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Review article

DECARBONIZING TRANSPORT: THE ROLE OF HYDROGEN FUEL CELL ELECTRIC VEHICLES IN REDUCING EMISSIONS

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ABSTRACT

Climate change, air pollution and noise, among other environmental problems, are increasingly affecting human society and the natural environment. Among the main sources of greenhouse gases and pollutant emissions in the atmosphere is the transport sector. To decrease the use of fossil fuels in the transportation sector, hydrogen fuel cell electric vehicles (HFCEVs) have been proposed as a potential alternative, among others. Although not completely green, from a life-cycle perspective, HFCEVs can have a lower climate impact than conventional vehicles, depending on how the hydrogen is produced. Widespread use of renewable energy sources can significantly reduce this impact. The research results show an increase in HFCEV sales recently (but far below the level of battery electric vehicles), concerns about the introduction of hydrogen in all transport sectors (road, rail, sea or air), still limited distribution of the infrastructure refuelling, and high production costs. HFCEVs could contribute to the decarbonization of transport and all efforts, including research and development, should be stepped up to support them and identify the best solutions to current challenges.

Keywords: *hydrogen, electric mobility, fuel cells, challenges, effects on the environment*

INTRODUCTION

It is believed that hydrogen can support the transition to mobility, based on renewable sources, offering a solution for the decarbonization of the transport sector, responsible for high emissions of greenhouse gases (Dunn, 2002, Veziroğlu, Şahin, 2008, Dutta, 2014, Fayaz et al., 2012, Larsson et al., 2015, Kim et al., 2020, Fragiacomo, Genovese, 2020, Soleimani et al., 2024). Hydrogen is very abundant in the environment, but it is always found bound to other chemical elements, such as oxygen. Hydrogen can be produced through a wide variety of technologies:

- Electricity-based hydrogen refers to hydrogen produced by the electrolysis of water (the process by which water is broken down into hydrogen and oxygen, which takes place in the electrolyzer, powered by electricity), regardless of the source of electricity.
- Hydrogen from renewable sources is hydrogen produced by the electrolysis of water, with electricity from renewable sources.

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- Fossil fuel hydrogen refers to hydrogen produced by various processes that use fossil fuels as raw material, especially natural gas or coal gasification; this type of hydrogen accounts for most of the hydrogen produced today.
- Fossil fuel hydrogen with carbon capture and storage is a component of fossil fuel hydrogen, but here the greenhouse gases emitted in the hydrogen production process are captured and stored.

Depending on how the hydrogen is produced, several colors have been proposed, such as black, brown, gray, blue, and green (Ravi, Aziz, 2022). Black and brown hydrogen refers to hydrogen produced from coal (black or brown) through gasification technology. Gray and blue hydrogen refer to hydrogen produced from natural gas, without or with carbon capture, and green hydrogen is produced by electrolysis of water, using renewable energy sources.

Currently, about three-quarters of annual hydrogen production is produced from natural gas, followed by coal. Only a small part of the hydrogen comes from the electrolysis of water (IEA, 2019). Hydrogen is predominantly used in industry: oil refining, ammonia production, methanol production or steel production. The use of hydrogen in transport is still very limited, although hydrogen is a promising option, especially in trains, local buses, trucks, coaches, special purpose vehicles, and boats used mainly in inland waterway transport (EC, 2020).

In the transport sector, most of the hydrogen is used in road transport, but it is also increasingly used in rail transport. Such trains are being tested and adopted in several places. In 2022, hydrogen consumption in road transport represented about 32 thousand tons, up 45% compared to 2021 (in 2020, consumption was about 15 thousand tons), because of increased sales of HFCEVs (IEA, 2023a).

Like fully electric vehicles, HFCEVs use electricity to power an electric motor. But unlike other electric vehicles, which are powered by a large and heavy battery (mostly a lithium-ion battery), HFCEVs produce electricity using a fuel cell stack, which can contain hundreds of fuel cells. A fuel cell is a device that generates electricity through an electrochemical reaction (Figure 1). Hydrogen and oxygen are combined to generate electricity, heat, and water. Each fuel cell is composed of two electrodes (a negative anode and a positive cathode), an electrolyte and a catalyst to speed up the reactions. A typical fuel cell works by passing hydrogen through the anode of a fuel cell and oxygen through the cathode. At the anode, a catalyst splits hydrogen molecules into electrons and protons. Protons pass through a porous electrolytic membrane to the cathode, while electrons are forced through a circuit, generating an electric current and excess heat. After passing

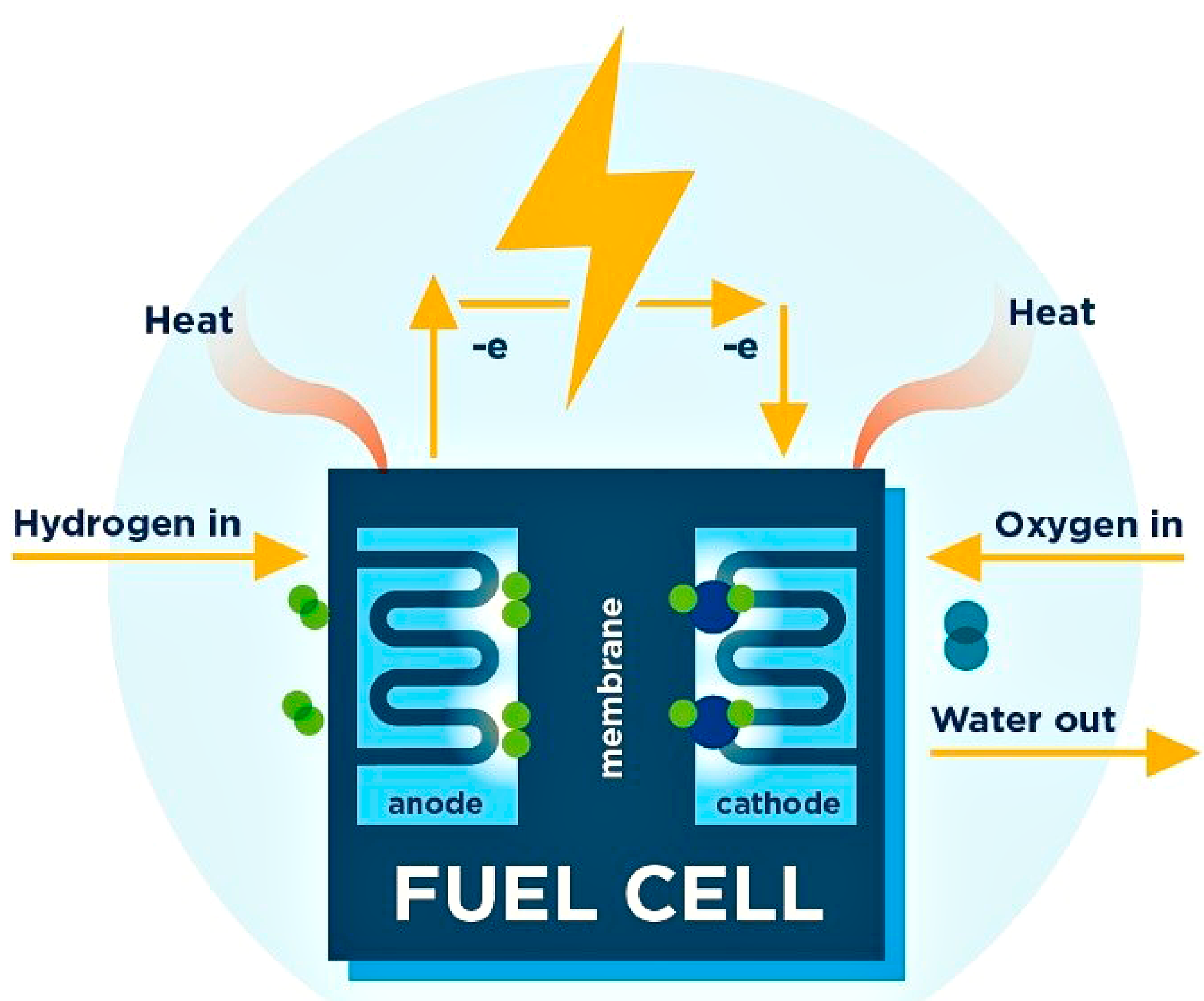

Figure 1. Operation of a hydrogen fuel cell
(Source: FCHEA, 2024)

through the circuit, at the cathode, the electrons combine with the protons and oxygen to produce water molecules (FCHEA, 2024). The electricity produced by the fuel cells powers an electric motor or is stored in a battery, which also takes the energy captured every time the vehicle brakes.

The first fuel cell, which produced electricity by combining hydrogen and oxygen, was invented by Welshman W. R. Grove in 1839. Although Grove discovered the principle of fuel cells, the first experiments were made by British engineer Francis Thomas Bacon in the early 1940s (The Chemical Engineer, 2012). Their first practical application was for the United States' Apollo space vehicles.

Hydrogen fuel cells are an environmentally friendly energy source, with the only byproducts being heat and water. However, fuel cell degradation is one of the key technological challenges reported (Wang et al., 2018, Zhao, Lee, 2019, Ren et al., 2020), which can affect vehicle performance over time.

HFCEVs have certain advantages over other technologies (Table 1): they significantly reduce greenhouse gas emissions compared to gasoline vehicles (depending on how hydrogen is produced); removes only water and heat in operation; they have high-energy efficiency; autonomy and refueling are comparable to classic vehicles; it operates silently and requires minimal maintenance (Halder et al., 2024). Finally, hydrogen is an abundant and renewable energy source, ideal in policies to decarbonize the economy.

Table 1. Comparison of different vehicle propulsion systems

Vehicle technology	Advantages	Disadvantages
Diesel engine vehicles	· Mature technology · Convenient refueling · High durability · Convenient prices	· High emissions of greenhouse gases and other pollutants · Noise pollution · Volatile fuel prices · Low-energy efficiency
Battery electric vehicles	· Relatively mature technology · No exhaust emission · Quiet engine, no noise	· Quite long recharge time · Relatively short battery lifetime · Relatively limited driving range · The supply of critical minerals needed for batteries
Hydrogen fuel cell electric vehicles	· No exhaust emission · Convenient refueling · Flexible driving range · High-energy density	· High technological costs · High cost of green hydrogen · Limited hydrogen infrastructure

In addition to HFCEVs, hybrid models have also been proposed that benefit from auxiliary energy sources (batteries, super capacitors). It is believed that these additional energy sources could reduce fuel cell degradation, increase fuel economy and provide energy during cold start (Das et al., 2017, Depature et al., 2020). But larger batteries are needed, especially plug-in batteries. Hydrogen can also be used in internal combustion engines as the main fuel or as an additional fuel by blending with other fuels (Gurz et al., 2017, Villar et al., 2020).

This study looks at the current situation of hydrogen-based mobility and the challenges it faces, including meeting hydrogen needs and its production cost, refueling infrastructure or environmental impact.

MATERIALS AND METHODS

This paper uses various quantitative and qualitative methods to collect, interpret and update data on hydrogen-based mobility and the challenges of its future evolution. The quantitative data used in this work were taken from international sources and databases (International Energy Agency, Hydrogen Council, Statista, Fuel Cell & Hydrogen Energy Association or H2stations.org), but also from consulting specialized articles and other sources. To highlight the evolution of some indicators, such as the global stock of hydrogen-based fuel cell electric vehicles, graphical methods were used which were subsequently interpreted.

Scenarios and estimates for the future development of hydrogen-based projects were based on data published by the International Energy Agency and estimates by the Hydrogen Council-McKinsey & Company. The identification of hydrogen's role in the global effort to combat climate change, technological challenges and its negative environmental effects during its life cycle was based on several scientific articles published in specialized journals as well as other sources such as Hydrogen Insight. Overall, the examination of the current state of hydrogen-based mobility and development challenges was based on specific analytical research.

RESULTS

Hydrogen-based mobility in road transport

Asian companies are the most advanced in the field of hydrogen-based road transport. One of the first research works on this type of energy was carried out by the Honda company. It began applying fuel cells to passenger vehicles in the second half of the 1990s, and in 2002 launched the FCX model simultaneously in Japan and the US. In 2008, Honda launched the FCX Clarity, the world's first HFCEV dedicated to mass production, followed by the Clarity Fuel Cell in 2016. The newest model, the 2024 CR-Ve:FCEV, is North America's first plug-in fuel cell electric vehicle, combining plug-in charging capability with fast hydrogen refueling (Honda Motor, 2024). HFCEV research and development programs have also been carried out by the Japanese company Toyota since 1992. It was only in December 2014 that Toyota was able to launch the first HFCEV, called Mirai (Toyota Motor Corporation, 2018). By 2022, around 22,000 such vehicles have been sold, mostly in the US and Japan, with 3,900 units sold in 2022 alone (Carbon Credits, 2023).

Another Asian company with early concerns in hydrogen mobility is Hyundai Motor. Following the Mercury project, from 1999, carried out in collaboration with United Technologies Corporation, the MercuryII vehicle resulted (Hyundai Motor Company, 2020). After the presentation of the ix35 Fuel Cell prototype (in 2010), sold in several countries around the world, in 2018 Hyundai launched the NEXO model, which became the best-selling HFCEV in the world in 2022, with 10,527 units (Hydrogen Insight, 2024a).

The first car manufacturer in China to develop HFCEV technology is SAIC Motor, which in 2001 launched the Phoenix No1 project. Following the 2016 Roewe 950, which was the first fuel cell sedan licensed and sold in China, in June 2020 the company produced the Maxus EUNIQ 7, the world's first fuel cell MPV (multipurpose vehicle). Recently, SAIC Motor has introduced various types of HFCEVs (multipurpose vehicles, light buses, coaches, light trucks or heavy trucks), operating in several cities in China (SAIC Motor, 2020).

In Europe, the BMW company relies on fuel cell technology and has been working on this technology since 2000. In their commitment to achieve net-zero emissions by 2050, the German company started developing its own hydrogen fuel cells and launched in February 2023 the BMW iX5 Hydrogen model. The objective of the German manufacturer is to bring this pilot vehicle to market by 2030 (BMW Group, 2023). Another German manufacturer, Mercedes-Benz, has designed the GLC F-CELL, a unique plug-in hybrid that combines innovative fuel cell and battery technologies for the first time; apart from electricity, the vehicle also runs on pure hydrogen (Mercedes-Benz Group, 2024).

In the United States, the General Motors company presented the Chevrolet Colorado ZH2 model, designed for more rugged terrain conditions, and NamX, a Moroccan startup, produced in 2022 a prototype SUV that benefits from a double hydrogen tank (a fixed tank and a detachable tank consisting of six replaceable hydrogen capsules), expected to be launched in 2026 (NamX, 2024).

Like passenger cars, the number of hydrogen fuel cell buses has also increased. The first concerns regarding the development of such vehicles were in the USA in the late 1980s and early 1990s. The most notable project was the Georgetown Fuel Cell Bus, which resulted in the first fuel cell (phosphoric acid-based) bus. Since the late 1990s, hydrogen fuel cell buses have been tested and experimented with in several places (Eudy et al., 1997). In 2001, the Toyota Company completed the FCHV-BUS1, a city bus powered by a hydrogen fuel cell hybrid system jointly developed with Hino Motors (Toyota Motor Corp., 2001). This bus was tested in Tokyo in 2003 and then a fleet of eight such buses was used at Expo 2005 in Aichi (Japan). Subsequently, various other companies produced hydrogen fuel cell buses, such as Foton, Yutong, Higer, Zhongtong, Sunwin (all from China), Hyundai (South Korea), Wrightbus (UK), Van Hool (Belgium), New Flyer (Canada), Mercedes-Benz (Germany) or Solaris (Poland).

To promote hydrogen-based buses, numerous programs have been funded in Europe, such as CUTE, CHIC, or JIVE. CUTE (Clean Urban Transport for Europe) was the first large-scale project to test 27 fuel cell buses in nine European cities (Hamburg, London, Barcelona, Stockholm, Porto, Stuttgart, Amsterdam, Luxembourg, and Madrid), during 2001-2006. It was followed by the CHIC (Clean Hydrogen in European Cities) project, carried out between 2010 and 2016, and the JIVE (Joint Initiative for Hydrogen Vehicles across Europe) projects, carried out between 2017 and 2020 (Fuel Cell Electric Buses, 2024). These projects demonstrated that mobility based on hydrogen can represent a solution for decarbonizing public transport and improving air quality in cities.

The success of these programs is exemplified by the case of the German transport company Regionalverkehr Köln GmbH (RVK), which has the largest fleet of fuel-cell buses. In 2011, RVK took possession of its first fuel cell buses, two Phileas 18 buses from the Dutch manufacturer APTS. Three years later, in 2014, two more New A 330 FC buses were purchased from Van Hool, and in 2020 another 35 buses of this type were ordered. In September 2024, RVK also introduced the first eight Solaris Urbino 18 hydrogen articulated buses, in addition to the 46 Solaris Urbino 12 fuel cell buses already in operation. In the future, 20 more Solaris hydrogen buses will be added: nine 12m buses and eleven 18m buses. By the end of 2025, RVK aimed to have almost half of its buses be hydrogen-based, i.e., 160 units (Marquordt, 2024, Solaris Bus & Coach, 2024).

Northern Irish company Wrightbus has built the world's first double-decker fuel cell bus, called the Hydroliner, which was officially launched in 2021 in Aberdeen. It now has fleets operating in five cities in the UK and Ireland (Aberdeen, Birmingham, London, Belfast and Dublin), which have cumulatively covered more than 1.5 million km (The Advanced Propulsion Center UK, 2024). Worldwide, as of June 2023, there were approximately 7,000 fuel cell buses, most (around 85%) in China. The second position was occupied by Europe, then South Korea, the United States and Japan (IEA, 2023a).

Hydrogen fuel cell trucks are also gaining popularity as an alternative to traditional diesel trucks. The stock of fuel cell trucks grew faster than that of light vehicles, growing by more than 60% in 2022, with a total of more than 8,000 units by mid-2023. In 2022, most sales took place in China, which now accounts for over 95% of the market, thanks to favorable policy and supporting infrastructure. Such trucks are also used in other countries. For example, Hyundai Xcient trucks have accumulated around 5 million km in Switzerland as of 2020, but also operate in Germany, South Korea and New Zealand. The partnership between Hyundai Motor and H2Energy aims to introduce 1600 Hyundai H2 Xcient Fuel Cell trucks in Europe (Hyundai Motor Company, 2020).

According to CALSTART's Zero-Emission Technology Inventory (ZETI), approximately 20 fuel cell medium- and heavy-duty truck models were available in 2022, with several additional models planned for 2023 (IEA, 2023). According to Blackridge Research & Consulting (2024), the main companies producing fuel cell trucks are: Beiqi Foton Motor, Dayun, Dongfeng Motor, FAW Group, Great Wall Motor, Hyundai Motor, Hyzon Motors, Nikola Corporation, SAIC Iveco Hongyan and SINOTRUK (China National Heavy-Duty Truck Group). Except Hyundai Motor, Nikola Corporation and Hyzon Motors (the last two are American), the rest are Chinese.

More and more HFCEVs have hit the world's roads lately (Figure 2). If in 2017 there were around 7,200 units, in the middle of 2023 it reached 80,000 units, of which 63,000 were light vehicles (IEA, 2023a). If in 2017 all HFCEVs were cars, today more than 20% of them are buses and trucks. This shows a shift to vehicles where hydrogen can be more competitive.

There are notable differences in the geographic distribution of different types of HFCEVs (Figure 3). South Korea is the largest market, with a stock of more than 32,000 such vehicles in the first half of 2023. About

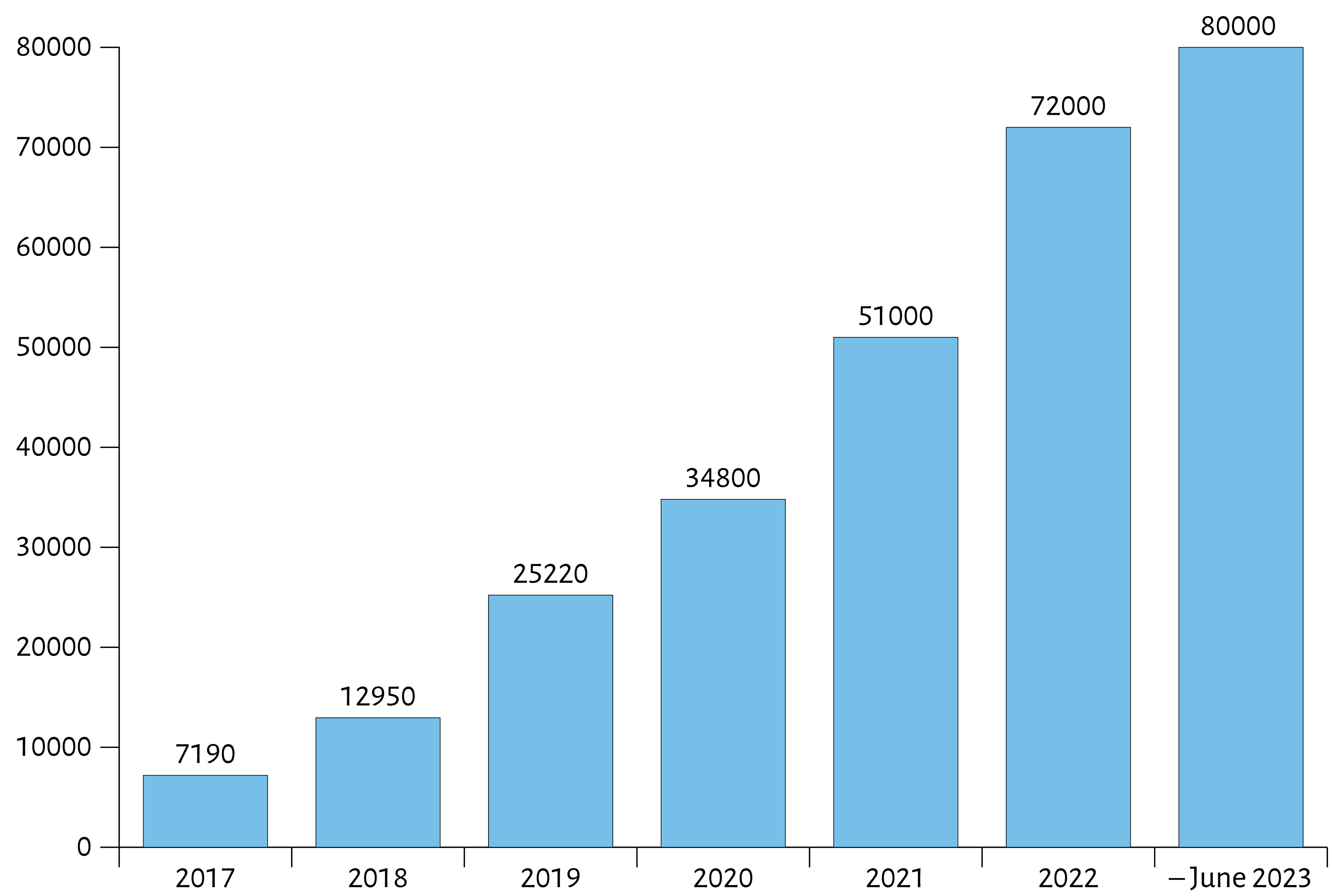

Figure 2. Fuel cell electric vehicle stock (2017-2023)
(Source: IEA, 2019b, IEA, 2023a)

15,000 HFCEVs were sold in 2022 and less than 3,000 in the first half of 2023 (some slowdown compared to the nearly 4,900 at the same time frame the previous year). As South Korea, the United States and Japan have focused their efforts on the implementation of light passenger cars, they hold 90% of the stock of this segment but have a few buses and commercial vehicles. On the other hand, China has the largest stocks of fuel cell buses and commercial vehicles (IEA, 2023a). In the United States, most HFCEVs are in California, while in Europe, Germany is in first place.

It is believed that as technology costs decrease, energy optimization improves, range increases, and fueling stations multiply, the demand for HFCEVs will increase (Tanç et al., 2019). According to the Hydrogen Council and other estimates, as the market grows and costs fall, HFCEVs could exceed 13 million units by 2030,

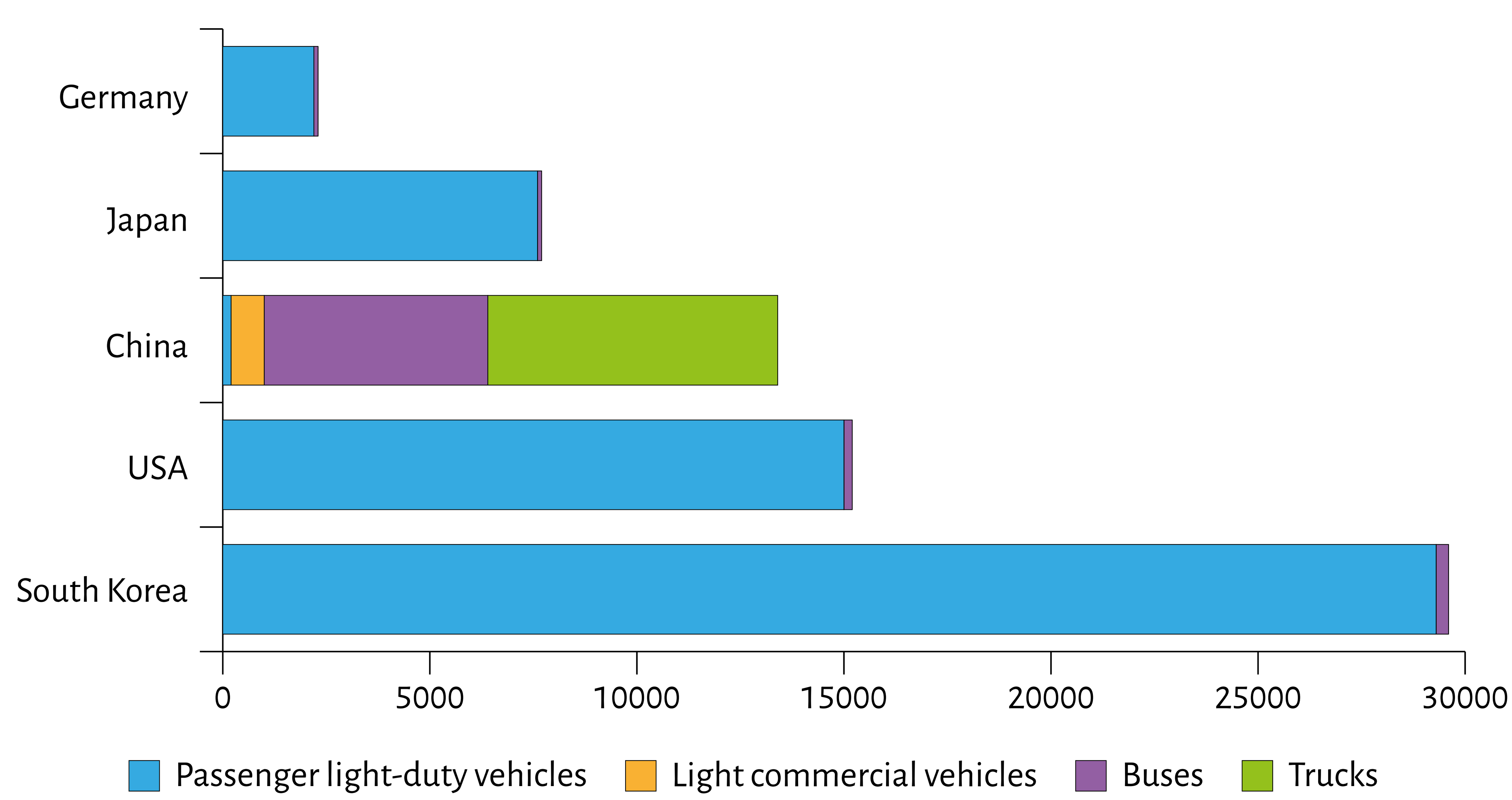

Figure 3. Global fuel cell electric vehicle fleet in selected countries as of 2022, by vehicle segment
(Source: Statista, 2023)

and commercial vehicles, including trucks, light commercial vehicles and buses, could exceed 1 million units (S&P Global, 2020, Hadler et al., 2024) (Table 2). For example, according to the Fuel Cell Vision 2030 strategy, Hyundai Motor Group aimed to increase the annual production capacity of HFCEVs to 700,000 units by 2030 (Hyundai Hotor Company, 2020). However, current growth rates are too low for these targets to be achieved.

Table 2. Hydrogen deployments 2020 vs. 2030 outlook

	Global		Europe		North America		Asia	
	2020	**2030**	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**
Electrolysis (MW)	134	NA	84	>10,000	9	NA	30	NA
Hydrogen Refueling Station (operational)	407	>10,000	170	3,700	66	4,300	163	2,560
FCEVs	16,000	13 million	1,300	4.2 million	7,800	3.7 million	6,300	5.1 million
Commercial Vehicles	1,600	1 million	91	45,000	32	300,000	1,500	650,000

Source: Hydrogen Council, cited by S&P Global, 2020

Hydrogen-based mobility in rail transport

In the railway sector, hydrogen is used to replace diesel. Alstom is the first railway company to invest in hydrogen fuel cell trains as an alternative to diesel for non-electrified lines. At InnoTrans 2016 in Berlin, Alstom presented the world's first passenger train powered by fuel cells, called the Coradia iLint. The first two trains of this type entered commercial service in September 2018 in Lower Saxony (Germany) and to date 41 trains have been ordered by two German Länder and tests have taken place in the Netherlands, Austria, Sweden, France, Poland, or Canada. The Coradia iLint achieves a top speed of 140 km/h, acceleration and braking performance comparable to a standard regional diesel train, but without the noise and emissions. On September 15, 2022, a Coradia iLint train traveled the record distance of 1175 kilometers without refueling (Alstom, 2024).

Alstom has signed contracts to supply hydrogen trains to Italy's Lombardy and Puglia regions to replace current diesel trains. The Ferrovie Nord Milano company in Lombardy signed a framework agreement in 2020 for the purchase of up to 14 Coradia Stream trains, of which 8 have already been ordered. In March 2021, four French regions (Auvergne-Rhône-Alpes, Bourgogne-Franche-Comté, Grand Est and Occitanie) ordered 12 Régiolis H2 trains powered by electricity and hydrogen. After testing, planned for 2024, they are due to enter commercial service in 2025 (SNCF Groupe, 2024).

As part of the H2goes Rail project (presented to the public in November 2020), carried out together with Deutsche Bahn and financed with 13.7 million euros, as part of the National Innovation Program for Hydrogen and Fuel Cell Technology, Siemens Mobility developed the Mireo Plus H hydrogen train. This train is presented as an alternative to diesel trains for long-distance operation. It has a range of approximately 1000 km and can reach speeds of up to 160 km/h. In September 2022, the first journey with this train took place at a test center in North Rhine-Westphalia. In 2022, Siemens received the first order of 7 Mireo Plus H trains from Niederbarnimer Eisenbahn for the Heidekrautbahn network in the Berlin-Brandenburg metropolitan region, with the trains planned to enter commercial operation from December 2024 (Siemens Mobility, 2024).

The first hydrogen train in the United States was tested in March 2024 in the state of Colorado. It is the Flirt H2 train, made by the Swiss manufacturer Stadler. During the test, the train traveled 2803 km. It is intended for the San Bernadino County Transportation Authority in California. Another four trains were ordered for the California State Transportation Agency (Hydrogen Insight, 2024b).

In Japan, East Japan Railway aims to commercialize the first hydrogen hybrid train, called Hybari (jointly developed with Toyota Motor and Hitachi), in 2030. A trial run of this train was shown to the media on the JR Tsurumi Line in Kanagawa Prefecture on February 28, 2024 (Nikkei, 2024, The Asahi Shimbun, 2024). In China, manufacturer CRRC has completed tests of the country's first passenger train running on hydrogen fuel cells. The train is designed to operate between non-electrified urban railway sections of up to 1000 km with a maximum speed of 160 km/h (Hydrogen Insight, 2024c).

Hydrogen-based mobility in sea and air transport

The Global Maritime Forum has identified many pilot and demonstration projects for the introduction of zero-emission technologies in maritime transport, including hydrogen-based ones. In July 2023, the European Union adopted the Maritime FuelEU regulation, to stimulate the more consistent use of low-carbon fuels in shipping (IEA, 2023a). In March 2023, the world's first hydrogen ferry, the MF Hydra, began operating in Norway. The commissioning of this ferry makes another substantial leap towards the goal of zero emissions for ferries, as well as the maritime industry in general. After tests carried out at the quay in Hjelmeland, Norled received final approvals from the Norwegian Maritime Authority. MF Hydra confirms Norway's world-leading position in the development of new green maritime solutions (Norled, 2024).

Also in March 2023, a gaseous hydrogen ferry was tested in San Francisco. Thus, the Sea Change ferry, owned by Switch Maritime, became the first commercial marine vessel in the United States powered by hydrogen fuel cells (Power Technology, 2023). In February 2024, India's first fuel cell ferry was launched at Cochin Shipyard. The adoption of green hydrogen as a marine fuel is an example of India's commitment to a sustainable future, aiming for net zero emissions by 2070 (Business Standard, 2024).

There are concerns about introducing greener fuels in aviation as well, including hydrogen-based fuels. Boeing has conducted six demonstration projects and has extensive experience using hydrogen as a fuel for launch vehicles and space applications. For example, in 2008, a two-seater Dimona made three flights in Spain, becoming the first manned aircraft in history to use power generated exclusively by hydrogen fuel cells (Boeing, 2024).

ZeroAvia took a step forward. On January 19, 2023, it made its first flight, at Cotswold Airport in Gloucestershire (England), using a prototype ZA600 electric hydrogen engine to power the left-hand propeller of a 19-seat Dornier 228. It was the largest hydrogen-electric powered aircraft at the time. ZeroAvia plans to power zero-emission commercial aircraft by 2025 (ZeroAvia, 2024).

Universal Hydrogen, a company founded in 2020, successfully completed the first flight powered by hydrogen fuel cells in March 2023. The company used a 40-passenger aircraft called the Lightning McClean, which took off from Grant County International Airport (USA) and flew for 15 minutes. The flight was the first in a series of flight tests over a two-year period, which will culminate in 2025 with the entry into commercial passenger service of ATR 72 regional aircraft converted to run on hydrogen. The company has orders from customers all over the world (Universal Hydrogen, 2023).

In 2020, Airbus launched an ambitious plan to bring the world's first up to 200-passenger hydrogen-powered commercial aircraft to market by 2035. To get there, the ZEROe project is exploring a variety of configurations and technologies revolving around establishing means of propulsion, either through hydrogen-electric hybrid fuel cells, or through the direct combustion of hydrogen. In this regard, the company has established dedicated development centers in France, Great Britain, Germany, and Spain. For testing, these technologies will be used by the Airbus A380 MSN1 aircraft (Airbus, 2024).

Several models of unmanned aerial vehicles or drones currently use fuel cells for power. They provide drones with longer flight times and quicker refueling compared to traditional battery-powered drones (FCHEA, 2024).

DISCUSSIONS

Hydrogen production

The expansion of hydrogen-based mobility, without considering other applications, implies an increasing need for hydrogen. Despite being the most abundant element in the Universe (Jain, 2009, Gurz et al., 2017), hydrogen does not exist as such, so it must be extracted from water by electrolysis or separated from fossil fuels. Both processes require a significant amount of energy to carry out, and the energy is not always renewable and can be expensive. Today, hydrogen is mostly obtained from natural gas and coal, and the production process removes carbon dioxide.

In 2022, global hydrogen production was 95 million tons (up 3% from 2021), being almost entirely used for industrial applications and produced almost exclusively from fossil fuels. More than 70% of global production was in China, the United States, the Middle East, India, and Russia. China is the largest consumer of hydrogen, with about 30% of the total, almost double that of the second consumer, the USA. For mobility, the annual hydrogen demand was very low, only 0.02% of the total. However, hydrogen demand has more than tripled since 1975. Low-emission hydrogen production in 2022 was less than 1 million tonnes (0.7% of global production), almost entirely from fossil fuels with capture and carbon storage. Hydrogen production from water electrolysis was very low, below 100 thousand tons, an increase of 35% compared to the previous year (IEA, 2023a). In 2023, according to the Hydrogen Council-McKinsei & Company, the production of hydrogen from renewable sources was about 150 thousand tons, which represented about 15% of the global production of clean hydrogen, which is 860 thousand tons.

Regarding hydrogen obtained by electrolysis of water with electricity produced from renewable sources, the electrolysis capacity reached 1.1 GW in 2023, increasing by about 60% compared to 2022 (700 MW). Much of this growth was driven by a single 260 MW project in China. Moreover, the largest installed electrolysis capacity is in China (610 MW), followed by the United States and Germany (60 MW each), then Spain, Taiwan, Sweden and Canada (each with approximately 25 MW). In China, 90% of electrolysis capacity is based on alkaline technology, while proton exchange membrane technology is more widespread in Europe and North America, accounting for 80% of total installed capacity (Hydrogen Council-McKinsei&Company, 2023).

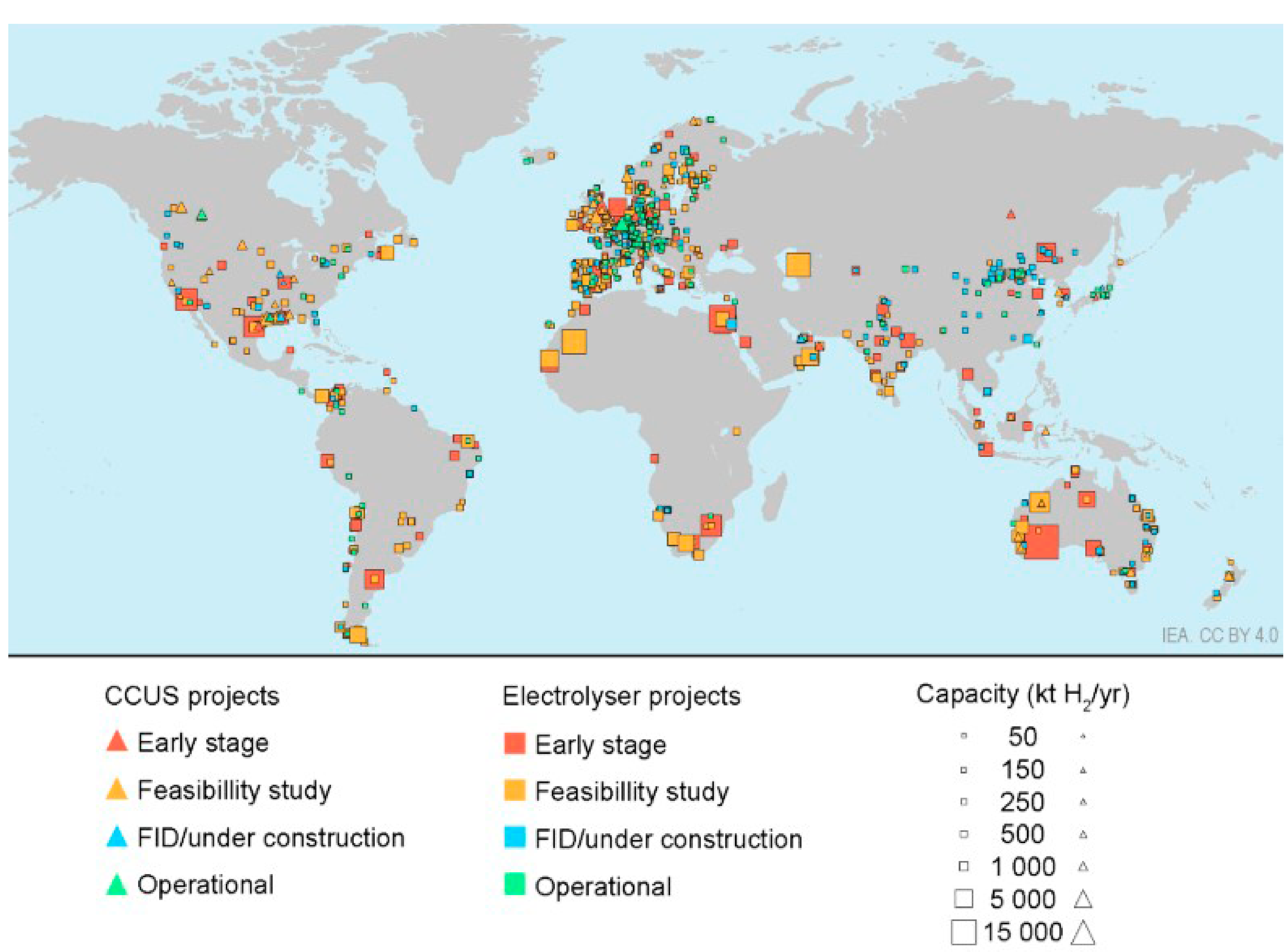

Figure 4. Map of announced low-emission hydrogen production projects
(Source: IEA, 2023a; IEA Hydrogen Projects, October 2023 release)

In addition to the 860 thousand tons/year of operational capacity today, about 2.2 million tons/year of clean hydrogen passed the final investment decision. The largest committed and operational capacity is low-carbon hydrogen (1.7 million tons/year), and the rest is hydrogen from renewable sources. North America (particularly the US) represents the largest market in terms of committed clean hydrogen capacity, with volumes of approximately 1.8 million tonnes/year. About 90% of these volumes are low-carbon hydrogen (Hydrogen Council, McKinsei&Company, 2023).

Although low-emission hydrogen still accounts for less than 1% of global hydrogen production and use, it could reach 20 million tons in 2030 if all announced projects are completed (Figure 4). However, projects that are currently under construction or have taken a final investment decision represent only 4% of production. The rest comes from projects that are undergoing feasibility studies (50%) or in very early stages. Electrolysis projects dominate among announced projects: over 70% of low-emission hydrogen production in 2030 could come from electrolysis, with most announced projects in Europe (mostly Spain, Denmark, Germany, Netherlands) and Australia. However, 55% of announced electrolysis projects are in the early stages of development (IEA, 2023a).

The cost of hydrogen production

Although the production cost of hydrogen may decrease as technology advances, it is currently a barrier to the widespread use of hydrogen. The production cost of hydrogen depends on the technology and cost of energy used, which usually show significant regional differences. The cost of hydrogen produced by electrolysis is also determined by the cost of the electrolyzer.

Currently, neither green hydrogen nor fossil fuel hydrogen with carbon capture is competitive with fossil fuel hydrogen. The estimated cost for hydrogen based on fossil fuels, especially natural gas, is around €1.5 per kg, being highly dependent on the price of natural gas. The estimated cost for fossil fuel-based hydrogen with carbon capture and storage is around €2 per kg, and the cost for green hydrogen at €2.5-5.5 per kg (EC, 2020). More recent data shows a green hydrogen cost of €3-8 per kg (PwC, 2022).

It is believed that as the production cost of renewable energy and the electrolyzer will decrease, green hydrogen will become more competitive, making it a viable source for various applications, including transportation. It is estimated that the cost of green hydrogen could drop by 30% by 2030 because of the falling cost of renewable energy and the increase in hydrogen production. Fuel cells, refueling equipment and electrolyzers can all benefit from mass production (IEA, 2019). The cost of automotive fuel cells has fallen by 70% since 2008 due to technological progress and increasing sales of HFCEVs (IEA, 2021a).

According to PwC (2022) estimates, the production cost of hydrogen will fall by about 50% by 2030 and then continue to fall steadily but more slowly until 2050. The production cost of green hydrogen in parts of the Middle East, Africa, Russia, China, USA, and Australia will be in the €1 per kg range by 2050, and in regions with limited renewable resources such as parts of Europe, Japan, and South Korea it will exceed €2 per kg, making these markets likely to import green hydrogen from elsewhere.

Already the cost of electrolytic hydrogen has fallen by 60% over the past ten years and is expected to halve by 2030 compared to the current situation. In regions where electricity from renewable sources is cheap, green hydrogen is expected to be able to compete with fossil fuel hydrogen by 2030 (EC, 2020). What is certain is that the cost of renewable electricity has already fallen significantly over the past decade, with an 80% reduction in the cost of solar modules between 2010 and 2020 (IEA, 2023a).

On the other hand, recently, the cost of electrolyzers has increased due to rising material and labor costs, ranging from $1700/kW to $2000/kW. Alkaline electrolyzers made in China are much cheaper than those made in Europe or North America, i.e., 750-1300 USD/kW. Inflation and rising labor costs have had a considerable impact on projects being developed. For example, the cost of Saudi Arabia's NEOM Green Hydrogen project has increased from $5 billion to $8.5 billion due to inflation, rising supply chain costs, and expanding the scope of the project to include lines of transport and other infrastructure equipment (IEA, 2023a).

Fuel cell vehicles versus battery electric vehicles

Both types of vehicles have zero tailpipe emissions. Unlike battery electric vehicles, fuel cell ones can be charged faster (within minutes), have a longer range, a longer operating time and are less affected by temperature, but are less efficient from an economic perspective (Lee et al., 2018, Halder et al., 2024).

If in the early 2000s, these two types of vehicles competed in the race to decarbonize the automotive industry, today battery electric vehicles are way ahead. Well over 10 million electric light-duty vehicles (including plug-in hybrid electric vehicles) were sold in 2022, i.e., 14% of all new cars sold in 2022. Regarding the stock of battery electric vehicles, in 2022 it exceeded 26 million (of which 30% plug-in hybrid electric vehicles) (IEA, 2023b).

Major car companies have been quick to electrify their lineups, while only a few hydrogen car models are available. In 2024, the top two hydrogen cars, the Toyota Mirai and the Hyundai Nexo, were priced above $50,000 and above $60,000, respectively (Table 3). On the other hand, a growing number of battery electric vehicles cost less, thanks to the falling price of lithium-ion batteries (MIT, 2023). In addition, electric vehicles have another crucial advantage: there is already a vast electric system.

Table 3. Some key features of Toyota Mirai and Hyundai NEXO

Vehicle model	Driving range (km)	Hydrogen tank capacity (kg)	Power of Fuel Cell System (kW)	Number of cells	Starting price (US$)
Toyota Mirai	575-647	5,6	128	330	50,190 (XLC) 67,115 (Limited) (in 2024)
Hyundai NEXO	570-611	6,3	95	440	60,135 (Blue) 63,585 (Limited) (in 2023)

Source: Hyundai Motor America, 2023, Toyota Motor, 2024

Regarding mobility, in 2021 Japanese transport company Tokyu Bus reported that the cost of refueling a hydrogen fuel cell bus was about 2.6 times that of an equivalent diesel bus, with natural gas hydrogen being the predominant use in Japan (Financial Times, 2021). According to a study by Eurac Research (cited by Hydrogen Insight, 2023), which collected daily operating data from 16 fuel cell electric buses and five battery electric buses operated by the local public transport company SASA in South Tyrol (Italy), between January 2021 and April 2022 found that, on average, battery electric buses were 2.3 times cheaper to run per kilometer than green hydrogen fuel cell equivalents. Also in January 2022, the public transport operator of the city of Montpellier (France) canceled a contract to purchase 51 buses powered by hydrogen fuel cells when it found that the operating cost was 6 times higher than that of electric buses. Furthermore, the cost of fuel cell powered buses was €150,000-200,000 higher than the cost of battery-powered buses (CleanTechnica, 2022).

Refueling and transport infrastructure

Widespread adoption of HFCEVs will require new refueling infrastructure to support it. An essential condition for the development of hydrogen-based mobility is safe, compact, lightweight and cost-effective hydrogen storage (Abe et al., 2019). There are several storage methods that can support the development of hydrogen-based mobility in perspective, such as liquefied hydrogen, compressed hydrogen, cryo-compressed hydrogen, physically adsorbed hydrogen, metal hydrides, complex hydrides or liquid organic hydrides (Usman, 2022). Today, the most used solution is the storage of hydrogen in gaseous form at high pressure.

According to H2stations.org (an information service of Ludwig-Bölkow-Systemtechnik), the most comprehensive website for information on hydrogen refueling stations globally, at the end of 2023, 921 stations were in operation worldwide, with 85 of stations more than in 2022. A hydrogen refueling infrastructure, in operation or under construction, was in 40 countries. Europe had 265 hydrogen stations, of which 105 were in Germany, 51 in France, 22 in the Netherlands and 17 in Switzerland. Furthermore, at the end of 2023, there were 166 stations in Japan, 174 in South Korea, and at least 197 in China. There were 100 stations in North America, of which 92 were in the United States (75 in California) and 8 in Canada.

The number of hydrogen refueling stations is expected to exceed 10,000 by the end of the current decade (S&P Global, 2020). In the European Union, the recently adopted Alternative Fuels Infrastructure Regulation requires hydrogen refueling stations to be installed every 200 km of the trans-European transport network. South Korea and Japan also plan to expand their networks to more than 600 stations each by 2030 (Hydrogen Council-McKinsei & Company, 2023).

Large-scale deployment of hydrogen will also need to be supported by an efficient storage and transportation system. There are currently 5000 km of hydrogen pipelines in operation, mainly in the United States and Europe. Most are closed systems owned by large hydrogen producers near industrial consumers (mainly refineries and chemical plants). The largest hydrogen network in Europe and the second in the world after the United States, of about 600 km, is in Belgium and is owned by Air Liquide. It is connected to networks in France and the Netherlands. Using existing natural gas pipelines can significantly reduce the cost of setting up hydrogen networks. A proven technology since the early 1970s is hydrogen storage in salt mines. Four hydrogen salt mines are currently operational, three in the United States and one in the United Kingdom (IEA, 2023a, IEA , 2021b).

The impact on the environment

Although hydrogen fuel cell vehicles do not emit carbon dioxide or pollute the air during use, the production of hydrogen and other associated production processes are responsible for a wide range of emissions, depending on the technology and energy source used (Granovskii et al., 2006, Offer et al., 2011, Cetinkaya et al., 2012, Yoo et al., 2018, Wang et al., 2020, Ravi, Aziz, 2022, Halder et al., 2024).

Currently, most of the hydrogen is obtained from fossil fuels, mainly natural gas. Greenhouse gas emissions are significantly lower for fossil fuel-based hydrogen with carbon capture and storage or electricity-based hydrogen (EC, 2020). For electricity-based hydrogen, life-cycle greenhouse gas emissions depend on how the electricity is produced (Offer et al., 2011, Halder et al., 2024). In the case of hydrogen obtained by electrolysis of water using grid electricity, produced mostly from fossil fuels, the well-to-wheel greenhouse gas emissions of HFCEVs are higher than those of gasoline vehicles (Wang et al., 2020). Green hydrogen has the lowest life-cycle greenhouse gas emissions. In 2022, as hydrogen was produced almost exclusively from fossil fuels, hydrogen production was responsible for approximately 900 million tonnes of carbon dioxide emissions (IEA, 2023a).

Strategies for the development of hydrogen-based technologies

According to the International Energy Agency (2021), to achieve the goal of net-zero carbon dioxide emissions by 2050, necessary to limit the increase in global temperature to 1.5 °C in accordance with the Paris Agreement, measures will be necessary to transform the energy system, such as increasing energy efficiency, changing consumption behavior, electrification, or expansion of renewable sources. The importance of hydrogen is reflected in its increasing share in final energy consumption. If in 2020, hydrogen and hydrogen-based fuels account for less than 0.1% of energy consumption, in 2050 its share is expected to rise to 10%.

According to the Net Zero Emissions by 2050 Scenario, by 2030 total hydrogen production must reach well over 200 million tons, of which 70% using low-carbon technologies (electrolysis or fossil fuels with carbon capture and storage). Hydrogen production must then increase to more than 500 million tonnes by 2050, based entirely on low-carbon technologies. Achieving these targets will require an increase in installed electrolysis capacity from 1.1 GW (in 2023) to nearly 850 GW by 2030 and to nearly 3600 GW by 2050 (IEA, 2021b).

By September 2022, 41 governments, accounting for nearly 80% of global energy-related carbon dioxide emissions, have adopted hydrogen strategies, which are key in financing (IEA, 2023a). Many strategies include targets for the adoption of hydrogen technologies, most of which focus on implementing low-carbon hydrogen production. In July 2020, the European Commission adopted a strategy on hydrogen in Europe (COM(2020)0301), which introduces as objectives the increase in electrolysis capacity to at least 40 GW to produce green hydrogen (i.e., 10 million tonnes) by 2030 and its widespread use from 2030. Green hydrogen is at the heart of the strategy, given that it has the greatest decarbonization potential and is therefore most compatible with the EU's climate neutrality objective (EC, 2020). To support hydrogen-based mobility, some countries (such as China, South Korea or Ireland) have offered subsidies for the purchase of HFCEVs and the development of hydrogen refueling stations.

Hydrogen technologies need investment to become truly viable. According to the Hydrogen Council-McKinsei & Company (2023), to date, investments committed to hydrogen end-uses have reached over $7.5 billion, of which $4.5 billion in Europe. The largest amounts were invested in the field of mobility ($4.5 billion), followed by the energy sector ($1.2 billion). Globally, 1,418 clean hydrogen projects have been announced by October 2023, of which 1,011 are planned for full or partial implementation by 2030. These projects mean investments of $570 billion and 45 million tons/year of clean hydrogen by 2030. The most projects were announced in Europe (540), followed by North America (248). Announced investments are geared towards clean hydrogen production and supply (about 75%), while infrastructure and end-use investments account for only about 10% and 15%, respectively. Although investments of $570 billion by 2030 have been announced, around $430 billion of investment projects are still needed by 2030 (i.e., 45% of the total requirement) to be in line with the Hydrogen for Net-Zero Scenario.

CONCLUSIONS

In the context of climate change, which already produces serious effects on the environment and human society, but also for other reasons, such as air pollution, urgent measures are needed to reduce greenhouse gas emissions and other noxes in the transport sector. Hydrogen-based mobility, although it currently has a minimal share in the transport sector, could represent a potential alternative to means of transport that use fossil fuels, as the impact on the climate is significantly lower if the production process of hydrogen uses renewable electricity.

However, hydrogen's potential to reduce carbon dioxide emissions depends largely on how it is produced. As electrolysis capacity increases and becomes more efficient, the production cost of hydrogen is expected to decrease, being closely related to the cost of renewable energy. If the cost of renewable electricity (especially solar and wind) continues to fall, interest in green hydrogen could increase. Currently, the use of hydrogen has the greatest advance in the field of road transport, but there are concerns about the implementation of hydrogen-based technologies in the other sectors of transport (rail, sea or air).

Although research and development programs in the field of hydrogen-based mobility have been underway for several decades, the technologies in the field have not yet reached maturity. Thus, research and development must continue at a sustained pace to increase the competitiveness of HFCEVs, which depends on the production cost of hydrogen and other technological costs, such as the cost of fuel cells. To really take hold also requires investment in the supporting infrastructure to enable easy refueling.

The transition to hydrogen-based mobility requires increased investment in green hydrogen production and supporting infrastructure. For a faster rate of growth, increased actions are needed to encourage new development projects, provide clear political signals in the direction of mobility and raise awareness among the population about the ecological role of this type of mobility.

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