a 10 MW photovoltaic power station were used to produce hydrogen, which was used in the CO_2 hydrogenation process to produce methanol.[42]
- In April 2021, Ningxia Baofeng Energy Group commenced the operation of the world's largest solar-powered hydrogen plant to provide feedstock for its coal-to-olefins project in Ningxia.

40 Department of Science and Technology for Social Development, Ministry of Science and Technology of PRC, The Administrative Centre for China's Agenda 21, Ministry of Science and Technology of PRC. Roadmap for Carbon Capture Utilisation and Storage Technology in China (2019). Beijing, 2019.

41 Nm^3 /h = normo-cubic metres per hour, e.g. one cubic metre of hydrogen gas per hour (or 90 g. of hydrogen per hour)

42 CAS https://english.cas.cn/newsroom/research_news/chem/202011/t20201102_247124.shtml

The facility was powered by a 200 MW solar photovoltaic park and the company intends to add more capacity in the future.[43]

- In Nov 2021, Sinopec launched the Sinopec Xinjiang Kuqa Green Hydrogen Demonstration Project, which was the world's largest photovoltaic green hydrogen production project under construction. The capacity of PV will reach 300 MW and hydrogen production will reach 20,000 tons/a. The green hydrogen produced will be supplied to Tahe Refinery to replace the company's existing hydrogen from fossil sources and it is expected to reduce carbon dioxide emissions by 485,000 tons/a.[44]
- In Nov 2021, the first set of 1,300 Nm^3/h alkaline electrolyser served in Pengzhou for China Huaneng Group was made by domestic manufacture John Cockerill.[45]

As PEM electrolysers operate more flexibly and are better suited to the volatility of renewable energy, the demonstration projects of PEM electrolyser technology are also in progress.

- In Sep 2021, the megawatt-level proton exchange membrane (PEM) water electrolysis hydrogen production system developed by Dalian Institute of Chemical Physics, Chinese Academy of Sciences, realized full power operation at the Hydrogen Comprehensive Utilisation Station of the State Grid Anhui Company. According to on-site testing, the system has a nominal hydrogen production capacity of 220 Nm^3/h and a peak hydrogen production of 275Nm^3/h.[46]
- In Sep 2021, Sinopec's first megawatt-level hydrogen production demonstration project from electrolysed water was launched in the Zhongyuan oil field. It will have a capacity of 2.5 MW with the ability to produce around 1.12 tonnes/day of ultra-pure hydrogen. The project is expected to be complete by Sep 2022.[47]
- In Nov, 2021, Sinopec's first proton exchange membrane (PEM) hydrogen production demonstration station was put into use by its affiliated Yanshan Petrochemical Company. The proton exchange membrane electrolyser's anode and cathode catalysts, bipolar plates and other key material components are all self-developed.[48,49]

China's vision of new production methods

In situ combustion

China is also testing in situ combustion in coal mines, where it is planned to realize in situ underground coal gasification with oxygen injection under high pressure and high temperature.

43 https://www.blackridgeresearch.com/news-releases/worlds-largest-hydrogen-plant-in-china-initiates-operations

44 https://www.prnewswire.com/news-releases/sinopec-lands-worlds-largest-photovoltaic-green-hydrogen-production-project-in-kuqa-xinjiang-301433733.html

45 https://hydrogen-central.com/john-cockerill-largest-single-hydrogen-electrolyser-stack/

46 CAS https://www.cas.cn/syky/202110/t20211011_4808445.shtml

47 https://www.upstreamonline.com/energy-transition/sinopec-announces-first-pem-green-hydrogen-project/2-1-1064013

48 SINOPECNEWS http://en.sasac.gov.cn/2021/11/09/c_8135.htm

49 State-owned assets supervision and administration commission of the state council http://en.sasac.gov.cn/2021/11/09/c_8135.htm

This technology could be used for in situ fluidized mining of deep coal for more than 1000 m underground. The output gases of this project are mixed gases of CO, CH_4, H_2, etc. In the future, the gases could be separated at surface for the production of H_2.

Methane pyrolysis

With abundant coke oven gas and coal bed methane resources, producing hydrogen by methane cracking is considered as a promising method in China. Nowadays, R&D is in progress by some domestic research institutions, such as Dalian University of Technology[50]. According to the Ministry of Natural Resources "China Mineral Resources Report 2021" by the end of 2020, China's natural gas reserves are 6,266.578 billion m^3, coalbed methane reserves are 331.554 billion m^3, and shale gas reserves are 402.617 billion m^3[51]. In 2021, China's natural gas production was 205.3 billion m^3, an increase of 8.2% over the last year and an increase of 18.8% over 2019[52]. It is expected that China's natural gas production will continue to grow, and the methane pyrolysis technology may have a great potential in the future.

Photocatalytic pure water splitting

Photocatalytic water splitting has attracted great interest as a means of cost-effective conversion of sustainable solar energy to valuable chemicals[53].

Researchers of the Dalian Institute of Chemical Physics, CAS successfully realized the high-efficiency photocatalytic water splitting process. This work was supported by the National Natural Science Foundation. The solar to hydrogen efficiency exceeds 4.3%[54].

In April 2021, Xi'an Jiaotong University and the State Power Investment Corporation signed a cooperation agreement to realize a demonstration project combining a system of photoelectric and thermal coupling with solar photocatalysis in Tacheng City, Xinjiang province. The hydrogen production of the project is 500 thousand Nm^3/a, and the technology is the fifth generation developed by Xi'an Jiaotong University[55].

50 Dalian university of technology http://team.dlut.edu.cn/meitangaoxiaoqingjieliyongtuandui/en/index/1125497/list/index.htm

51 http://www.mnr.gov.cn/sj/sjfw/kc_19263/zgkczybg/202111/P020211105382623655125.pdf

52 https://recordtrend.com/chinese-economy/national-real-estate-development-investment-in-2021-from-national-bureau-of-statistics/

53 Efficiency Accreditation and Testing Protocols for Particulate Photocatalysts toward Solar Fuel Production, Joule, Volume 5, Issue 2, Pages 344-359 - https://doi.org/10.1016/j.joule.2021.01.001

54 Journal of the American Chemical Society - https://pubs.acs.org/doi/10.1021/jacs.1c00802

55 Xi'an jiaotong University - http://mfpe.xjtu.edu.cn/info/1076/6624.htm

France/Europe

France

In France, industrial hydrogen production represents more than 900,000 tonnes per year. The three most important are: desulphurization of petroleum fuels (60%), ammonia synthesis mainly for fertilizers (25%) and synthesis, mainly for fertilizers (25%) and chemicals (10%). Ninety-four percent of ammonia is produced from fossil fuels in France (gas, coal, hydrocarbons). The production of hydrogen is responsible for 11.5 Mt of CO_2 emissions in France, i.e. about 3% of national emissions.

Concerning the production

Specific funds are devoted to industrial deployment (€275m), technology bricks and demonstrators (fuel cells, tanks, materials, etc.) (€350m), electrolyser Gigafactory projects (e.g McPhy preselects Belfort as the location for its electrolyser Gigafactory), hydrogen applications, priority research programme (€65m), etc.[56] Strong cost reduction is targeted for electrolytic hydrogen, for all electrolysis technologies and operation modes[57]. It includes the option to use excess nuclear generating capacity for example during night times and the waste heat of nuclear plants. The issue is the amortization of electrolysers, which is difficult in intermittent operation mode. On the other hand, in the case of continuous operation, recurrent high electricity prices during daily peak demand could also hamper fast amortization. The objective is to reduce costs to 2 to 3 €/kg in 2028[58].

A huge national research project has been lunched mainly to improve the electrolyser and fuel cell technologies (PEPR_H_2, French Research Network on Hydrogen). The CNRS and the CEA are the leaders.

The CEA is developing a high-temperature reverse fuel cell.

Engie, Uni of Grenoble, UPPA, 45-8, IFPen and a couple of other labs are working on natural hydrogen. The region Nouvelle-Aquitaine is starting an evaluation of its potential (HYNAT). Natural hydrogen has now found its place in the law, published in March 2022. The ecosystem gets organized with the recent creation of the association EarthH_2[59].

56 https://www.wfw.com/articles/the-french-hydrogen-strategy/

57 Operation modes: during periods of low prices, all year round except in high price periods, on the sites of renewable electricity generation

58 https://www.actu-environnement.com/media/pdf/publireportages/environnement-et-technique/hors-serie-hydrogene-2021.pdf https://www.actu-environnement.com/media/pdf/publireportages/environnement-et-technique/hors-serie-hydrogene-2021.pdf

59 https://www.pole-avenia.com/fr/article/earth2?msclkid=26646dc0b4d211ec960f3ea490ba7446

Engie and the CEA are working in the photosynthesis.

Nothing is done concerning the *in situ* combustion since there is currently not any production of coal or of heavy oil left.

UPPA, Storengy and Terega are working on H_2 storage in salt caverns. One of the questions is the role of the microorganisms that may result in changes of the gas composition during longer-term storage. All the operators of gas storage are working together for the first demonstrator HyPSTER together with German and British research groups[60].

Concerning the integration

The gas transport company GRTG is studying with its partners the phenomenon of steel embrittlement to evaluate the security of the pipes (for blends or pure H_2).

Many projects to test H_2 integration into the energy mix, to neutralize CO_2 and reinject synthetic methane into the network (JUPITER 1000), to boost biomethane production by injecting H_2 into synthetic gas in Methycentre or Hycaunnais[61], to test the blend of H_2/CH_4 in the distribution grid (GHRYD) are ongoing.

A couple of cities, such as Versailles and Pau, have already H_2 fuel cell buses.

Since the COP21, there are H_2 filling stations in the Paris area and a fleet of taxis using it (Hype with Air Liquid). They were a few hundred in 2021.

Globally all the main energy companies, Total Energies, EDF, Engie have dedicated teams and are developing new business units.

Concerning innovative ways to produce low-carbon hydrogen

The Sophia Antipolis research centre (Persee project) is working on low-temperature plasma processes (around 1,100°C) to directly separate methane into carbon black and hydrogen.

Some technologies allow electrolysis to be carried out directly from solar energy and thus to manufacture solar panels that directly deliver hydrogen[62]. Studies and patents exist; the first pilots are under construc-

60 https://hypster-project.eu

61 www.storengy.com/en/our-offers-and-services/renewable-gases/our-renewable-gas-projects

62 S. Hilliard, D. Friedrich, S. Kressman, H. Strub, V. Artero and C. Laberty-Robert, ChemPhotoChem, 2017, 1, 273-280

tion in France (See figure on the side in the Engie research Laboratory).

Hydrogen from syngas technology makes it possible to produce green hydrogen using much the same process as second-generation biogas (For instance in France: Haffner Energy process[63]).

BRGM was exploring the possibilities of producing hydrogen from enzymes (by bacterial or biological activity) as early as 2003, and other laboratories have continued the research. The CEA currently has patents on the production of hydrogen from whey in vertical bioreactors and is seeking to make a first demonstrator in a dairy.

The principle of producing hydrogen by oxidation (biomimicry) is close to what nature does, one oxidizes iron in the ferrous state (Fe_2+) which releases hydrogen by passing to the ferric state (Fe_3+). Research is being conducted in France, mainly in Grenoble, on catalysts to lower the temperature at which this reaction is effective (Brunet, 2019). Magnetite is a by-product of this reaction and its market value, especially for filters, improves the economy of the system.

Europe

For memory: CO_2 emissions of the European energy sector amounted to more than 3 billion tons in 2018[64]. Abating these emissions to arrive at Net Zero-Emissions by 2050 requires efforts never seen before, except in times of war. In particular, the drastic reduction of primary energy use poses a major challenge.

Hydrogen could fill the gap in the European decarbonisation strategy (Green Deal). Policymakers are increasingly tilting towards the acceptance that hydrogen should play an important part in the European economy, making it an integral part of the European strategy towards decarbonisation. This fact highlights the convictions of the European Commission regarding the crucial role of hydrogen in the transition towards carbon neutrality. However, while a roadmap has been established[65], the strategy has not yet given rise to firm and binding plans.

63 www.haffner-energy.com

64 Source: Eurostatt

65 https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf : Hydrogen Roadmap Europe - a sustainable Pathway for the European Energy Transition

Conclusion

Production

Regarding the H_2 production modes, the main differences for China and France/Europe are related to the use of coal. It will remain an important source of H_2 in China with a decreasing environmental impact through *in situ* combustion, to avoid CO_2 and other gas emissions.

Both countries see the great potential of water electrolysis in the production of low-carbon hydrogen, although the French horizon for low carbon H_2 production is focused on electrolysis, while China aims to develop a diverse low-carbon hydrogen production system.

Regarding methane pyrolysis, both countries are looking closely at this technology and see its disruptive potential. France doesn't hope to have methane in excess for the coming tens of years but having the technological brick may open new markets. China is hoping to have in the future enough methane to use it. Both recognize that if the large gas producers manage to produce H_2 by these kinds of techniques, it will change the market. The gas reserves are huge and the energy needs to transform it through H_2 and black carbon present the best energetic balance.

Chapter 3

H_2 use for industry

Issues and context

Issues

The aim of this chapter is to describe:

- the options for China and France/Europe regarding the use of decarbonised hydrogen as a chemical;
- the concerned industry sectors having priority;
- the quantities involved, and
- the timescale on which this will occur in the coming years.

Context

The global hydrogen market is estimated at approximately $135 billion in 2018 with a prospect of reaching $200 billion in 2023, with a growth rate of 8% differing between geographic regions. World production in 2018 was around 70 Mt/year of high purity hydrogen from 273 Mt of hydrocarbons (mainly methane) to which must be added 40 Mt/year of hydrogen coproduced with carbon monoxide and used in chemical processes. Annual French production is slightly less than 1 Mt/year.

The main distributors of hydrogen in the world are: Air Liquide (France), Air Products and Chemicals (US), Praxair (US), Iwatani (Japan), Linde (Germany), Messer Group (Germany), etc.

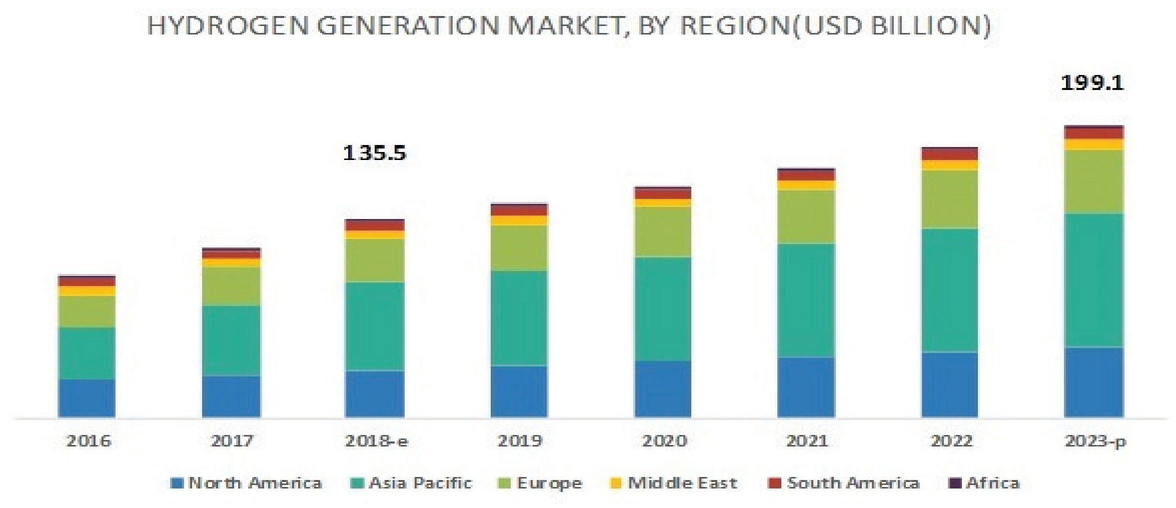


Figure 12 — World Hydrogen Market, by region(US$ billion) - Markets and Markets® - 2018

Pure hydrogen is mainly used for its chemical properties:

- the primary use (nearly 50% of world demand) is to convert heavy petroleum fractions into light products and to desulfurize the final products. Environmental requirements have greatly increased the demand for desulfurization. The hydrogen sulphide produced by the process accounts for the bulk of the world's sulfuric acid production;
- the second use (nearly 45% of world demand) is the production of ammonia (NH_3 gas), which is used for the production of fertilizers for which demand is growing.

Hydrogen is also used for the production of other molecules (methanol, ethanol, amides, H_2O_2...). Finally, the reducing properties of hydrogen are used in various industries (iron ore reduction, metallurgy, glass, welding, electronics, etc.).

China

To achieve carbon neutrality by 2060, making breakthroughs in zero-carbon/low-carbon process reengineering technologies in hard-to-abate sectors is extremely important.

Green hydrogen produced by renewable power will play an essential role in decarbonisation. In 2017, a strategic priority project of « transformational Clean Energy Technology and Demonstration has been launched by CAS (Chinese Academy of Sciences), promoting innovation and demonstration projects for an energy technology revolution. Hydrogen is one of the three key platforms for the energy revolution and industry process reengineering.

Five industrial sectors are concerned: Refineries, Chemical-, Steel-, Cement- and non-ferrous metal industries.

Coal-based chemical

(Coal to methanol, coal to olefins, coal to ammonia, coal to liquid fuels, etc.)

In 2019, hydrogen demand of synthetic ammonia production was about 10.8 million tons, demand for methanol production was about 9.1 million tons, demand for hydrocracking and hydrorefining and coal to oil was about 8.2 million tons, totalling 28 million tons[66].

The production costs of the CTM (coal to methanol) and GH-CTM (green hydrogen-coal to methanol) processes were calculated in this study, and the prices of coal, steam, electricity, oxygen, and methanol were set to 88.6 US$/t, 6 US$/GJ, 0.064 US$/kWh, 142 US$/t, and 328.6 US$/t, respectively. The exchange rate of the US dollar and RMB was set as 1 US$=RMB 7.0. In addition, 4% of salvage rate and 15 years of depreciation were added. The calculated production cost of the GH-CTM process was 201.75 US$/t, 23.95% lower than that of the CTM process[67].

Petrochemical industry

In China, hydrogen demand in the chemical industry will continue to grow until 2030, from 18.22 million tons in 2018 to 21.7 million tons[68]. In 2050, hydrogen demand in the chemical industry is expected to be over 37 million tons[69].

As the price of renewable energy power in China will have fallen sharply, the cost of green hydrogen will be competitive. The model of "Industry + green hydrogen" is expected to be applied in the chemical industry on a large scale, which can meet the requirements for both energy consumption and the reduction of carbon emissions at the same time and help chemical companies make a profit. "Industry + green hydrogen" has a profound impact on the production process in the petrochemical industry, which may lead to a very obvious differentiation between companies and production methods.

66 China Hydrogen Energy and Fuel Cell Industry Development Report(2020), China Hydrogen Alliance, People's daily press

67 Wang Dongliang, Meng Wenliang, Zhou Huairong, Li Guixian, Yang Yong, Li Hongwei. Green hydrogen coupling with CO_2 utilisation of coal-to-methanol for high methanol productivity and low CO_2 emission[J].Energy, 2021, 231:1-11. https://doi.org/10.1016/j.energy.2021.120970

68 White paper of hydrogen energy and fuel cell industry in China 2020, China hydrogen energy alliance

69 China 2050:A zero-carbon vision of a fully modernized country Energy transitions commission & Rocky Mountain Institute https://www.rmi-china.com/index.php/news?catid=18

Cement

Cement is a resource-based raw material, important for national economic development. Cement production in China has ranked first in the world for more than 30 years. In 2020, cement production in China is around 2400 million tons[70], accounting for 58% of world production. According to the prediction of IEA, cement production in China will continue to rank first in the world for the foreseeable future[71].

In 2020, carbon dioxide emissions from the cement industry in China are around 1.42 billion tons, accounting for nearly 12.7% of China's total carbon emissions. The carbon emission intensity of China's cement industry is about 592kgCO_2 per tonne of cement, and about 860kgCO_2 per tonne of cement clinker. According to the statistics of China Building Material Science Institute, process emissions account for the largest share (~56%)[72]. (According to the report of McKinsey, cement manufacturing is a highly complex process and process emissions account for ~52%)[73].

Alternative fuel technology refers to replacing fossil fuels such as coal and oil with carbon neutral or low carbon emission intensity fuels. They are used to supply the large amount of heat required for the calcination process in the cement precalciner and rotary kiln, thereby reducing direct emissions. Hydrogen is one of the alternative fuels. Hydrogen is a carbon-neutral substance and its latent heat of vaporization (LHV)[74] is nearly four times that of standard coal. If the substitution rate of coal by green hydrogen energy is 100%, carbon emissions are reduced by about 32%.

Hydrogen alternative technology has many advantages, but due to insufficient technical maturity and cost issues, it is currently at the stage of pilot research in China and there is currently no industrial application. In the near future, both China National Building Material Group and China Building Materials Federation are preparing to carry out a small trial of hydrogen energy substitution in cement kilns.[75,76] According to the technology roadmap for the cement industry from the Chinese Ministry of Science and Technology and China National Building Materials Group, hydrogen energy alternative technologies will start to be promoted for application in the cement industry from 2035 onwards.

70 National bureau of statistics - https://data.stats.gov.cn/search.htm?s=%E6%B0%B4%E6%B3%A5

71 Technology Roadmap Low Carbon Transition in the Cement Industry 2018, IEA https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry

72 China Building Material Academy report data

73 Thomas C, Sebastian R, Patrick S and Ken S (2020). Laying the foundation for zero-carbon cement. McKinsey & Company. Available at: https://www.mckinsey.com/industries/chemicals/our-insights/laying-the-foundation-for-zero-carbon-cement [Accessed 11 June 2022].

74 LHV is the amount of heat stored in a combustion material excluding the latent heat of vaporization of water, whereas HHV is additive of LHV and latent heat of vaporization of water.

75 https://www.cnbm.com.cn/CNBM/000000020001/61144.html

76 https://www.cbmf.org/cbmf/yw/7103343/index.html

Energy intensity of the cement production process is about 100 kgce/t (kilograms of coal equivalent/tonne) cement clinker[77]. Without considering hydrogen substitution, if cement production is all from coal, the total fuel cost is about RMB 100/t cement clinker.

Currently, replacing fuel coal with hydrogen does not have competitiveness in terms of cost, which is the main reason for limiting the adoption of hydrogen substitution in China's cement industry. In the future, if the cost of hydrogen production decreases, it will promote the large-scale application of hydrogen substitution technology in the cement industry.

Steel

According to statistics from the World Iron and Steel Association, the carbon emission intensity of steel industry is 1.8 tons CO_2/t crude steel[78]. In 2019, steel production in China is about 900 million tons and carbon emission is around 1.7 billion tons, accounting for about 16% of domestic carbon emissions[79]. The carbon emission in the steel production process mainly comes from the reduction of iron ore, crude steel production by decarburizing from pig iron and crude steel formed. Carbon emissions from iron reduction process accounts for 90% of the entire steelmaking process. Therefore, reducing the carbon emissions of the reduction process is very important for the low-carbon development of the steel industry.

Hydrogen metallurgy refers to the gas-based direct reduction process or other hydrogen-rich metallurgical technologies that use hydrogen to produce sponge iron. Relevant studies have shown that the hydrogen consumption in the reduction process is about 550 Nm^3/t iron[80,81]. Domestic hydrogen smelting technology is still at an early stage of R&D. Most companies are still in the stage of project planning and signing contract agreements. Only a few companies have set the goal of utilizing green hydrogen as clean energy in the steelmaking process. Some researchers indicated that hydrogen metallurgy projects can be carried out step by step. In the first phase (until 2025), pilots will be into operation to study the feasibility of large-scale industrial hydrogen smelting. In the second phase (until 2030), hydrogen production from coke oven gas, chemical and other by-products will be industrialized. By 2050, the hope is that green hydrogen of high purity produced from renewable energy and nuclear power will be applied in the steel-

77 GB 16780-2021 « The norm of energy consumption per unit products of cement »

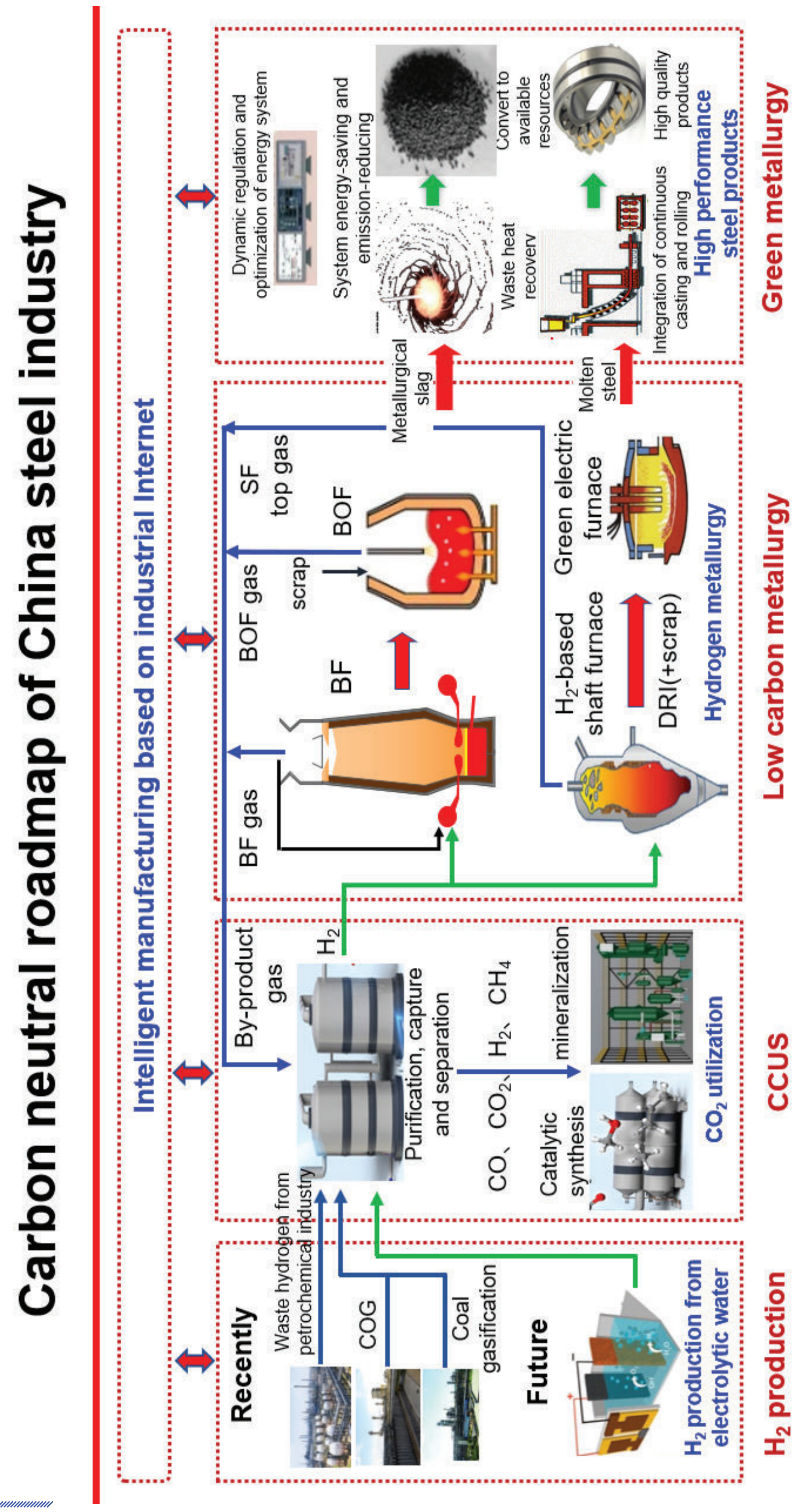
78 World steel association - https://www.worldsteel.org/media-centre/press-releases/2021/sustainability-indicators-2021-and-our-sustainability-journey.html

79 Path to steel carbon neutrality 2021, Energy transitions commission & Rocky Mountain Institute https://www.rmi-china.com/index.php/news?catid=18

80 Nm^3 /t = normo-cubic metres per tonne, e.g. one cubic metre of hydrogen gas per tonne of iron

81 Vogl V, Ahman M, Nilsson L J. Assessment of hydrogen direct reduction for fossil-free steelmaking[J]. Journal of Cleaner Production, 2018, 203: 736-745.- https://doi.org/10.1016/j.jclepro.2018.08.279

making process, at a competitive cost[82]. Currently, the cost of different hydrogen production technologies is still an important issue for the introduction of hydrogen metallurgy. The roadmap for hydrogen-based steel making is illustrated in the figure next:



82 Primary exploration of hydrogen metallurgy, Metallurgy industry press. 氢冶金初探

France/Europe

In France, one of the priorities is to decarbonise the industry by replacing high-carbon hydrogen with low-carbon hydrogen.

Refeneries and chemical industry

The potential for decarbonisation is mainly in refineries, chemical industries, such as involved in the production of ammonia and methanol and some sectors like electronics and food industry for smaller quantities.

As for ammonia, it is compulsory to produce Nitrogen with low-carbon energy in the fractional distillation of air and then to make NH_3 with the HABER-BOSCH reaction.

As for Refineries the total consumption is 16 TWh/year which is supposed to decrease with less use of fossil fuels but, on the other hand, an increase of H_2 consumption to desulfurise fuels is expected.

Ammonia accounts for 8 TWh , other chemicals for 3 TWh.

For these sectors low-carbon H_2 would be produced by electrolysis while the process itself does not change. The challenge is related to the cost.

Cement industry

Cement is made with clinker obtained by heating at 1,450 °C a mix of limestone (80%) and clay (20%). Various additives may be used: slag (coming today from the steel industry but which disappears if reduction of steel is made with H_2), fly ash, pozzolans. French cement industry produces 16,5 million tonnes/year and emits almost 10 million tons/year of carbon. The emission of CO_2 is due to heating energy (30%) and to the process itself of transforming the calcium carbonate ($CaCO_3$) into lime CaO (70%). The reduction of CO_2 emission is planned to be obtained by using decarbonated sources of heat and by modifying the cement itself: decreasing of the percentage of clinker, increasing of the percentage of limestone, capture and use the CO_2 produced (one experience by Vicat: capture of CO_2 and used to produce an aggregate marketed to industry). It is also planned to reduce the global use of cement by 15%. There is no clear impact of H_2 use in the cement industry.

Steel

For steelmaking, H_2 might be used as a reduction agent (CO is nevertheless a stronger reduction agent) for iron ore. Hybrit, Hydrogen breakthrough ironmaking technology is a joint venture led by the Swedish steel company SSAB. The purpose is to eliminate $C0_2$ emissions in the whole value chain for iron and steelmaking by replacing coal with fossil-free electricity and hydrogen. An alternative heating technique and bio-oil are used for sintering of pellets. Hydrogen produced by electrolysis with renewable electricity is stored and used for the reduction of iron ore ($Fe_2O_3 + H_2 \rightarrow Fe + H_2O$). The refining from iron to steel (DRI/HBI) uses fossil-free energy in an electric arc furnace (EAF) instead of a blast furnace (BF), see figure 14 below.

R&D is still going on for the HYBRIT project, the pilot phase has begun and will end by 2025, the demonstration phase will last until 2030.

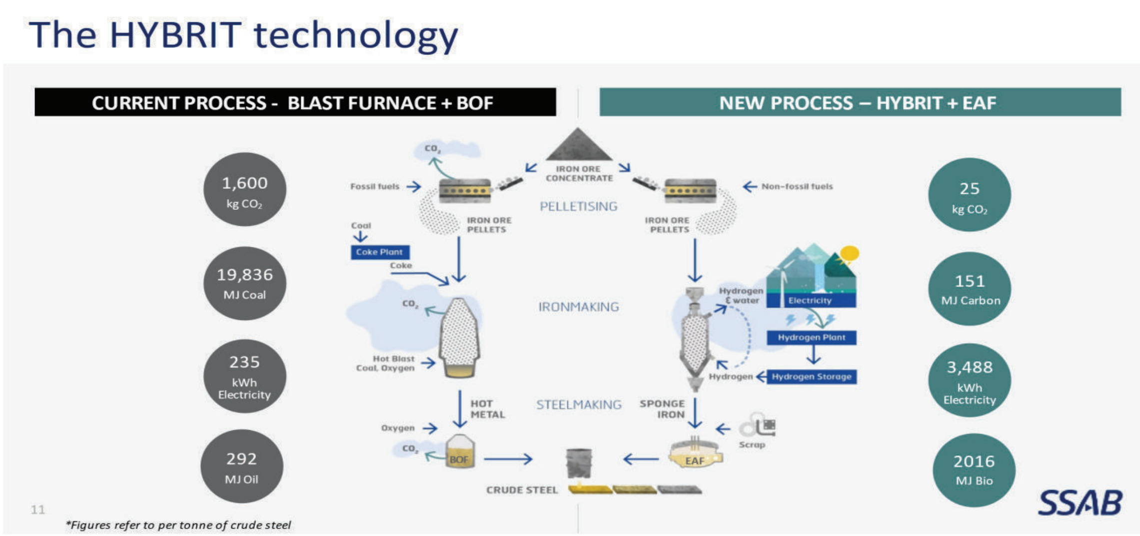


Figure 14: Hybrit processing technology @Researchgate.net

On a European scale, volumes might be important in the long term. But it is not yet clear whether the hydrogen based process or the electric process with direct reduction (Ulcowin process) will be the more economical.

Conclusion

Industrial sectors to be decarbonised are almost the same in the two countries: refineries, steel industry, cement, chemical industries…

In China one of the challenges is the widespread use of coal for chemical processes because it is an important national resource.

As for the cement industry, CO_2 may be decreased with carbon-free fuels such as green H_2 but the CO_2 emission from the heart of the process (calcium carbonate transformed in lime) is unavoidable.

As for steel, carbon-free steel can be obtained but the heart of the process, direct reduction of iron (DRI) by H_2 is possible but there is still a need for further R&D to make it economical.

Chapter 4

H_2 Use as an energy carrier

Issues and context

Issue

The purpose of this chapter is to present the choices of both countries for the use of hydrogen as an energy carrier and explain the reasons, taking into account economics.

The different potential uses are presented: direct combustion, use in stationary or mobile fuel cells to produce electricity. The status of these different technologies and the place they could occupy in the future in Europe and in China is presented. It is also planned to use hydrogen as inter-seasonal energy storage, particularly for electricity production mixes including large shares of intermittent sources even if the business plans remain to be established. Mobility is one of the major potential uses of hydrogen able to play a role in the decarbonisation of the economy; it allows the use of carbon-free fuel and a greater autonomy compared to batteries. These different perspectives are presented for Europe and China.

Context

Carbon free hydrogen has drawn interest for its capacity to provide energy services without emitting any pollutant: this is the promise of a fully decarbonised energy carrier that does not produce fine particles, provided the hydrogen can be produced from hydrocarbons with CO_2 capture or by electrolysis. Energy can be partly recovered by combustion of the hydrogen, pure or mixed with other hydrocarbons, or by a direct conversion to electricity using fuel cells (FC). Hydrogen can also be combined with various molecules to produce electro-fuels, synthetic methane from captured carbon being the most obvious.

Each solution comes with its own combination of efficiency and costs, very dependent on the whole chain from production to consumption. In any case, without a significant price on carbon emissions, energy provided by hydrogen will be more costly than energy from any other conventional source: most hydrogen needs to be produced, requiring primary energy sources, costly systems for the conversion and new storage and delivery systems. Nevertheless, some applications may offset the increased price by providing additional services: zero emission, of course, but also independence from energy networks, potential for storage, mobile use with greater autonomy… The service provided and the comparison with alternative solutions, using all available parameters – not only cost – will determine the future of hydrogen as a fuel carrier.

Hydrogen for energy

Energy can be recovered from hydrogen in the form of either heat, electricity or mechanical energy in an internal combustion engine. Any solution is to be considered in a global perspective, including hydrogen production and delivery, in order to provide accurate cost estimates.

Stationary use

Heat

Hydrogen can be used for combustion, pure or mixed with methane up to a concentration of about 20% by volume, allowing the continued use of existing gas infrastructure that is largely amortised. While mixing with hydrocarbon fuels allows a reduction of overall carbon emissions, this path cannot be considered other than temporary as it offers only a rather limited reduction in carbon emissions: carbon capture is much cheaper and decarbonises the entire production. It should be noted that combustion, unless in the absence of nitrogen (oxy-combustion) or at low temperature in the presence of a catalyst, still produces nitrogen oxides.

Considering prices ranging from €1.75 to €4.40/kg (RMB 15 to RMB 37/kg) for carbon-free hydrogen leads to \$52 to \$130/MWh (RMB 380 to RMB 950/MWh) to be compared to the actual costs of \$9 to \$30/MWh (RMB 63 to RMB 235/MWh) for natural gas[83].

83 Based on IEA, The Future of Hydrogen, June 2019: US\$ 3-11 / million Btu.

Power

Electrolysis caused a real frenzy in many European countries, on the assumption that intermittent production in excess (solar or wind) could be used to produce H_2 that can be stored. This hydrogen would later be drawn from storage and converted back to electricity when the demand for power peaks. While costs and efficiency considerations do not support this option as a viable solution for massive power generation on the grid, it still has some appeal for specific situations, isolated sites or backup situations, for example.

The most efficient solution to produce electricity would be gas turbines, in direct cycle or supplemented by a steam turbine (combined cycle). Current turbines, which can achieve up to 60% efficiency in the combined cycle, accept only a small proportion of hydrogen as fuel, and natural gas remains the main fuel. Manufacturers are developing 100% hydrogen gas turbines (Mitsubishi, Siemens, General Electric); most, however, are not planned for release before 2030.

Direct conversion of hydrogen to electricity by means of fuel cells looks very attractive but the efficiency is slightly lower than CCGT and fuel cells have a shorter service life and significantly lower power output than CCGT. Research aims at improving both lifetime and efficiency degradation over the years. The highest hopes lie with high-temperature cells, which can be used reversibly for electrolysis and for converting hydrogen back to electricity.

Gas turbines avoid the need for high-purity H_2 required by fuel cells. Natural hydrogen currently extracted in Mali, 96% pure, can be transformed without problems to electricity via a gas turbine, which will be impossible with the current fuel cells without gas separation.

Cost analysis is not very straightforward due to the need to introduce the yearly operating times, hydrogen being used as backup during peak demand (10%, 20%, 30% of the time?) Assuming decarbonised hydrogen prices ranging from €1.75 to €4.40/kg (RMB 15 to RMB 37/kg) and 55% efficiency for fuel cells and 60% for CCGT, the cost in terms of hydrogen per MWh ranges from €90 to €200/MWh (RMB 635 to RMB 1,600/MWh). Considering $1,000 per installed kW capacity for conversion to electricity, both for CCGT and fuel cells, adds €40 to €80/MWh (RMB 320 to RMB 630/MWh) to obtain the electricity production cost. Reversible cells would, of course, avoid these supplementary costs[84].

Electro fuels

The main hurdle of hydrogen is its very low volumetric energy density: 7 to 10 times lower than hydrocarbon fuels when compressed, and still 4 times lower when liquefied. Combined with

84 Most frequent assumptions for actual costs (see IEA 2019 for example).

other molecules, it can be converted to more conventional fuels while still providing a reduction in overall carbon emission.

Methane is an obvious example: by combining hydrogen with captured carbon from power plants or other carbon-intensive industries, cleaner gas may be produced. But *in fine*, the carbon initially captured will be released in the atmosphere: it would, however, have been "used" twice, which can be considered as an improvement.

Other hydrocarbon fuels than methane can be synthesized, and great hopes are placed in the bio-production of these molecules. Especially engineered algae or other bio-organisms are actively researched.

Ammoniac and formic acid are also investigated for their well-known means of production or because of research-mature new pathways. While not as efficient for energy production – requiring a conversion back to hydrogen or new engines under development – their logistic is much easier than those for hydrogen.

Methanol can appear as a convenient alternative e-fuel, easy to synthesize and easy to substitute for conventional fuels in vehicles and in supply chains. Hydrogen is introduced in the gasification process to improve its yield and lower carbon emissions during production. However, the resulting fuel is very carbon-intensive. Moreover, the energy density of methanol is half the energy density of regular gas fuels, which means bigger gas tanks and bigger engines for the same vehicle range and power.

According to IEA[85], indicative prices for synthetic methane – the cheapest of all electro fuels – will come down from $180 to $260/MWh in the near future, to $30 to $35/MWh in the long term. Ammonia is roughly twice cheaper. That is to be compared to actual prices for natural gas, as low as $10/MWh for producing countries.

Hydrogen for mobility

Hydrogen-based electric mobility benefits from greater autonomy and a much shorter recharging time than battery-based electric mobility. The energy density of the hydrogen system (tank, fuel cell and hydrogen) per unit of mass and volume compared to its battery equivalent makes it a good candidate for heavy and long-distance transport (typically over 600 km for personal mobility).

85 IEA, The Future of Hydrogen, June 2019.

In addition, the conversion of hydrogen into electricity does not generate harmful gases (SOx, NOx, etc.) or fine particles, which makes hydrogen mobility also well suited for urban use.

Individual mobility

The cost of the on-board system for mobility, which includes electricity production (hydrogen tank, fuel cell, intermediate storage battery) and the electric propulsion chain, is substantial. Considerable reductions are expected from improved cell performance and a strong series effect.

Beyond that, one can think of long-distance road transport for which batteries are not a viable solution. A few hydrogen distribution points on the busiest roads could help decarbonise a sector that contributes significantly to carbon emissions.

Energy prices for mobility are very dependent on the natural resources of the countries, and on their level of taxation. Therefore, they are very difficult to compare. Setting aside infrastructure or equipment[86], individual mobility with internal combustion engines costs around US$ 2 to 5/100 km[87], or US$ 6 to 12 including taxes in most countries. Production costs for electricity (with high levels of carbon emissions in most of the world) usually range from US$ 10 to 60/MWh, with prices for the consumer usually between US$ 100 and a record of US$ 390/MWh in Germany. Mobility with batteries could cost as low as US$ 1 or 1.5/100 km, but for high-end electrical vehicles an average of US$ 2 to 3/100 km in most countries and up to almost US$ 6 in Germany. If it is considered that low-carbon hydrogen production prices will start from US$ 2 to 5/kg before taxes, hydrogen is not far from the price range of the other solutions for mobility. Considering 1 to 1.5 kg of hydrogen for about 100 km with a personal vehicle leads to US$ 2 to $7.5 per 100 km. Systemic concerns (production and distribution of hydrogen) and taxation will be the decisive factors in the development of hydrogen mobility.

Public transportation and heavy mobility

Hydrogen bears its greatest potential where no other solution can be considered as practical: high autonomy, high power, quick refuelling. Utility vehicles, farm vehicles, construction vehicles, public transportation, trucks, trains or other heavy carriers are opportunities of choice for hydrogen. Aircraft applications have also attracted lots of attention, and solutions are still being investigated.

Local fleets of hydrogen taxis, buses or delivery vehicles are already experimented for their ability to be supplied by a few, potentially private, fuelling stations. Long-distance trucks would need a better network of hydrogen supply stations before developing.

86 These are of course critical matters, but beyond the scope of this discussion: it is impossible to compare infrastructure and equipment developed over a hundred years with new technologies yet to fully mature.

87 For an average car requiring 6l/100 km, gasoline prices according to IEA and BP Statistical Review of World Energy.

Local transportation by rail is considered with great interest by many regions in France and Europe, for lines that would not be cost-effective to electrify.

The cost equation is similar to the one for individual mobility, but taxes on fuel for professionals are usually lower. On the other hand, these vehicles frequently belong to fleets or are used on specific routes or areas: refuelling stations are less of a concern, just a small number of stations being required and sometimes able to be coupled with a power station to allow for lowest electricity prices.

Sustainable Aviation Fuel (SAF) based on a chemical combination of hydrogen and CO_2 to form synthetic hydrocarbons will be part of the decarbonisation of air travel and transport, together with biofuels and e-fuel.

System deployment

Even as hydrogen systems face strong difficulties in terms of costs and planning, one can discern domains where hydrogen might prove useful or economically realistic. It is necessary to identify paths enabling the development or preparation of these hydrogen systems, as many attractive applications are expected in the (far) future.

A hurdle for mobility: the distribution of hydrogen

The development of hydrogen mobility requires the distribution of fuel to users. Individual mobility requires a highly meshed network that needs time to be developed. Hydrogen distribution stations require investments significantly in excess of €1 million and must either be supplied – by truck at present, possibly by pipeline in the long-term – or produce their hydrogen on site by electrolysis: they are then about 80% more expensive. Beyond the few existing demonstrators, such installations can only be profitable with large distributed volumes. The development of a network, prior to the sale of vehicles, is hardly conceivable without public support.

Hydrogen as a fuel

Hydrogen is a high value, costly product: as such, using it as a simple combustible to produce heat should be considered as a last resort or temporary solution – to provide markets for an emergent hydrogen economy or ensure a longer life for equipment already installed. Many other ways to produce heat without carbon emission are much cheaper than hydrogen.

On the other hand, electro fuels based on hydrogen, while costly, offer an alternative to fossil fuel where no other solution seems available, and do not require major shifts in energy infrastructure (other than for their production).

On the difficulty of planning

Because of the small number of hydrogen vehicles to be produced in the years to come, hydrogen fuelling stations for the general public would obviously be underused. It is therefore reasonable to expect that hydrogen mobility will initially develop only from a more limited number of distribution points, effectively reserving its use for targeted fleets.

In view of the number of vehicles considered in the near future, it is clear that local markets will not be enough to support equipment and system suppliers, who will need to aim for a global strategy: support policies must be conducted with this vision in mind. An international benchmark is required to apprehend the variety of approaches of different Western and Asian countries, including South Korea, which is particularly ambitious.

China

In its strategy toward carbon neutrality, China sees hydrogen as an essential energy carrier in situations where electricity cannot be used, mainly for transportation.

Synthetic methanol, produced with hydrogen and captured carbon dioxide seems worth being considered as an option for replacing natural gas for heating purposes.

Mobility

Hydrogen

In 2021, more than 9000 fuel-cell vehicles were in operation in China. China plans to increase this number to 50 000 in 2025, and the number of fuel cell vehicles may reach 1 million in the next decade. At the same time, the number of refuelling stations may exceed 5 000 while the cost of hydrogen would decrease from 40 CNY/kg H_2 (5.40 €/kg H_2)[88] to 25 CNY / kg H_2 (3.40 € / kg H_2). The hydrogen currently used for transportation is mainly an industrial by-product: it will be gradually substituted by "green" hydrogen during the next decade.

On-site production of hydrogen at refuelling stations is favoured over centralized production, which entails higher costs for storage and transportation. Domestic on-site production of hydrogen in a refuelling station is in a trial operation in Foshan City, Guangdong Province since July 2021.

88 1 € = 7.43 CNY, 1 CNY = 0.14 €

Hydrogen is produced by a skid-mounted, natural gas reforming unit, with a capacity of up to 500 Nm^3/h H_2, and an electrolyser provides another 50 Nm^3/h H_2. An effort to promote on-site production of hydrogen in China has led to rationalizing the safety distance for refuelling stations through the modification of the technical code (GB 50516 2021 Version) and other regulations.

Electro fuels

Methanol and ammoniac represent the main electro fuels considered by China. Currently, green methanol can be produced at about CNY 6.6 /kg (0.9 €/kg). The costs for electro fuels are relatively high due to high conversion losses, high transportation and distribution costs. However, it is expected to decrease significantly by 2050, due to scale economies, learning effects and reduction of renewable electricity price.

Another disadvantage is the low overall efficiency of electro fuels, compared to BEVs.

Methanol

In March 2019, the eight departments of the Chinese government jointly published "Guiding Opinions on the Application of Methanol Vehicles in Certain Regions". The pilot projects of methanol vehicles in 10 cities in 5 regions has been completed from 2012 to 2018, and the cumulative mileage of 1024 methanol vehicles has reached 184 million kilometres consuming 24,000 tons of methanol fuel.

The Chinese government strongly supports a wide distribution for methanol vehicles. Geely Automobile is at the forefront of the manufacturing of methanol vehicles. It has formed mass production capacity in the passenger car and commercial vehicle fields and plans to produce a lot of methanol vehicle models in the future. Geely Automobile is also piloting the M100 methanol car in Iceland, using renewable methanol from the Icelandic Carbon Recycling International company (CRI).

Ships in China are required to use low-sulfur fuel oil, shore power, and clean energy to reduce pollutants emissions and improve the air quality by the 2015 "Implementation Plan for Marine Emission Control Zones in the Pearl River Delta, Yangtze River Delta, and Bohai Rim (Beijing-Tianjin-Hebei) Waters" from the Ministry of Transport of China. The latest 2018 national standard "limits and measurement methods for exhaust pollutants from marine engines "(GB 15097-2016) further restricts the emissions of marine fuels and opens opportunities for alternative fuels such as methanol.

The China Classification Society (CCS) Wuhan Code Institute is in a leading position for the standardisation of methanol ship fuel. Their "Guidelines for Ships Using Alternative fuels" has been implemented formally on December 2017, providing a standard for the utilisation of alternative fuels including methanol in ships.

In 2020, China produced 85% of its methanol consumption, a little over 80 million tons. More than half was devoted to the production of hydrocarbons (methanol to olefin, MTO) and 15% used as fuels for road vehicles, methanol boilers or marine vessels. Chinese fuel standards define different levels of mixing with hydrocarbon fuels, but the government strongly encourages pure methanol fuels for automobile applications. China vigorously promotes battery electric vehicles and hydrogen fuel cell vehicles, but methanol vehicles are one of the key technologies promoted in China's low-carbon transportation transformation.

In 2016, the first methanol heavy truck called "Remote M100 Methanol heavy truck" was successfully launched into operation by Geely company, and other enterprises (Sinotruk, Shaanxi Automobile Group…) have also carried out R&D and production of heavy mobility.

China has developed its own methanol fuel cell technology, but methanol fuel cell vehicles still need more research. In 2015, Suzhou hydrogen clean power supply technology co. LTD modified a 6 metres commercial electric vehicle into methanol-reforming hydrogen fuel cells "electric – electric" hybrid cars[89]. In 2017, the company integrated its methanol fuel cell system into the T7 light trucks of Dongfeng automobile company.

This strategy is twofold:

- Indirect fuel cells: methanol is a good carrier for hydrogen storage. Methanol and water reforming produce hydrogen, used for power generation with a fuel cell. Waste heat of methanol and water reaction can keep the battery at the best temperature. Hydrogen is produced on board, while it is consumed by the vehicle. Core technologies include methanol reforming hydrogen production technology, hydrogen purification technology, hydrogen fuel cell technology, etc.
- Direct fuel cells: the chemical energy of methanol oxidation reaction is directly converted into electrical energy, avoiding the complex reforming unit. The cell structure is simple, convenient and flexible with high energy conversion efficiency, low emissions and no noise, etc. The core technology includes proton exchange membrane technology, high efficiency catalyst technology, inhibition of methanol penetration, etc.

89 Electric – electric hybrid in the context of fuel cells signifies that there are two electric sources for the electricity supply in the car; an electric rechargeable battery and a fuel cell.

Ammonia

Ammonia is expected to be the main fuel for seafaring shipping. The production of ammonia is therefore expected to be upscaled multifold.

Energy networks

China sees hydrogen as an important way to solve the problem of incorporating renewable energy. In 2021, the National Development and Reform Commission and the National Energy Administration of China issued the "Guiding Opinions on Accelerating the Development of New Energy Storage", and hydrogen energy was listed in the category of "new energy storage". However, the technical pathways and resource potentials of large-scale hydrogen storage are still unclear, which restricts the use of hydrogen in energy networks.

Blending hydrogen with natural gas in existing networks can be a temporary path to provide low-carbon energy while hydrogen-specific infrastructure is developed to deliver pure hydrogen to end-users.

Long-distance transportation of hydrogen by blending it into natural gas grids is being tested as prototypes or as commercial demonstration projects (one in operation by State Power Investment Corporation (SPIC) in Chaoyang City, Liaoning Province. Another is under construction in Zhangjiakou City, Hebei Province). Activity in these areas in China is still very limited. The Jilin Province, which plans to increase the share of natural gas in its energy mix, is looking to improve its gas infrastructure and is therefore especially interested in the blending of hydrogen in its network.

If hydrogen blending were to be pursued, it would require the adoption of international harmonized safety standards and national regulations on the maximum blend of hydrogen in natural gas networks.

France/Europe

The French strategy considers decarbonised hydrogen as an important option for high duty and heavy mobility, when electric batteries cannot provide enough autonomy. "Hydrogen meets the need for high engine power or long-distance autonomy, especially for captive fleets that travel long distances in tight traffic flows: light commercial vehicles, heavy goods vehicles, buses, refuse collection vehicles, regional or inter-regional trains in non-electrified areas[90]."

90 Stratégie nationale pour le développement de l'hydrogène décarboné en France, September 2020.

Utility and collective passenger vehicles represent a major economic sector for France, with a large fleet and an important turnover. Many jobs are involved in the development and industrialization of strategic components (fuel cells, tanks, power electronics) shared by the different types of vehicles.

Photo: Hype

The Hype company Paris exploits a fleet of hydrogen taxis: starting with 5 cars in 2015 and one refuelling station in the centre of Paris, the Hype fleet is expected to reach 700 vehicles in Paris by the end of 2022, with the ambition of 40 000 by 2025 and 100 refuelling stations.

While the hydrogen used by Hype at this stage comes from fossil sources, the main goal is to develop a real-life laboratory for zero-emission mobility in a major city. In the years to come the refuelling service will be opened to partnerships with public services and operators of heavy urban transportation or last kilometre logistics.

Source: Alstom Handout

Germany inaugurated on August 2022 the world's first railway line powered entirely by hydrogen. A fleet of 14 trains provided by the French company Alstom is replacing diesel locomotives on a 100 kilometres line near Hamburg. Up to 4,400 tonnes of CO_2 could be avoided each year, provided that the hydrogen is sourced as an industrial by-product or from zero-carbon electrolysis. Commercial trials began in 2018 with two hydrogen trains, and experimentations have also been conducted in Austria, Netherlands, Sweden, Czech Republic and France. Alstom claims that German, Italian and French regions have already ordered more than 50 hydrogen-powered regional trains, albeit the French models will allow powering either from fuel-cells or by regular overhead line.

Planes or ships relying on hydrogen are considered in a longer perspective and solutions should be experimented during this decade. To produce the first low-carbon plane within 10 years is a clear goal of the France 2030 plan, recently announced. In 2022, Airbus launched its multi-year demonstrator program, intending to develop three ZEROe concepts of aircraft powered by hydrogen combustion through modified gas turbine engines. Liquid hydrogen will be used as fuel for combustion with oxygen.

Photo DDM

To speed up the deployment of hydrogen-powered professional mobility, a strong emphasis is put on the pooling of demand, both in the industrial and mobility sectors, on a territorial scale. The goal is to develop efficient partnerships between local authorities and manufacturers in order to synchronize the emergence of the offer and the development of uses.

Energy networks

As a vector that can be stored for a long duration, hydrogen has the potential to ease the development of renewable energies while improving the stability of the power grid. Conversion back to electricity or injection into natural gas networks is considered. Experiments are planned, or beginning, to assess the potential, both technical and economic, of the different pathways.

The Jupiter 1000 program led by GRTGaz, the main TSO (Transmission System Operator) in France for the transportation of gaz, began in Fos-sur-Mer to assess the potential of power-to- produced from excess renewable electricity. Hydrogen from two 0.5 MW electrolysers, one alkaline and one PEM, is fed to the gas network (operating since 2020 without any impact on the clients). Starting in the summer of 2022, the plant will allow the conversion of hydrogen to methane, using captured CO_2 from a nearby factory. Supported by the European Union and French agencies, local project partners (CNR, McPhy, Leroux & Lotz), and a research centre (CEA), the project intends to


ATEE

inject up to 200 m^3/h of hydrogen or 25 m^3/h of methane into the gas network.

However, in the near and foreseeable future, it can be expected that the necessity to decarbonise hydrogen for industry and to provide new solutions for transportation will take precedence over any such use: the high value of decarbonised hydrogen advocates for use in situations where there is no other solution.

Conclusion

Both China and Europe consider hydrogen as a critical asset to decarbonise transportation. Heavy mobility and fleets stand as priority targets, for public transportation or utility vehicles. Local experiments are underway on both sides to field-test hydrogen vehicles and supply chains, however, still mostly with non-decarbonised hydrogen.

E-fuels raise a strong interest by their potential to accommodate actual systems and logistical chains with minimal transformations and circumvent the problematic low density of hydrogen. China considers that ammonia may become one alternative fuel for seafaring shipping, whereas Europe seems less interested in the subject and much more focused on aviation fuels, including synthetic fuels.

China holds high hopes on synthetic methanol and carries significant efforts towards vehicle and methanol production. However, methanol synthesis still relies on coal gasification, leading to very carbon intensive fuels.

The very high ratio of intermittent renewable power sources planned by some European countries leads to a critical need to develop such technologies. The years to come will shed light on the economic viability of this solution. China also sees the potential of hydrogen in the area of energy storage, but the technological pathways for large-scale hydrogen storage are still unclear, which restricts its promotion.

Chapter 5

Manufacturing technology, industrial players

Issues and context

This chapter aims to analyse the manufacturing of the technology needed and the type of industrial players involved in the industrial and technological value chain of hydrogen in China and in Europe.

The technological value chain is composed of 4 macro components: production, transport / storage, distribution and uses .

The first ecosystem is linked to the production of green hydrogen, the second to its transport and storage and the third to the optimal use of hydrogen, namely in the mobility field, one of the most disruptive fields.

As described in the second chapter, most of the technologies exist but must be improved through incremental and continuous innovation with the aim of producing the components with reliable quality and lower costs through robotized and massive production.

In France the production of decarbonised hydrogen will be mainly through water electrolysis with decarbonised electricity: excess REN, hydro and nuclear. The bottleneck for using PV and onshore wind alone is the low-capacity utilisation (load factor) of electrolysers resulting in too low or even negative return on investment.

Production of carbon-free hydrogen

The bipolar plates for the electrolysers may be produced by stamping, electro-erosion, machining, 3D printing. All the necessary elements already exist. As far as pure performance is concerned, there is no disruptive effect to be expected as the technologies are already close to the thermodynamic optimums. The production process is to be adapted to the size of the electrolyser which is likely to get larger and larger. They will be less and less transportable and erected directly on the final site, either close to the green electricity generation site or close to the users and buyers of hydrogen.

Electrolysers: Characteristics and their role in a decarbonised intermittent electricity system.

Electrolysers and fuel cells can be designed in a modular way:

- each elementary module (or cell) consists of a stack of plates;
- the cells that make up a functional unit are piled up in series to form stacks. The stacks can be connected in series or in parallel depending on the desired application.

To summarize, the three fully mature types of electrolysers are today:

- low-pressure alkaline electrolysers whose technology is close to the chlor-alkali electrolysers used for chlorine production. The hydrogen produced must be compressed. Thyssen is the world leader in this field and has installed hundreds of MW worldwide;
- new generation alkaline electrolysers, 30 bars in output, in France McPhy is selling this type of electrolyser. The power of the stacks is 2 MW maximum, diameter from 1 to 2 m;
- PEM electrolysers, output at 60 bar. The power of the stacks is a maximum of 1 MW; the diameter is of the order of a metre and the length is a few metres.

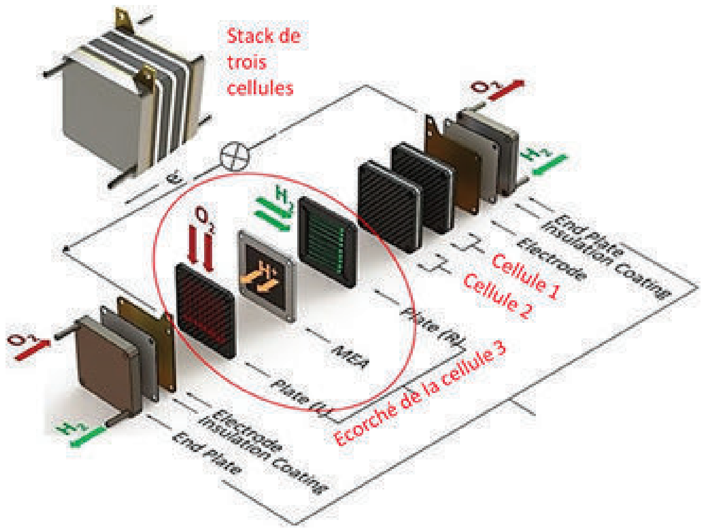


Figure 15: Schematic presentation of a fuel cell stack

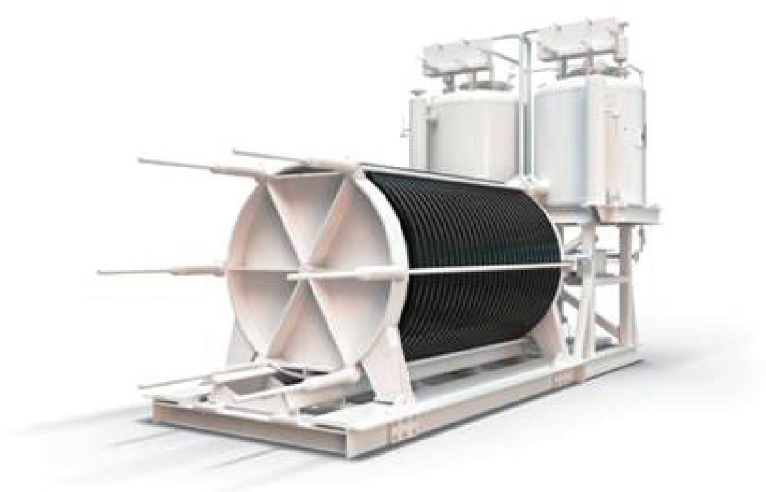


Figure 16: High-pressure electrolyser - 1 MW - © Neel

For the two principles, the power of the stacks is limited by their mass. Beyond a certain limit, they can no longer be transported by road or rail but must be assembled on site, which is a disadvantage. The stacks are assembled in series and/or parallel depending on the desired installation. One of the performance criteria of the stacks is the current density (Faraday's law) measured in g of hydrogen produced per cm^2 of electrode.

PEMs have a higher density than alkaline but a loss by Joule effect. As a result, alkaline electrolysers are more efficient.

To avoid supplementary compression of hydrogen at the outlet of the electrolyser, the pressure within the electrolyser must be increased, but this requires thicker vessels; in addition, the dimensional stability of the cells must be ensured.

In fact, a global techno-economic optimum is sought and proposed by manufacturers.

Beyond the electrolysers presented above, the main elements are storage, transport, distribution and consumption. These elements interact to form a system, the coherence of which depends on the different aspects mentioned above, but also on the flexibility of the electrolysers, i.e. their ability to operate with variable electrical power. This flexibility allows the electrolyser to decrease or increase its power according to the electrical power available as a result of variations in intermittent electrical production and the variability of its consumption.

Other production methods

The production of hydrogen from methane by SMR should be associated with **Carbon Capture and Storage.** Investors and developers in this field have to be encouraged by incentives and by simplification and adaptation of the regulations and laws concerning the use of the subsoil.

Transport

Transport of hydrogen, presently on trucks and through pipelines, will probably be developed by extension of the present hydrogen pipeline grid. There is considerable scope for research and investment by gas system operators to manufacture and operate the extended gas system for transporting hydrogen, taking into account the embrittlement of steel when in contact with concentrations of more than 50% hydrogen, depending on the pipelines and gas mixtures[91]. Various plastic pipes can also suffer embrittlement.

An H_2 grid system includes H_2 storage on the surface and in the subsoil. Investors and developers in this field could be sensitive to simplification and adaptation of the regulations and laws concerning the use of the subsoil.

H_2 can be transported as a liquid in ships but the low temperature makes it technically and economically difficult.

91 https://www.nrel.gov/docs/fy13osti/51995.pdf

It is also possible to transform H_2 into ammonia, methanol or other chemical combinations where established technologies for their transportation in liquid form can be easily used.

Mobility

In the field of mobility, hydrogen is supposed to be mostly used in *fuel cells* to produce electricity for electric mobility (personal vehicles, trucks, buses).

Fuel cells

The fuel cells are made of the "stacks" (plates + membranes) (see pages 46 and 47). The membranes used for the PEMs are based on a fluorosulphonated polymer (PFSA) whose main properties are water tightness and proton conductivity. Nafion, invented by Dupont (now Chemours), has a proven quality and know-how, but there are now several producers of almost "equivalent" polymers. The manufacture of the membrane itself (in particular the deposition of charged inks and catalysts) is currently dominated by W.L. Gore (United States), but many smaller and competent companies are positioning themselves in this promising market.

Manufacturing process

The comprehensive development of the entire system necessary for hydrogen-based mobility implies the breakdown into its constituent elements: the embarked tanks for various pressures and volumes, the fuel cells and their components (membranes, catalysts), the associated power electronics, the controls, the most suitable electric motors, the compressors adapted to the different types of storage, the recharging stations, etc. It will be necessary to create an infrastructure to distribute hydrogen, and public authorities are indispensable to initiate and sustain the mobility market (regulatory, fiscal aspects, etc.).

The value chain

In the value chain of the hydrogen system and for the players that are involved in it, it is of utmost importance to make a distinction between industrial manufacturers of the components (and their subcontractors) which are the true value-added partners on the one hand and, and the integrators in the form of car factories on the other hand. Public incentives should be focused on the generation of added value in order to dynamise the manufacturing chain and not on the integrators or the final buyer. This orientation is required to allow a deep and efficient transformation of the industrial system.

China

In China, the hydrogen value chain is emerging and is rapidly growing. A primary investigation of the industry players is organized in Production, Storage and Transport and End-use.

The production is split into fossil fuel (4 companies), industrial by-product (4 Companies), HTSE (6 companies), purification equipment (3 companies). Storage and transport are split into hydrogen liquefaction (2 companies), gas logistics (3 companies), liquid logistics (3 companies), solid logistics (2 companies). End use is split into Industry (4 companies), Transport (3 companies), Energy storage (3 companies).

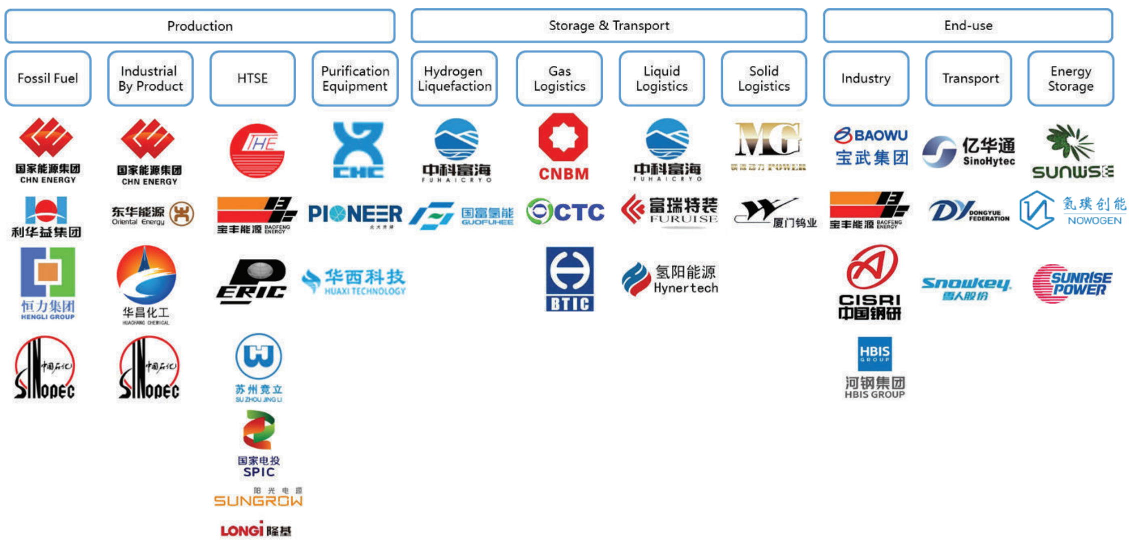


Figure 17: Hydrogen value chain in China

The hydrogen projects are widely distributed on the Chinese territory. The following figure shows the location of:

- the giga-scale production of green hydrogen, above 1 GW, and blue hydrogen (above 200 kilotons per year);
- the large-scale industrial use for refineries, ammonia production, methanol production, Steel production and industry feedstock;
- integrated hydrogen economy, that is cross-industry and projects which integrate different types of end uses;
- transport, trains, ships, trucks, cars, and other mobility applications;.
- infrastructure projects, including hydrogen distribution, transport of hydrogen, conversion and storage.

Figure 18: Hydrogen projects in China

Source:Hydrogen Insights-An updated perspective on hydrogen investment, market development and momentum in China, Hydrogen Council, Mckinsey&Company

The economy of hydrogen is supposed to grow from now on. The value of the demand of hydrogen in China is foreseen to reach 37.15 million tons in 2030 and 130 million tons in 2060. The percentage of hydrogen in end-use energy is foreseen to be 5 % in 2030 and 20 % in 2060[92].

According to a study conducted by IRENA, China presents a large green hydrogen production potential at low levelized cost (US$ 0.65/kgH_2 to 2 US$ 0.78/kgH_2) mainly because of the high-quality solar resources[93]. Another study conducted by PwC also shows that China is among the regions with the lowest production cost of green hydrogen[94]. Based on these studies, China will have sufficient domestic supply of green hydrogen with low cost. However, considering the unbalanced distribution of resources in China, it is still possible that for some regions, it will be cheaper to import hydrogen from international markets than from other parts of China. Nevertheless, China is not likely to be a significant importer of green hydrogen.

92 White paper of hydrogen energy and fuel cell industry in China 2019, China hydrogen energy alliance

93 IRENA (2022), Global hydrogen trade to meet the 1.5°C climate goal: Part III – Green hydrogen cost and potential, International Renewable Energy Agency, Abu Dhabi.

94 https://www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html

A part of the hydrogen is supposed to be produced from fossil methane (SMR) in association with Carbon Capture and Storage. Several demonstration projects are located in Shengli Oilfield or Ordos basin. The technology used for storage is "Enhanced Oil Recovery" EOR.

France

The hydrogen sector today employs nearly 2,000 people in France. The prospects for developing the hydrogen industry in France are estimated at approximately €8.5 billion in annual revenues in 2030 and €40 billion in 2050. Furthermore, a potential €6.5 billion of exports is expected by 2030. More than 40,000 jobs are foreseen in the sector in 2030 and more than 150,000 jobs in 2050, accompanied by a reduction of CO_2 emissions by -10 to -12 Mt CO_2 in 2030 and by -55 Mt in 2050.

The main objective of the National Hydrogen Plan presented on June 1, 2018, is to reduce our country's greenhouse gas emissions, in line with the Climate Plan and European commitments.

In September 2020, in the context of the post-covid economic recovery plan, a national strategy for the development of decarbonised hydrogen in France was presented. It involves a budget of 7 billion euros from now to 2030, with a first 2 billion euros within the recovery plan. It includes the development of a French industry for electrolysis, the development of heavy mobility with decarbonised H_2, and the reinforced R&D for future use of hydrogen.

The decarbonised hydrogen is supposed to be produced by electrolysis of water, using decarbonised electricity. As the French electricity is produced mainly by hydro and nuclear generation, this electricity is decarbonised and allows producing decarbonised hydrogen. This feature makes the position of France for green hydrogen different from most of the other European member states. Among them, certain member states use mainly coal or lignite and fossil gas to produce electricity and decided to stop their nuclear production or to do so soon.

Various **electrolysers** factories are under construction.

GENVIA (created by CEA, Sclumberger, Vinci, Vicat and Agence regionale Occitanie) has an agreement with ArcelorMittal, Ugitec (steel), and Vicat (cement) regarding a proprietary solid oxide technology. GTT (transport and Technigaz) acquired Areva H_2Gen to develop PEM electrolysers. McPhy is developing high-pressure Alkaline electrolysers and has been chosen for the project GreenH_2Atlantic in the framework of the European Call for tender Horizon 2020-Green Deal. Sylfen is developing a reversible electrolyser.

Two companies are developing industrial production of **fuel cells and high-pressure reservoirs**, Symbio and Plastic Omnium:

- Symbio (Faurecia 50%, Michelin 50%) is producing fuel cells for trucks used by final distribution fleets proposed by Renault, Stellantis and for city buses.
- Plastic Omium and Symbio produce 700 bar reservoirs for embarked H_2 storage in cars, trucks and railway train.
- EKPO, a new company owned by Plastic Omium issued from Plastic Omnium and ElringKlinger produce fuel cells.

Advanced research has been coordinated by Geodénergie (Group of Scientific Interest GIS of 10 industrial and 7 public companies) to develop the storage of hydrogen in saline cavities. Several sites are under study and one cavity already existing at a depth between 930 and 970 metres is selected to make experiments, test and water-tightness measurements.

The Hypster project founded by the EC is now developing the first large-scale pilot in Europe with Storengy, Armines, INOVYN (UK), ESK (DE), Element energy, Ineris and Axelera.

Europe

The aim of the EU Hydrogen Strategy is to decarbonise hydrogen production and expand its use in sectors where it can replace fossil fuels.

Yet, today, hydrogen represents a modest fraction of the global and EU energy mix, and is still largely produced from fossil fuels, notably from natural gas or from coal, resulting in the release of 70 to 100 million tons CO_2 annually in the EU.

The EU intends turn clean hydrogen into a viable solution to decarbonise different sectors over time, installing at least 6 GW of renewable hydrogen electrolysers in the EU by 2024 and 40 GW of renewable hydrogen electrolysers by 2030. Investment cycles in the clean energy sector run for about 25 years.

The EU considers that hydrogen may be produced through a variety of processes. These production pathways are associated with a wide range of emissions, depending on the technology and energy source.

Even if everybody agrees that nuclear electricity is GHG emission free, it is a controversial item between the member states, which produce nuclear electricity and the member states, which have decided to not, or no longer, use nuclear electricity. The EU taxonomy is a classification system establishing a list of environmentally sustainable economic activities. Nuclear electricity is included in this list with several constraints. However, it is not confirmed that 'Renewable hydrogen' which is hydrogen produced through the electrolysis of water (in an electrolyser, powered by electricity generated from renewable sources, such as wind power and solar energy), could include nuclear generated electricity.

Several possibilities of carbon storage exist, namely in the North Sea, either as Enhanced Oil Recovery in depleted gas or oil reservoirs, or in deep natural saline aquifers.

Importation of hydrogen produced overseas is envisaged by some countries. The importation supposes a business model where the cost of production is low, and the load factor is high. Various solutions with PV, Windpower and large Hydropower installations are envisaged. The business model should include long-distance hydrogen transportation either by pipelines from North Africa for instance or by shipping of liquefied green ammoniac produced from green hydrogen in Africa, in Australia or South America, for instance.

The EU Commission, which aims to have 40 gigawatts of electrolysis capacity installed by 2030, assumes that, with more production, the cost of electrolyser will halve by 2030 and in 2040 green hydrogen will be competitive.

Germany

Germany has launched the H_2 global green hydrogen initiative: founding members of the initiative include Siemens Energy, Thyssenkrupp, VNG, Deutsche Bank, Salzgitter, Uniper, Hamburger Hafen und Logistik, Neuman & Esser, Reederei F Laeisz, Viridi RE, Enertrag, Nordex, Green Enesys, MAN Energy Solutions, Hydrogenious LOHC and Linde.

The national target of 5 GW electrolysis capacity by 2030 is supposed to be achieved or exceeded but would only account for around 40% of demand.

H_2Global green hydrogen import initiative aims to establish 500 MW of electrolysis capacity outside the EU with Eur900.00 million ($1.10 billion) of funding support.

First cargoes of hydrogen or derivatives such as ammonia are expected from 2024.

Six potential exporters (Saudi Arabia, Canada, Australia, Russia, Ukraine and Chile) are under common approach. New exporters could rise if the market is developing.

Italy

Italy plans to raise up to 1.5 billion euros ($1.79 billion) to build a 1 gigawatt-per-year electrolyser factory as part of plans to become a European green hydrogen hub, internal documents and sources said.

Spain

In Spain, Iberdrola has submitted 53 hydrogen-related projects to the Next Generation EU programme, which would activate investments of €2.5 billion to achieve an annual production of 60,000 t/year. The green hydrogen production capacity under this plan would be equivalent to 20% of the national target (4GW installed capacity by 2030) and would ensure that around 25% of the hydrogen currently consumed by Spain would not generate any CO_2 emissions. In Castil-la-La Mancha, Iberdrola operates 2,376 MW of renewable energy - wind power and photovoltaic.

United Kingdom

In the United Kingdom the Green Hydrogen for Scotland partnership – made up of Iberdrola subsidiary ScottishPower, British gas company BOC, and UK-based energy storage company ITM Power – plans to build a 20 MW hydrogen production (Proton Exchange Membrane PEM) and storage facility at ScottishPower's 539 MW Whitelee wind farm. The Whitelee wind farm is also set to add a 40 MW solar farm and a 50 MW/50 MWh battery storage project.

The existence of this infrastructure is crucial for the H_2 deployment and market. The centralized approach (as the current one for electricity in Europe with an interconnected grid) or decentralized market with H_2 mainly produced and used locally is a political and economic question.

Gas pipelines operators

The **gas pipelines operators** of 21 European member states have agreed to develop the "**European Hydrogen Backbone**" with a potential hydrogen grid of 40 000 km, connected to Russia, Maghreb and Turkey, allowing exchanges between member states and import.

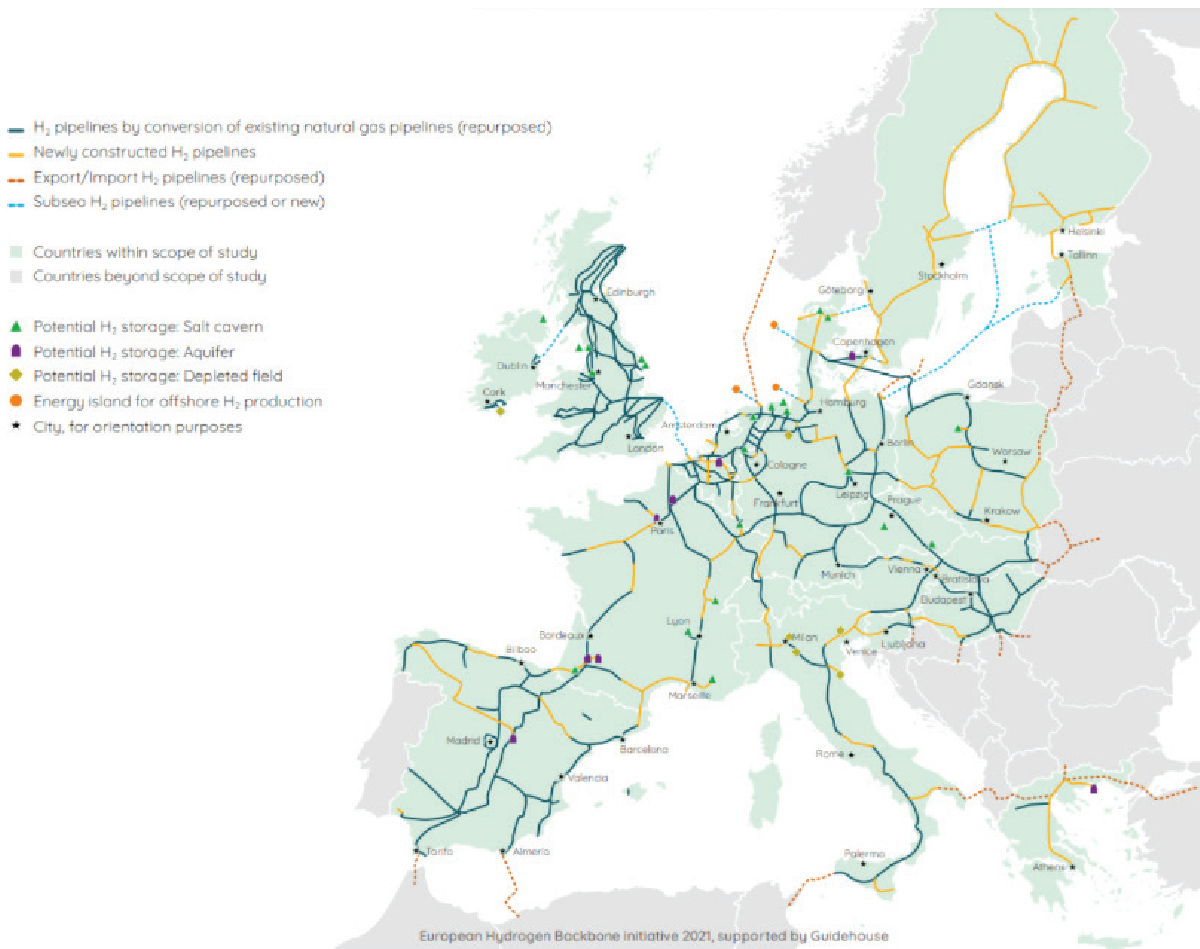


Figure 19: European Hydrogen Backbone Initiative 2021

Conclusion

The capacity to produce hydrogen without CO_2 emission is crucial for the development of the hydrogen-based industry. And the resulting cost is also crucial. The local production will be completed by importation of hydrogen or derivatives from abroad by long-distance pipes or maritime shipping. Transport of hydrogen and derivatives is an industrial and strategic challenge.

The role of hydrogen in the near future is not definitely assessed. However, it is already certain that hydrogen will be used for any type of long-distance heavy transport, such as truck-, train-, and river-transport and maybe sea shipping. Other applications are under analysis. It is clear that the development of electricity in many fields of industrial applications will increase rivalry and emulation between battery-only and battery plus H_2 fuel cells. This central decisional item is the cost of the CO_2-free H_2. In Europe, the present value of the CO_2 in the EU ETS is not yet sufficiently high to bridge the gap between H_2 from fossil methane and green H_2 and to allow industrialists to invest in the field of green H_2 without public support (such as, for exemple, a guaranty of yearly volume. As the price of the CO_2-free H_2 is dependent on the load factor of the electrolysers, the adequate use of a mix of ENR, hydro and nuclear production is probably the most rational choice to reach an affordable price for H_2.

The aim is to increase the power, decrease the cost, keeping the feasibility of alkaline electrolysers. It is also relevant to note that some subcomponents, such as membranes and catalysts, are key. New types of electrolysers have to be developed such as high-temperature solid oxide. As for mobility, fuel cells, tanks, power electronics, H_2 stations are mature and need to be industrialized mostly for heavy-duty vehicles.

Chapter 6

Safety

Properties of hydrogen

As is the case for any energy product (electricity, gasoline, natural gas, lithium...), the use of hydrogen poses safety problems and must be the subject of regulations and good practices. The precautions to take for the use of hydrogen are related to its highly flammable nature and the wide range of relative percentages of air and hydrogen mixes which are potentially explosive. Thus, the use of hydrogen, which is in gaseous form under the usual conditions, may seem similar to that of natural gas, which is widely used, but it is not simple.

Hydrogen is a substance with high energy versus mass density, but low energy versus volume density. For it to ignite or explode, the following conditions must be met simultaneously:

- A concentration of hydrogen in the air between 4% and 75% volume. In **an open environment,** this condition can only be met in a limited volume, due to the great lightness and high diffusion speed of hydrogen, which results in a rapid dilution in the air. However, an accumulation of hydrogen **in a confined environment** can easily reach concentrations in the above range.
- A source (spark, hot spot), the energy of which has to locally exceed the minimum ignition energy of hydrogen (which varies according to the concentration of hydrogen and oxygen and which can be as low as values obtained by electrostatic discharges of human origin) is necessary to start the explosion. Note that hydrogen heats up when it relaxes (reverse Joule-Thomson effect) this increases the risk of explosions.

It is noted that the combustion of hydrogen creates a very hot flame, more than 2 000 °C, but almost invisible in broad daylight. This aspect is obviously to be taken into account in relief operations.

The ignition of a cloud of gas formed during a leak from a pipe or a storage can, in some configurations, give rise to an explosion. This explosion is a sudden release of energy resulting in the propagation of a flame front and an overpressure wave.

Two different explosion regimes are possible:

- Deflagration: in this case, the flame front moves at subsonic speed. Gases ahead of the flame front are compressed by volume expansion (piston effect). This results in a continuous increase in overpressure. For hydrogen in air at stoichiometric conditions (for each hydrogen molecule there is half a molecule of oxygen), the deflagration rate is 2.6 ms^{-1}. In the presence of oxygen, the speed can increase up to 11-12 ms^{-1}, a value that can further increase depending on the confinement (example explosion in a tube).
- Detonation: the speed of the flame front is supersonic, the hydrogen-oxidizer mixture is compressed under quasi-adiabatic conditions, resulting in the formation of a shock wave. The detonation range of hydrogen varies depending on the geometry of the confinement, the ignition energy and the ratio of the mixture. The literature mentions examples of detonations occurring with hydrogen concentrations of 11% or less.

But hydrogen also has very favourable characteristics in terms of safety:

- its flame does not radiate much heat, which, in the event of a fire, greatly limits the risk of propagation by thermal radiation;
- the flame is not toxic (no danger in case of contact, inhalation…)

China

Based on the Medium and Long-term Plan for the Development of a Hydrogen Energy Industry (2021-2035) in China, it is proposed that by 2025, the number of fuel cell vehicles in China will be around 50,000 and more hydrogen refuelling stations will be deployed. With the large-scale deployment of hydrogen fuel cell vehicles and hydrogen refuelling stations, the safety of hydrogen in the public domain should be taken very seriously.

Regulation

Hydrogen is flammable and explosive and is classified as a hazardous chemical along with gasoline and natural gas in China and is subject to strict regulations regarding the location and capacity of hydrogen production, as well as its storage, transport and utilisation. Unlike gasoline and natural gas, hydrogen is not included in the current energy laws and regulations, and its use is more restricted. In the draft energy law of China issued in 2020, hydrogen was categorized as another new energy source. Although the importance and potential of hydrogen are not fully reflected, the inclusion of hydrogen energy in the draft may promote the development of relevant industries. It is also expected that hydrogen as an energy source will be regulated in a mode similar to natural gas and gasoline.

Currently, there are no dedicated administrative departments in charge of the use of hydrogen energy. The safety of hydrogen is currently subject to regulation by the Ministry of Emergency Management of China, which is in charge of the general safety issues related to the production, storage, transportation and utilisation of hydrogen.

In general, although there are many regulations in the hydrogen value chain, the laws and regulations are still deficient in China. However, both the central government and local provinces and cities are developing strategic plans to promote the hydrogen industry. In many Chinese provinces and cities, the development of certification of hydrogen testing and refuelling stations is given high priority[95].

Current Practices

Currently, the approval of hydrogen refuelling station construction in China is very cautious due to safety considerations. With hydrogen being included in energy statistics by the National Bureau of Statistics and encouraged by the National Energy Administration in China, hydrogen is expected to be included in the energy management system, and the number of hydrogen refuelling stations will rapidly increase. For the construction and operation of hydrogen refuelling stations, operational safety is the top priority for their management.

For the operation of refuelling stations in Dalian, a *Gas Cylinder Filling Permit* is required, and all the operators need to obtain the s*pecial equipment safety management and operator certificate*.

95 Jianfu, W. (Feasibility Study of Large scale Development of Hydrogen Energy Industry in China from the Perspective of Safety Laws and Regulations in Li, Y. H. Phoumin, and S. Kimura (eds.) eds.), Hydrogen Sourced from Renewables and Clean Energy: A Feasibility Study of Achieving Large scale Demonstration ERIA Research Project Report FY2021 No. 1 9 , Jakarta: ERIA, pp.1 53 2 10

Prior to issuing permits, the Dalian Market Supervision Bureau also contracted Dalian Boiler and Pressure Vessel Inspection and Testing Research Institute Co, Ltd. - a national comprehensive cylinder quality inspection and supervision centre - to examine the operation of hydrogen refuelling stations in order to ensure that they comply with the "Special Equipment Production and Filling Unit Licensing Rules" (TSG 07-2019) and the "Hydrogen Refuelling Station Safety Technical Specifications" (GB/T 34584-2017), as well as other requirements. The hydrogen refuelling station's regional management, certification, operations, and 24-hour safety monitoring system covering the entire station are reviewed comprehensively. It is also ensured that the "emergency cut-off" system is set up in multiple areas such as tanks to ensure the safety of filling during the operation of the equipment. An additional "Special Equipment Appraisal and Review Work Memorandum" is also required to record and supervise the rectification of the issues during the operation.

The approval of hydrogen refuelling stations has been carried out with remarkable achievements in many cities:

In 2018, the first local management document for hydrogen refuelling stations, *Interim Provisions for the Approval and Management of Hydrogen Refuelling Stations*, was issued in Wuhan. For hydrogen safety issues, the document requires hydrogen refuelling stations to refer to urban gas projects. A qualified safety evaluation agency shall be entrusted to prepare the safety pre-evaluation before project construction.

In 2018, China's first *Interim Measures for the Administration of Hydrogen Refuelling Stations* was issued in Foshan. It proposes regulations on administrative approval, safety systems, and safety management.

In 2020, Zhangjiakou issued the *Safety Supervision and Management Approach for the Hydrogen Energy Industry*, which is China's first approach for the safe supervision and management of the entire hydrogen industry chain. It includes the company's own safety management, the key points for safety operation, and the management responsibilities of various regulatory departments.

Hydrogen fuel cell buses are vehicles equipped with high-voltage electrical devices while at the same time using hydrogen as fuel, where the risk of fire caused by sparks does exist. Therefore, it is a great challenge to ensure the safety of hydrogen fuel cell vehicles. Currently, the safety of fuel cell vehicles is mainly ensured by the design of the vehicle, where experience in the design of battery electrical vehicles can be used, such as the inspection of the vehicle, as well as the design to ensure safety in case of collision. Additional safety designs specifically for the use of hydrogen are also required. For example, vehicles should be equipped with hydrogen leak detection, pressure sensors, alarm and emergency cut-off systems. For hydrogen fuel cell buses, the high-pressure hydrogen cylinders are located at the top of the bus, so that the hydrogen system will not be harmed in case of a collision. Furthermore, as the density of hydrogen is lower than air, hydrogen can be vented in case of a leakage.

In order to ensure its safety, inspections of the hydrogen storage cylinder are required on a regular basis during the operation of fuel-cells vehicles. However, there is no unified training system specifically for the fuel cell bus drivers regarding safety issues, although the manufacturers of the fuel cell vehicles may provide some training for the drivers.

To ensure the safety of fuel cell vehicles under various scenarios, inspection and hydrogen testing organizations are essential. Currently, China has implemented several hydrogen testing centres, which indicates a major step in the development of hydrogen:

Construction of the first national hydrogen testing organization in China, the National Hydrogen Power Quality Supervision and Inspection Center, was started in 2020 by China Automotive Engineering Research Institute Co. Ltd. The centre focuses on the inspection and testing of fuel cell stacks, fuel cell systems and key components, hydrogen storage systems, hydrogen power systems, etc.

The Great Wall Hydrogen Testing Technology Center was established in 2018 by the Great Wall Motor Co. Ltd. which focuses on hydrogen storage safety testing, fuel cell testing, system performance testing, vehicle performance testing, and life cycle testing.

The first 95 MPa level high-pressure hydrogen equipment test platform was built in Beijing, China, which is equipped with fire, fatigue, leakage and reliability performance assessment tests applied to various hydrogen storage vessels, valves and other components in the presence of hydrogen.

Standardisation

Hydrogen safety standards are important for safe use in the industry, and they are mainly governed by the Standardisation Administration of China (SAC). Within the SAC, there are four committees related to the development of national hydrogen standards, namely the National Standardisation Technical Committee of Hydrogen Energy (SAC/TC 309), Fuel Cell and Flow Battery (SAC/TC 342), Road Vehicles (SAC/TC114) and High-Pressure Gas Tanks (SAC/TC 31).[96] Currently, China has more than 100 hydrogen national standards, and about 30 of them are

96 Yang, Yanmei, et al. "Development of Standards for Hydrogen Safety." E3S Web of Conferences. Vol. 194. EDP Sciences, 2020.

related to hydrogen safety. In addition to that, there are also local and group standards in the hydrogen safety area. All these standards contribute to a safety standard framework for hydrogen safety in China. Regarding the development of the hydrogen industry in China, the preparation of hydrogen safety standards is essential to keep in pace with the development of technologies.

Among these standards, the GB 4962-2008, technical safety regulation for gaseous hydrogen use, is a mandatory standard and provides the safety requirements for the use, replacement, storage, compression, fuelling, discharge, fire control, emergency treatment, and safety protection of gaseous hydrogen. For hydrogen refuelling stations, the GB 50516-2010, technical code for hydrogen fuelling stations, is China's mandatory national standard for the design and construction of new, renovated and expanded hydrogen refuelling stations. This standard makes general requirements for sites selection and general layout of hydrogen refuelling stations, and makes technical and safety requirements for various system equipments and facilities such as hydrogen refuelling facilities, fire safety facilities, electrical installations, building facilities, water supply and drainage, heating and ventilation, etc. Finally, construction, installation, acceptance and operation management is stipulated. For hydrogen fuel cell vehicles, GB/T 24549-2009, fuel cell electric vehicles – safety requirements, provides the safety requirements of fuel systems, power circuit systems, functions, fault protection and collision of fuel cell electric vehicles using gaseous hydrogen.

France

Good practices, standardisation and regulations for refuelling hydrogen stations

Good Practices

Ademe, in collaboration with Ineris and members of Afhypac, has published two documents[97] regarding good practices on the safety of distributed generation facilities and hydrogen refuelling stations.

Conception

The practices developed for risk management aim first and foremost to avoid as far as possible any risk of hydrogen leakage.

97 Guide d'information sur les risques et les mesures de sécurité liés à la production décentralisée d'hydrogène https://www.ademe.fr/guide-dinformation-risques-mesures-securite-lies-a-production-decentralisee-dhydrogene et Guide d'information sur la sécurité des véhicules à hydrogène et des stations-service de distribution d'hydrogène https://www.ademe.fr/sites/default/files/assets/documents/guide-securite-h2-vehicules-station-service-8506.pdf

The appropriate design level of the components of a hydrogen installation, such as a high-pressure storage tank, is validated and certified by extremely severe testing during qualification tests. The nature and level of stresses to which the system is subjected during these tests far exceed what it will have to withstand during its operational life. For example, for a gaseous hydrogen storage tank, at a working pressure (WP) of 700 bar, the test pressure is 1,050 bar (1.5 x WP) and the burst pressure is 2,100 bar (3 x WP).

In the event that a hydrogen leak should nevertheless occur within the installation, means of minimising the consequences are provided for: detection, supply interruptions (hydrogen, electricity, etc.), ventilation, etc.

- the immediate and systematic detection by hydrogen sensors of an abnormal hydrogen content is put in place;
- system components that may be exposed to a release or leakage of hydrogen shall be completely isolated from ignition sources.

Ventilation is the central element of the safety device. It is the best way to rapidly dilute hydrogen in the ambient atmosphere and reduce the possibility of the formation of flammable or explosive clouds. Today, access to tunnels and car parks is allowed for hydrogen vehicles. However, preparations for standardisation are underway at European level[98].

Adequate and specific safety for the use of hydrogen must be systematically integrated into the design of components and systems, in the same way as for the use of natural gas or petrol (also valid for regulations applying to service/filling stations and for vehicle design).

Use

Like any energy system, a system using hydrogen must receive special attention during its operational life cycle: operation, maintenance, servicing, repair, rest, storage, etc.

As a result, manufacturers have made every effort to establish good practices and to translate them into documents for users. It is thus necessary to follow the precautions for use/storage/ transportation/preventive maintenance... issued by the manufacturers and, if necessary, to ensure adequate labeling.

The companies in charge of servicing or maintaining these systems receive dedicated training and they use appropriate equipment that enables them to intervene safely.

98 PNR for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces 03/19 - 02/22 - https://trimis.ec.europa.eu/project/pnr-safety-hydrogen-driven-vehicles-and-transport-through-tunnels-and-similar-confined

Discussions are continuing between Afhypac experts and the administrations concerned in order to address the issue of the presence of hydrogen vehicles in underground car parks (currently the parking of hydrogen vehicles in underground car parks is not prohibited: the Civil Security simply recommends avoiding doing so) and in tunnels (CETU). In France, there are no regulations on the circulation of hydrogen vehicles in tunnels, but their use does not anticipate any particular difficulty[99].

Standardisation

Without having the force of law, standardisation is an incentive to use the best manufacturing and control techniques. It defines solutions, levels of quality and standardisation that make it easy to comply with regulations.

In France, standardisation is under the authority of AFNOR.

The service station standards are the European and national versions of international ISO norms. They are prescribed to implement the 2014 European directive on alternative fuel supply infrastructures, which encourages the deployment of hydrogen filling stations along the road networks of the European Union, in particular, to guarantee the safety and interoperability of equipment. There are three founding voluntary norms. The first, NF EN 17127 (ISO 198801:2020(en)) applies to filling stations dispensing gaseous hydrogen. The second, NF EN 17124 (ISO 14687-2), specifies the quality characteristics of commercially available hydrogen and the corresponding quality assurance to ensure product consistency for use in fuel cell-equipped road vehicles. The third, NF EN ISO 17268, covers connection devices for the refuelling of land vehicles with gaseous hydrogen to define the design, safety and operating characteristics. All three were published in the Afnor collection between January 2017 and November 2018.

Regulation

To ensure good practice in the design and use of a hydrogen installation or system, it is necessary to have appropriate regulations and to establish a platform for standardisation.

The current regulations apply to centralised hydrogen production facilities in the chemical industry.

A specific regulation for hydrogen used as an energy carrier is being put in place at national and/or European level. For the French case, a presentation in June 2017 provides an update on French regulations (Hydrogen Days in the Territories).[100]

99 Hydrogen Fuel Cell Electric Vehicle Tunnel Safety Study – Sandia Laboratories – 2017

100 http://www.aphypac.org/documents/publications/colloques/Point_r %C3 %A9glementation_JH2Nantes_cor.pdf

A ministerial order101 n°0246 regulates the design and operation of gaseous hydrogen distribution stations in order to guarantee total safety for the user. It limits the distribution pressure to 700 bar and the flow rate to 120 g/s[102], which means that cars can be recharged in less than a minute, since a light vehicle consumes just over one kilogram of hydrogen per 100 kilometres. It prescribes minimum distances from other equipment (5 metres from electric vehicle charging stations and from charging stations for other fuels).

Good practice, standardisation and regulation for hydrogen vehicles

Good Practices

Ademe, in collaboration with Ineris and Afhypac members, has published a document[103] of best practices on the safety of hydrogen vehicles.

Conception

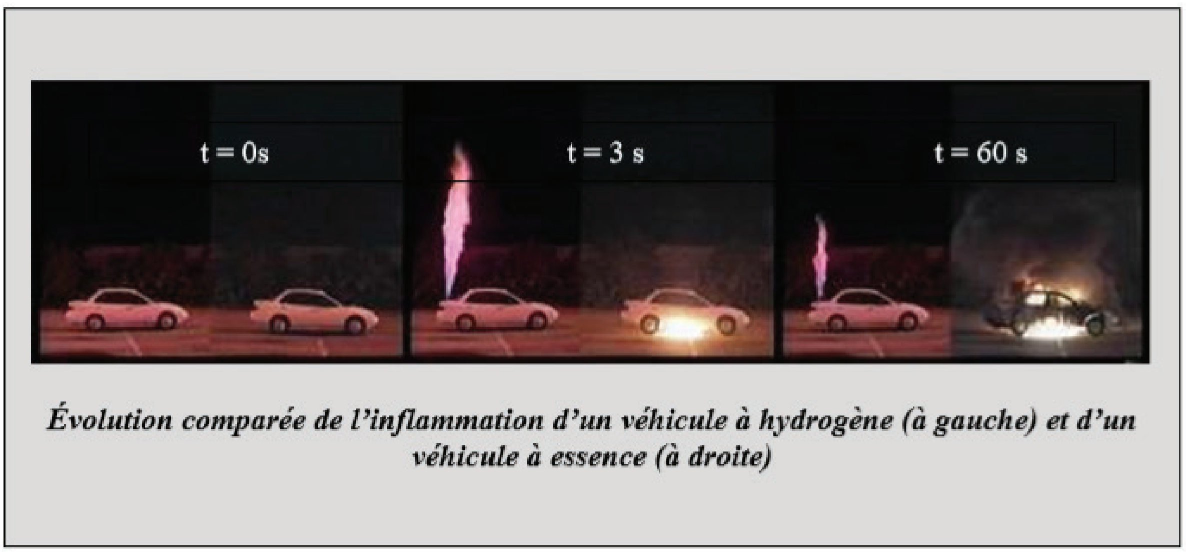


Figure 20 — The flame due to a hydrogen leakage is strictly vertical and does not radiate much[104]

Source: M. Swain, Fuel Leak Simulation, Miami: Proceedings of the 2001 DOE Hydrogen Program Review NREL/CP- 570-30535, 2001

The manufacturer shall ensure in particular that the hydrogen components and system:

- operate correctly and safely and reliably withstand electrical, mechanical, thermal and chemical operating conditions without leakage or visible deformation during their expected service life;

101 https://www.legifrance.gouv.fr/eli/arrete/2018/10/22/TREP1816561A/jo/texte

102 The Ministerial Order sets the normative framework that limits the flow rate to 60 g/s for fillings at 700 bar; 120 g/s is reserved for trucks/buses at 350 bar.

103 Guide d'information sur la sécurité des véhicules à hydrogène et des stations-service de distribution d'hydrogène https://www.ademe.fr/sites/default/files/assets/documents/guide-securite-h2-vehicules-station-service-8506.pdf

104 https ://www.youtube.com/watch ?v=W3QNNF4ptl4 .

- are protected against overpressure;
- use hydrogen-compatible materials if they are to come into contact with hydrogen;
- resist to a range of temperature fixed by regulation[105].

Standardisation

Numerous international norms are applicable to hydrogen vehicles, including the ISO 23828:2013 norm on measuring the energy consumption of hydrogen vehicles; the current NF EN ISO 17268 norm on connecting devices for the refuelling of land vehicles with gaseous hydrogen; the ISO 19881:2018 norm on on-board tanks.

Regulation

Hydrogen-powered cars have been certified in France since December 2011.

New models of hydrogen vehicles undergo severe tests before they are put on the market (crash tests) https ://www.youtube.com/watch ?v=W3QNNF4ptl4 .

In addition to conventional certification rules for internal combustion vehicles and rules related to the electrification of the propulsion system, fuel cell vehicles are subject to specific European regulations, including EC Regulation 79/2009 and its implementing Commission document 406/2010 applicable to the approval of hydrogen vehicles[106].

These two regulations require, notably, proof of the operating safety of the hydrogen system as well as a "type approval" for the most sensitive (where the pressure of gaseous hydrogen is greater than 3 MPa) components (or technical entities), guaranteeing their safety by means of test cycles.

Thus, in addition to the containers with their mountings, regulators, valves or solenoid valves, pressure-, hydrogen temperature- and flow sensors of the high-pressure part, hydrogen hoses; the entire filling line, pressure relief valves, sensors, detection probes and hydrogen leakage detectors are subjected by regulation to a set of tests for pressure cycles, tightness, wear and tear and corrosion resistance.

105 Mesures d'exécution du réglement EC n°79/2009

106 The regulations will be replaced on 2022/01/05 by: REGULATION (EU) 2019/2144 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 27 November 2019 on type-approval requirements for motor vehicles and their trailers, and systems, components and separate technical units intended for such vehicles, as regards their general safety and the protection of vehicle occupants and vulnerable road users, amending Regulation (EU) 2018/858 of the European Parliament and of the Council and repealing Regulations (EC) No 78/2009, (EC) No 79/2009 … https://eur-lex.europa.eu/legal-content/fr/TXT/?uri=CELEX:32019R2144

In the event of an accident: intervention and rescue services

In parallel with the development of safety regulations governing the use of hydrogen, appropriate procedures for intervention by emergency services have been established.

Training courses for firefighters are already in place, based on practical knowledge of these uses. In particular, the National Superior School for Fire Fighting Officers (ENSOSP) based in Aix-en-Provence provides training for intervention on hydrogen fires for emergency services worldwide.

These training courses were developed as part of the European HyResponse programme involving seven French (the consortium leader ENSOSP, Air Liquide, AREVA SE), English and Italian partners. The aim of this project, which ran from June 2013 to September 2016, was to develop a real training platform dedicated to hydrogen risk for first interveners, the firefighters. Financed within the framework of the FCH JU, simulation workshops or simulation exercises in virtual reality enabled the validation of a good practice guide and the definition of a training offer in this field.

It should be noted that the fire brigades of the Manche region are equipped with hydrogen-powered vehicles for their daily interventions.

Figure 21 a — Hydrogen powered vehicle for the French Manche department

source : https://www.automobile-entreprise.com/Les-pompiers-de-la-Manche-roulent,4593

Training in intervention on hydrogen fires at the Ecole nationale supérieure for Fire Brigade Officers (ENSOSP - Aix-en-Provence)

Figure 21 b —Hydrogen vehicle and Intervention on hydrogen fire

Summary and Recommendation

Hydrogen has been used industrially for many years with a very satisfactory level of safety despite its potential risks of ignition and explosion.

Existing standards and regulations will have to be adapted to the increasing number of uses, particularly by the general public, and to take account of feedback from experience, it being recognised that the technologies to prevent and limit risks are available. Pre-normative, normative and regulatory efforts should therefore be continued at the European level, in particular for the safety of consumer or semi-consumer applications. In pursuing current practices, regulatory work must involve the administration and all stakeholders (fire brigades, technical centres, equipment manufacturers, operators, users, etc.).

Under this condition, safety issues are not prohibitive for the development of hydrogen.

Conclusion

Safety issues are essential for public or semi-public utilisation such as mobility.

Therefore, it is a priority to achieve international standards and regulations.

Chapter 7

With net zero carbon emission policy, a roadmap for hydrogen; benchmark France, Europe and China

Issues and context

Issues

This chapter aims to quantify the main uses of hydrogen at the 2030 and 2050 horizons , as well as the production methods that will be implemented. This chapter will provide approximate data for the two main ways to produce carbon-free hydrogen: 1) electrolysis and 2) the traditional way + CCS.

The provided information includes estimates on the electrical power and energy required for the production by electrolysis, and on the geological storage needs of CO_2 (CCS) according to the production methods envisaged for hydrogen.

Context

Roadmap benchmark

Europe and China have decided a carbon zero emission net policy, 2050 for Europe and 2060 for China; hydrogen will play a role in these policies.

Like other advanced areas in the world, Europe and China develop a hydrogen roadmap.

Benchmark trajectory for decarbonised hydrogen:		
	2030	2050
France	0.7 Mt H_2/year	4-6 Mt H_2/year
Europe(EU+UK)	10 Mt H_2/year	65 Mt H_2/year
China	~5.6 Mt H_2/year	~74.6 Mt H_2/year
China Hydrogen Energy and Fuel Cell Industry Development Report (2020) China Hydrogen Alliance, People's daily press		

Technologies

There are two main mature technologies to massively produce decarbonised hydrogen:

- CCUS (carbon capture utilisation storage) for hydrogen produced by fossil energy
- Electrolysis of water by decarbonised electricity, hydro, nuclear and intermittent renewable energies.

Infrastructure investment

The above trajectories will need huge infrastructure investments; for example, the French objective of 4-6 Mt/year hydrogen in 2050, if totally produced by electricity would mean more than 300 TWh/year, i.e. approximately 60% of the total annual present French electricity demand.

Alternative H_2 generation methods

Considering the huge amount of electricity needed, methane reforming and coal gasification with CCUS should also be developed.

Experience with CCS is expanding; several industrial projects are under development, for example:

In Europe, in the North Sea, Northern Lights project with 3 to 5 Mt/Year CO_2 storage by 2030, developed by Equinor, TotalEnergies and Shell, or Net Zero Teesside project 08 to 6 Mt/Year CO_2 storage.

Emerging technologies such as methane pyrolysis technology could also reduce electricity demand and would require less than half of the energy needed for electrolysis.

The strategy

The EU hydrogen strategy describes a three-step approach to establishing renewable hydrogen at the heart of the hydrogen economy.

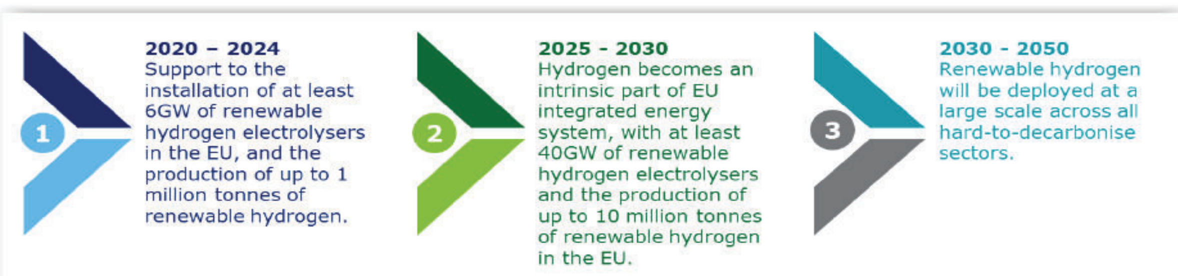


Figure 22 Three-step approach of the EU hydrogen strategy

Source: Hydrogen for Europe study

Some EU Member States as well as Norway and the UK have already established national H_2 strategies translating into firm roadmaps and industry. However, many uncertainties and hurdles persist. In particular, the financial risks for massive investments are still hovering over many projects, retarding innovative technology development and deployment that could lead to substantive cost reduction for H_2 production. The question of benefits from green or low carbon hydrogen is still open as the price of CO_2 emission permits in order to reach the 2050 target of net-zero emissions is still too low and focused incentive schemes are still missing. However, the EU Hydrogen Strategy has a strong link to the European Clean Hydrogen Alliance, counting already more than 1 400 members[107], with the key aim of identifying and building up a clear pipeline of viable investment projects by bringing together public and private stakeholders.

In September 2020, **France** announced a new hydrogen strategy (following the first plan in 2018) with a 7 billion € of investment until 2030 to accelerate.

Three priorities:

- decarbonise the industry and create a new industrial sector for electrolysis.
  The industries to decarbonise are refineries mainly to desulfurize fuels, chemical industries like ammonia and methanol, metallurgy and some specific sectors such as electronics, agri-food.

  One of the goals is to install 6.5 GW of electrolysers. This new industrial sector is emerging at a European scale (see above) not only on electrolysers but on other components (Fuel Cells, tanks...)

- The second priority is to develop a heavy-duty mobility, taking advantage of the autonomy and the reduced time to fill up the tank. (Heavy mobility is composed of regional trains, long distance trucks, boats, fleets of vehicles to avoid 6 Mt of CO_2 in 2030)
- The third priority is about developing research and innovation all along the hydrogen chain.

These priorities have been implemented in France in harmony with the European strategy such as the clean hydrogen alliance able to finance new projects.

Regarding the transport and use of hydrogen, several avenues are possible: blending hydrogen with natural gas in existing pipelines or developing a new hydrogen transfer and service station network. For the latter to be realized, very little is known regarding the optimization of such networks. Policymakers are now in the bind to facilitate the transition towards a hydrogen economy in selected sectors of the economy with appropriate regulations.

107 Including companies such as Linde, Air Liquide, Air Products, Airbus, Siemens, Bosch, BMW, Renault, Veolia, Thyssenkrupp, EDF (Electricité de France), Danfoss, just to name a few (https://ec.europa.eu/docsroom/documents/42749/attachments/1/translations/en/renditions/native)

At the same time, achieving climate neutrality by 2050 necessitates a substantial acceleration of decarbonisation measures in the **EU energy system**. The production of green hydrogen requires renewable energy resources. This may include biogas, but the available quantities will remain modest. While costs in crucial power technologies such as wind and solar are steadily decreasing as new wind- and solar farms are installed, it remains difficult to foresee the evolution of renewable electricity prices even in the short term, which depend on market mechanisms, not to mention the longer term.

In the future, hydrogen might also be obtained by combining Steam methane reforming (SMR) with Carbon capture and storage (CCS), but this does not figure as a major path in the EU strategy. Another potential avenue is pyrolysis of methane to hydrogen and carbon black, which does not directly produce CO_2 emissions.

In 2019, within the EU, the currently functioning 300 electrolyser operations produced less than 4% of total hydrogen production.

The European Commission has announced the following capacities needed for hydrogen production: Installation of 6 GW electrolyser capacity based on renewable electricity to produce 1Mt of hydrogen by 2024 and installation of 40 GW electrolyser capacity with the same characteristics to produce 10 Mt of hydrogen by 2030. In a third phase, from 2030 onwards and towards 2050, renewable hydrogen technologies should reach maturity and be deployed at a large scale to reach all hard to decarbonise sectors where other alternatives might not be feasible or have higher costs[108]. Statkraft states that green hydrogen will account for 20% of European power demand by 2050[109].

Furthermore:

- a new study by the European hydrogen backbone initiative estimates 2,300 TWh of hydrogen demand in EU+UK by 2050 corresponding to 20-25% of future EU and UK energy demand;[110]
- according to this study, sufficient potential exists to produce this quantity as green and blue hydrogen within the EU and UK (subject to public acceptance of an accelerated expansion of renewable installed capacity even beyond currently planned expansion). However, an alternative — deviating from the framework of the French National Low-Carbon Strategy (SNBC) — could be to resort to hydrogen imports from other countries, which could be more competitive.

108 A hydrogen strategy for a climate-neutral Europe, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

109 https://www.reuters.com/business/energy/green-hydrogen-account-20-european-power-demand-by-2050-statkraft-2021-10-21/

110 https://hydrogen-central.com/2021-european-hydrogen-backbone-demand-supply-transport-hydrogen/

Indeed, some of the northern EU states are seriously looking at hydrogen imports. Germany, Belgium and the Netherlands are seriously considering substantial hydrogen imports from countries such as Australia, Chile, Northern Africa. Others like France, Hungary and Poland are dubious[111], saying Europe should, first of all, strive to develop its own industrial hydrogen production capacity.

The opponents of large-scale H_2 importation are Europe's electricity giants, who have urged the European Commission to impose a carbon tariff on hydrogen imports[112] so as to avoid fossil-based, and thus manifestly charged with CO_2 emissions, hydrogen imports penetrating the EU market.

Pipeline transport is more cost-effective than seaborne transport and power lines. Networks of hydrogen pipelines are already in operation in France, Belgium, the Netherlands and Germany to transport excess hydrogen from one chemical plant via the natural gas grid to another chemical plant where it is used as feedstock.

In China, in the long term, the proportion of China's green hydrogen is expected to increase dramatically. Hydrogen demand in China will reach 96.90 million tons in 2050,[113]of which the proportion of green hydrogen will increase to 70%,[114] benefiting from the reduction of renewable energy costs and carbon emission restriction. Assuming that by 2050 unit electricity consumption by green hydrogen production through electrolysis in China is declining and reach to 4 kWh/ Nm^3 H_2, electricity demand for green hydrogen production by electrolysis will reach about 2,540 TWh, which will account for about 17% of the domestic power generation at that time. It is predicted that under the scenario of high renewable energy ratio in China in 2050 (renewable energy power generation accounted for 85%, the total power generation will be 15,200 TWh).[115]

In the short term, the use of industrial by-product hydrogen is given a higher priority in China for places where such resources are available. It is also encouraged to demonstrate the production of hydrogen from renewable energy in places which are rich in wind, solar, hydropower, and other renewable energy resources.

111 https://www.euractiv.com/section/energy-environment/news/eu-countries-clash-over-scale-of-future-hydrogen-imports/

112 https://www.euractiv.com/section/energy/news/electricity-giants-call-for-carbon-tariff-on-eu-hydrogen-imports/

113 China 2050: A zero-carbon vision of a fully modernised country, Energy transitions commission & Rocky Mountain Institute - https://www.rmi-china.com/index.php/news?catid=18

114 China hydrogen energy and fuel cells Industry development Report (2020), China Hydrogen Alliance, People's daily press

115 China 2050 high renewable energy penetration scenario and roadmap study, Energy research institution of national development and reform commission

In the long run, renewable electricity prices in China will decline gradually and electrolysis technology will be more and more mature. Therefore, the cost of green hydrogen in China will decline dramatically and its competitiveness will increase substantially at the same time.

Priority of hydrogen use based on cost of CO_2 avoided

The various uses of hydrogen will be in competition, and priorities where hydrogen should be used, should be made on the basis of the cost of CO_2 avoided.

Europe and China are implementing carbon price mechanisms. Carbon pricing and its stability, in a system of quota exchange, will be critical for the development of decarbonised hydrogen.

Energy mix and hydrogen policies

Europe and China have currently a carbonised electrical mix and priority in the utilisation of the growing installed power of wind and solar is aiming at the progressive phasing out of fossil fuels, coal and gas utilities. The excess energy related to intermittency will offer limited opportunities for producing decarbonised hydrogen with a sufficient load factor for optimal amortization of the electrolysers.

That is why several countries plan to import hydrogen from foreign countries by pipeline or maritime transport.

France has a decarbonised electricity (nuclear and hydro) and then decarbonised hydrogen can be promptly developed by electrolysis with the combination of nuclear, hydro and intermittent renewables, while ensuring a high load factor of electrolysers.

Table 5: Hydrogen utilisation in 2050

Estimate of uses of hydrogen in 2050 (TWh) *		
	EU plus UK**	China***
1. Industry	1190	**1639**
chemical industry (includes e-fuel production and industrial process heat)	900	**937**
ammonia	110	**289**
Steel + cement	180	**Steel: 248** **Cement: 165**
2. Energy	450	**951**
heavy load road + railway	200	**563**
Aviation + shipping	100	**338**
Buildings heating	150	**50**
3. Electricity	600	**65**
TOTAL	2240	**2655**
* (data presented use low heating value (LHV) with 33,36 KWh/Kg of hydrogen)		
** European Hydrogen Backbone June 2021		
*** China 2050: A zero-carbon vision of a fully modernized country, Energy transitions commission & Rocky Mountain Institute -https://www.rmi-china.com/index.php/news?catid=18		

According to IEA report "Net Zero by 2050, A roadmap for the global energy sector", worldwide uses of hydrogen would be 7,200 TWh/year for industry, 6,800 TWh/year for energy, 3,400 TWh/year for electricity storage, with a total of 17,400 TWh/year.

If for example in 2050 total hydrogen production in EU + UK is from electrolysis, it would require electrical demand of 3,500 TWh, which is approximately the electrical consumption estimate in EU + UK in 2030.

According to prediction from China Hydrogen Alliance, in carbon neutral scenario in 2030, renewable hydrogen production in China will reach 5 million tons/a, hence about 93 GW electrolysers intended to be installed and it would require electrical demand of 280 TWh /a (operating hours: 3,000h/a, 5 kWh /Nm^3 H_2). In 2060, renewable hydrogen production in China will reach 100 million tons/a, hence about 500 GW electrolysers intended to be installed and it would require electrical demand of 4,032 TWh /a (operating hours: 8,000h/a, 3.6 kWh /Nm^3 H_2).[116]

116 China hydrogen energy and fuel cells industry development Report(2020). China Hydrogen Alliance, People's daily press

This will need

- a very important development of decarbonised electricity (variable energies solar and wind, nuclear, and hydroelectricity),
- together with a strong development of CCUS.

Worldwide, IEA Vision in 2050 for hydrogen production is 60% by electrolysis and 40% with CCUS.

Glossary

Term	Definition
Anaerobic digestion	a process through which bacteria break down organic matter—such as animal manure, wastewater biosolids, and food wastes—in the absence of oxygen
Black H_2	hydrogen derived from coal
Blue hydrogen	hydrogen production from hydrocarbons or coal with CO_2 capture and storage.
Carbon emission intensity	CO_2 emissions per GDP given as kg CO_2 per GDP in U.S. dollars.
Clean hydrogen	refers to renewable hydrogen or hydrogen generated from GHG-free sources including nuclear.
Climate plan	a detailed and strategic framework for measuring, planning, and reducing greenhouse gas (GHG) emissions and related climatic impacts.
Coal gasification	a process for producing syngas (mainly H_2 + CO) from coal and water, air and/or oxygen at temperatures around 1000°C, depending on the process (up to 2000°C).
Cushion gas	refers to gas (CO_2, N_2, etc.) that is injected into an H_2 storage facility to maintain pressure when H_2 is withdrawn for use.
Direct combustion	hydrogen can be directly used as fuel in internal combustion engines, or for heating water, similar to natural gas.
Electricity-based hydrogen	refers to hydrogen produced through the electrolysis of water (in an electrolyser powered by electricity), regardless of the electricity source.
Energy carrier	a substance (fuel) or sometimes a phenomenon (energy system) that contains energy that can be later converted to other forms such as mechanical work or heat or to operate chemical or physical processes.
EOR	Enhanced Oil Recovery: the practice of extracting oil from a well that has already gone through the primary and secondary stages of oil recovery

EU-ETS Market	the EU (CO_2) Emission Trading System (ETS) is a cornerstone of the EU's policy to combat climate change and its key tool for reducing greenhouse gas emissions cost effectively. It is the world's first major carbon market and remains the biggest one.
Fatal H_2	hydrogen as an industrial co-product is also called fatal hydrogen
Fossil-based hydrogen	refers to hydrogen produced through a variety of processes using fossil fuels as feedstock, mainly natural gas, liquid hydrocarbons, or coal.
Fossil-based hydrogen with carbon capture	a subcategory of fossil sourced hydrogen, where the greenhouse gases emitted in the hydrogen production process are captured.
Fuel cells	an electrochemical cell that converts the chemical energy of a fuel (often hydrogen) and an oxidizing agent (often oxygen) into electricity through a pair of redox reactions.
Green H_2	the green hydrogen pathway is defined as the combination of power generation from renewable sources or nuclear and water electrolysis.
Greenhouse gases(GHG)	responsible for the greenhouse effect include carbon dioxide, methane, nitrous oxide, and water vapour (which all occur naturally), and fluorinated gases (which are synthetic).
Grey H_2	hydrogen derived from hydrocarbons
High-temperature electrolysis	using protonic ceramic fuel cells (PCFC) or solid oxide electrolysis cells (SOEC)
Inter-seasonal energy storage	is the storage of energy for periods of up to several months
Low-carbon hydrogen	encompasses "clean" hydrogen but also fossil-based hydrogen with carbon capture and electricity-based hydrogen, with significantly reduced full life-cycle greenhouse gas emissions compared to current mainstream hydrogen production.
Methane pyrolysis	a suitable high-temperature (>1000°C) technology for converting natural gas into hydrogen without CO_2 emissions
Native hydrogen	present in the subsurface, it mainly comes from the water/rock interaction and is thus constantly regenerated.
Net-zero emissions target	Same as "Paris Agreement"
Paris agreement	sets out a global framework to avoid dangerous climate change by limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C
Photovoltaic power generation	a method for generating electric power by using solar cells to convert energy from the sun into a flow of electrons by the photovoltaic effect
Pilot phase	a small-scale implementation where engineers start placing equipment in and around a facility
Proton exchange membrane	polymer-electrolyte membrane or proton-electrolyte membrane PEM

Renewable hydrogen	is hydrogen produced through the electrolysis of water (in an electrolyser, powered by electricity), using electricity from renewable sources.
Steam methane reforming (SMR)	a process in which methane from natural gas is heated, with steam, usually with a catalyst, to produce syngas, a mixture of carbon monoxide and hydrogen used in organic synthesis and as a fuel
Synthesis gas (syngas)	Synthesis gas (syngas: $CO + H_2$) can be produced from a variety of sources and is a versatile inter-mediate for the production of chemicals and fuels.
Value chain	a value chain is a set of activities that a firm operating in a specific industry performs in order to deliver a valuable product (i.e. a good and/or service) to the end customer.

Acronyms and abbreviations

3D	3-Dimensional
AEM	Alkaline electrolyte membrane
ATR	Autothermal
AWE	Alkaline water electrolysis
BF	Blast furnace
CAE	Chinese Academy of Engineering
CCS	CO_2 capture and storage
CCUS	Carbon capture, utilisation and storage
CTM	Coal to methanol
DRI	Direct reduction of iron
EAF	Electric arc furnace
EOR	Enhanced oil recovery
EU ETS	EU emissions trading system
FCs	Fuel cells
FYP	Five-years plans
GH-CTM	Green hydrogen-coal to methanol
GLN	Global location numbers
HBI	Hot Briquetted Iron
HTSE	High temperature (steam) electrolysis
HYBRIT	Hydrogen breakthrough ironmaking technology
IEA	International energy Agency
ISC	*In situ* coal conversion technology
LCOE	Levelised cost of electricity
NATF	The National Academy of technology of France

O&G	Oil & Gas
PCFC	Protonic ceramic fuel cells
PEM	Proton-electrolyte membrane
PFSA	Fluor sulphonated polymer
PV	Photovoltaic
R&D	Research and development
REN	Renewable Energy
SMR	Steam methane reforming
SOEC	Solid oxide electrolysis cells
TRL	Technology readiness levels
WGSR	Water gas shift reaction

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