MSc Program
Engineering Management

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Comparison of Hydrogen Policy, Focusing on Green Hydrogen Deployment in the EU and Japan

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
Dipl.-Ing. Dr. Gustav Resch

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Vienna, 19.04.2022

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Affidavit

I, **TOMOKO FURUSAWA, MPP**, hereby declare

1. that I am the sole author of the present Master's Thesis, "COMPARISON OF HYDROGEN POLICY, FOCUSING ON GREEN HYDROGEN DEPLOYMENT IN THE EU AND JAPAN", 92 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

The core objective of this thesis is to compare hydrogen policies with a focus on green hydrogen deployment in the European Union (EU) and Japan, to capture lessons learnt and best practices, and to identify how a suitable policy or approach may look like for other countries that consider adopting green hydrogen in the near future.

Green hydrogen is produced with renewable electricity through water electrolysis, which is the focus of this thesis. It is called *renewable hydrogen* or *clean hydrogen* in the EU and *CO_2-free hydrogen* or *clean hydrogen* in Japan.

Adopting green hydrogen requires the availability of inexpensive renewable power and electrolysers and the efficient and flexible performance of the latter, the cost and availability of its transport and storage infrastructure, and the availability of a sufficient number of skilled personnel. All these aspects need to be covered under hydrogen strategies, plans and actions, and an enabling policy framework with concrete financial instruments to be established when countries envisage to adopt green hydrogen. Strong national stakeholder (government, industry, academia, and investors) collaboration and partnerships are essential. Regional coordination and support, as seen in the EU, and international cooperation are also necessary to accelerate the adoption and deployment of green hydrogen.

The hydrogen strategies of the EU and Japan both provide overall targets and measures on the future role of hydrogen in their (multi-) national energy systems and economies. The EU and Japan likewise started from a research and development (R&D) level, with continued hydrogen demonstration and deployment. Both strategies adopted a phased approach to integrating hydrogen into their energy systems, indicating short-, medium- and long-term actions with concrete targets and measures, as well as the provision of substantial financial support. They recognized the necessity of using low-carbon (blue) hydrogen to replace existing hydrogen and create an economy of scale of green hydrogen in the transitional phase until around 2030. Existing multilateral partnerships and initiatives also support their actions and accelerate electrolyser technology improvement and green hydrogen uptake. Where applicable, cooperation on the regional level, as seen in the EU, enables countries to achieve a coordinated deployment of green hydrogen across Member States. Each country has a different base for its policies and actions, depending on its social, economic, and political priorities, as well as available resources and infrastructure. Still, the lessons learnt and best practices from the hydrogen strategies of the EU and Japan provide useful perspectives for those countries that may consider adopting green hydrogen in the near future.

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Countries where renewable energy resources are affordable and sustainable, and where higher renewables shares in their energy mixes have been or will be achieved, appear to have a higher potential for adopting green hydrogen. If produced in a sustainable manner, green hydrogen would be a promising option as an energy carrier by providing flexibility and long-term storage capacity and contributing to decarbonization. It can be expected that in the near future, with the right policies put in place, green hydrogen could become one of the most reliable and affordable energy carriers for many countries and contribute to achieving the climate change goals and environmental benefits altogether.

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1 Description of Research Problem

If produced sustainably, hydrogen is a clean fuel that can be stored and transported. It provides flexibility and new possibilities which can support accelerated implementation of climate change actions. With a strong potential to bridge one important gap for variable renewable energies like hydropower, wind, and solar photovoltaics, it serves as a vector for renewable energy storage, alongside batteries (stationary and in transport), pumped hydropower, or other forms of storage, ensuring backup for daily and seasonal variations and connecting production locations to distant demand centres. The European Commission (EC) estimates that over 20% of the global energy demand may be supplied by clean hydrogen by 2050 (EC, 2020a: 1,2). Hydrogen is becoming essential to support the global effort to implement the Paris Agreement adopted in 2015, as well as the contribution to achieving energy security in many countries (EC, 2020a: 1,2). To achieve a profound, or eventually full, decarbonization of economies, countries will need to work together and implement coordinated and wide-range actions in various economic sectors (IRENA, 2021b: 9).

Almost all Member States of the European Union (EU) signed the *Hydrogen Initiative* in 2018 and have included plans for clean hydrogen in their national energy and climate plans. The EU implements the Cohesion Policy and utilises the Cohesion Fund, which enables all Member States in the EU and the EU as a whole to achieve harmonious and sustainable development, as well as the EU's 2050 climate-neutrality goal (EC, 2020a: 1).

In October 2020, Japan announced the aim to achieve net zero greenhouse gas (GHG) emissions by 2050. It has also been promoting hydrogen to decarbonise its economy. By deploying hydrogen, Japan plans to decarbonise industrial processes and economic sectors. The country launched its Basic Hydrogen Strategy in 2017 and hosted the Hydrogen Energy Ministerial Meeting in 2018, the world's first cabinet-level discussion devoted to hydrogen. In June 2019, the Statement of the Future Cooperation on Hydrogen and Fuel Cell Technologies was signed by the Ministry of Economy, Trade and Industry of Japan (METI), the European Commission Directorate-General for Energy, and the United States Department of Energy. These high-level forums are expected to further accelerate the progress in hydrogen technologies globally (METI press, 2019).

For the last few years, an increasing number of countries has adopted national hydrogen policies and strategies, and some more are expected to follow. The costs for hydrogen produced with renewable energy are becoming lower, while the urgency of cutting GHG emissions increases. This has driven a favourable momentum for green hydrogen (IRENA, 2019c: 5).

This thesis aims to clarify the policy and economic context of EU's and Japan's hydrogen strategies - and initiatives for green hydrogen in particular - that stem from renewable origins, examining the progress made, identifying the challenges and opportunities, and describing its international and future implications to other countries. The findings will be useful and applicable to countries or regions, especially to some emerging economies that may consider deploying green hydrogen in the near future, while at the same time sharing energy challenges similar to the EU and Japan. These include increasing electrification and energy demand, as well as reliance on foreign fossil fuel imports while achieving sustainable economic growth.

Thus, related key research questions are:

- What are the pros and cons of enhancing the use of green hydrogen (and what are the alternatives)?
- What are the policies for green hydrogen deployment in the EU and Japan?
- What are the challenges, opportunities, best practices, and lessons learnt from such policy planning and implementation?
- How are the relevant plans and actions being developed and implemented?
- What kind of financial and technical support/cooperation is provided?
- How may optimal policies or approaches for green hydrogen deployment/adoption look like for replication by other countries that may consider deploying green hydrogen in the near future?

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2 Description of Methodical Approach

2.1 Method of approach

This master thesis was written based on literature review and research, including various reports and articles from credible national and international institutes, such as the International Renewable Energy Agency (IRENA), the International Energy Agency (IEA), and the Hydrogen Council, as well as scientific journals, such as Renewable Energy Journals and ELSEVIER.

Other information resources from the websites of the EC and the Japanese Government were also referred to and utilised to analyse the policy and regulatory framework on green hydrogen.

The information was collected and extracted with the following keywords: (i) *Europe hydrogen*, (ii) *Japan hydrogen*, (ii) *green/renewable/CO_2-free/clean hydrogen*, and (iv) *electrolyser/electrolysis*, for the period between 2017 and 2021, since there have been significant development and progress in green hydrogen, especially over the last few years. Green hydrogen is hydrogen produced through water electrolysis fueled by renewable energy (IRENA, policy 2020), which is the focus of this thesis. Green hydrogen is referred to as *renewable hydrogen* or *clean hydrogen* in the EU, and *CO_2-free hydrogen* (hydrogen produced by renewal sources or hydrogen produced by mostly imported fossil fuel plus carbon capture and storage (CCS)) or *clean hydrogen* in Japan.

First, the information and data in the literature were collected and used for analysis from economic, technological, and environmental perspectives. The information collected was organized and assessed to propose an optimal policy for green hydrogen adoption.

While not exhaustive, this approach allows to form the evidence base for this paper and serves as a guidance for developing the proposals herein.

2.2 Structure of work

This master thesis is organized into six chapters, as follows:

Chapter one outlines a brief background of the research and the current situation of green hydrogen deployment in the EU and Japan.

Chapter two details the motivation and methodology of the research conducted.

Chapter three, Green Hydrogen, describes what is considered as green hydrogen and informs on the status of related technologies and developments. Green hydrogen produced via electrolysis is the focus of this thesis, as it is considered one of the most promising and sustainable energy carriers. Some major pros and cons, benefits, challenges, and opportunities of green hydrogen are explored, albeit in a non-exhaustive manner.

Chapter four, EU's and Japan's Green Hydrogen Deployment Policy, reviews the pathway and policy of green hydrogen deployment in the EU and Japan, including green hydrogen production, demand, supply chains and ongoing demonstration projects. The analysis essentially compares the EU's and Japan's policy and regulatory framework, technical and financial support for green hydrogen deployment provided so far, and action plans for the next decades.

Chapter five describes the results and the summary of comparison, and suggestions for suitable policies and approaches. It also provides lessons learnt, best practices of green hydrogen deployment, and recommendations for the optimal policy which could be replicated in other countries and regions.

Chapter six concludes this thesis with a comparison and summary of the results, best practices and lessons learnt, and provides suggestions for suitable policies and approaches.

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3 Role of Green Hydrogen in the Energy System

3.1 Green hydrogen

Climate change is the primary driver for hydrogen in the energy transition. In 2015, the global community committed itself to take action to limit global warming to below 2°C, which requires that CO_2 emissions decline by around 25% by 2030 from 2010 levels and reach net zero by 2050.

As the world strives to cut GHG emissions and reach carbon neutrality by 2050, energy-intensive industries and transport are poised to face significant challenges. Green hydrogen, produced by renewable power, can help reduce carbon dioxide (CO_2) emissions by half to abate sectors such as industry, steel, chemicals, and transport, long-haul transport, shipping, and aviation. Owing to a reduction of renewable energy costs, hydrogen is expected to become a cost-competitive clean energy carrier globally by 2030. Especially in locations that are remote from electricity grids or whenever high energy density is required, hydrogen can become a suitable energy carrier for applications, and can serve as a feedstock to produce synthetic fuel (IRENA, 2021b: 9).

Green hydrogen could provide additional system flexibility and storage of renewable energy, which will also contribute to enhancing energy security and reducing GHG emission and air pollution as well as fostering innovation (IRENA, 2021b: 9).

In 2019, around 120 million tonnes (Mt) of hydrogen were generated, around 60% of which is pure hydrogen and 30% is a mixture with other gases (IRENA, 2019c: 9) and less than 1% is green hydrogen. Around 95% of all hydrogen is produced from natural gas and coal and used mainly on-site in the refining industry and for ammonia production, which makes around 60% of hydrogen use. Around 5% of hydrogen is a by-product from chlorine production through electrolysis. (IRENA, 2019c: 9).

Green hydrogen can be transported for long-distance in large quantities after converted into ammonia, methanol, methane, and liquid hydrocarbon. When hydrogen is combined with oxygen, the chemical reaction produces electricity which is hydrogen fuel cell. Fuel cells are used for energy production, small-scale electricity grid or for backup purposes, or transport purposes, including fuel cell electric vehicles (FCEV). As a chemical, green hydrogen can reduce GHG

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emissions from sectors where hydrogen from fossil fuel is widely used, including oil refining, methanol, and ammonia production (IRENA, 2020c: 16).

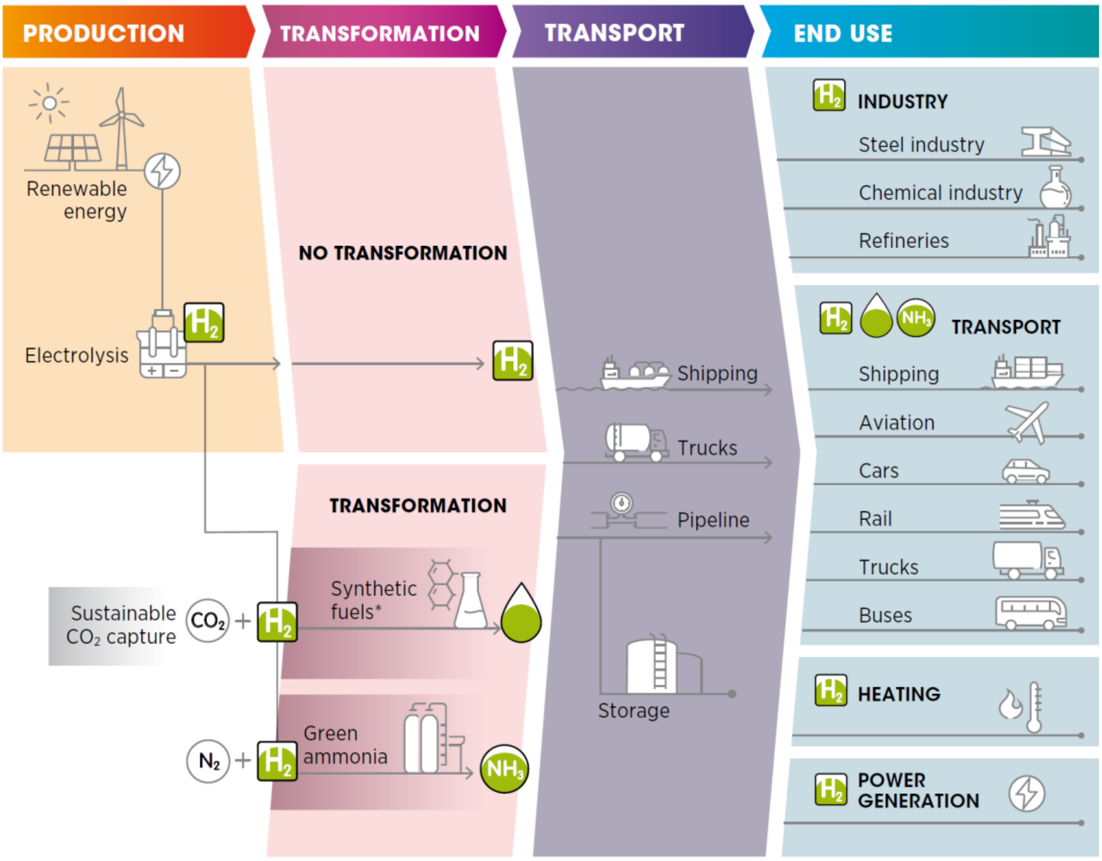

Figure 1: Schematic overview of green hydrogen production, conversion and end uses *(Source: IRENA, 2020b)*

By 2050, it is expected that 160 Mt of green hydrogen will be produced in the world per year, which would at the same time account for 5% of total final energy consumption (IRENA 2020a: 30). This demand for green hydrogen production would equal 30-120 EJ of renewable electricity needed for electrolysis, or 8-30 petawatt-hours. This quantity of green hydrogen will require approximately 4-16 terawatts (TW) of renewable power to generate green hydrogen in 2050. In 2019, global power generation capacity accounted for 7TW, with 1TW of solar and wind power capacity in place (IRENA, 2019c: 22). Significant scale-up of electrolysers is necessary to produce the expected amount of green hydrogen, requiring additions of between 50GW and 60GW per year of new electrolyser capacity from 2020 until 2050 (IRENA, 2020a: 30).

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However, blue hydrogen may also play a role in the transition phase until around 2030, when demand for green hydrogen might outweigh supply because of limited renewables capacity or transport infrastructure, for example.

3.1.1 Green hydrogen production

Hydrogen can be produced with multiple processes and from difference energy sources. A colour code nomenclature on hydrogen is widely used, as shown in Figure 2 below.

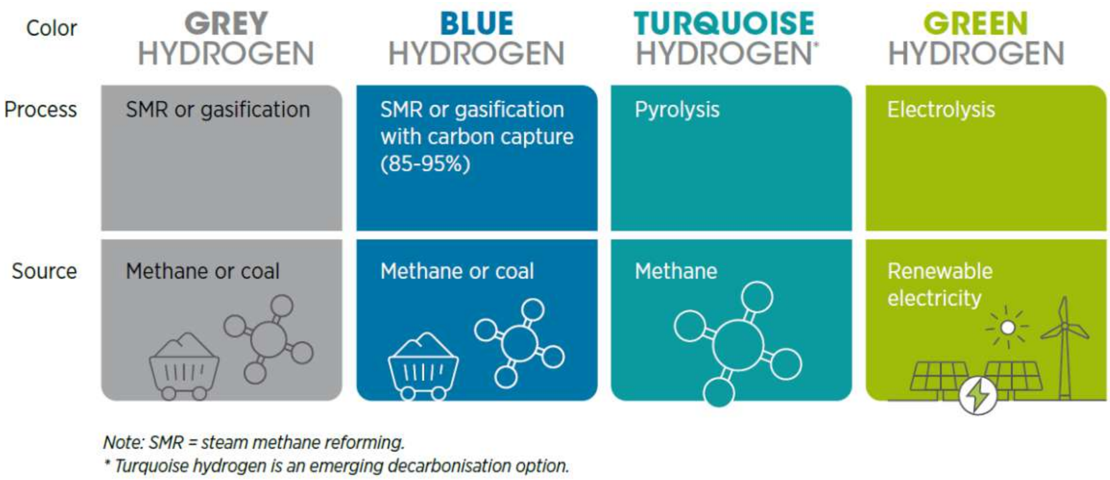

Figure 2: Selected shades of hydrogen *(Source: IRENA, 2020b)*

Grey hydrogen – produced with fossil fuel, i.e., from methane using steam methane reforming (SMR) or coal gasification. Grey hydrogen is the hydrogen mostly produced currently. Life cycle GHG emissions of the production of fossil-based hydrogen are high (EC, 2020b).

Blue hydrogen – produced with fossil fuel combined with carbon capture, utilisation and storage (CCUS), is expected to facilitate the transition and expansion of a hydrogen market. Over 75% of hydrogen currently produced is blue hydrogen. GHG emissions of the production of fossil-based hydrogen with carbon capture or pyrolysis are lower than those of fossil-fuel-based hydrogen (EC, 2020b).

Turquoise hydrogen – produced with natural gas as feedstock, but without CO_2 production. It is still at the pilot stage.

Green hydrogen – produced with renewables electricity through water electrolysis to separate hydrogen from oxygen, which is the focus of this thesis. It is called *clean or renewable hydrogen* in the EU, and *CO_2-free hydrogen* in Japan. Life cycle GHG emissions of the production of renewable hydrogen are close to zero (EC, 2020b).

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While less common than electrolysis, green hydrogen may also be produced by reforming biogas (instead of natural gas) or by biochemical conversion of biomass. (EC, 2020b).

There are four types of electrolysis technologies currently used:

i. *“Alkaline electrolysis (AEL) - 61% of installed capacity in 2020 (IEA, 2021a: 116). Used by industries since the 1920s, it is mainly for non-energy purposes, particularly in chlorine manufacture. Although the technology is fully mature, further research is needed on how the use of variable renewables may affect the operation and maintenance of the system.”* (IRENA, 2020e, 180)

ii. *“Proton exchange membrane (PEM) - 31% of installed capacity in 2020 (IEA, 2021a: 116). It has been deployed at a commercial scale, although it is not yet a fully mature technology. To reduce costs and upscale production, further improvements in the materials, membranes, performance and design of stacks are necessary and expected.”* (IRENA, 2020e, 180)

iii. *“Solid Oxide Electrolyser Cells (SOEC) – It is less mature and some small-scale pilot projects are ongoing. It is a type of high-temperature electrolysis, has potential advantages to producing low-cost green hydrogen, with higher overall efficiencies.”* (IRENA, 2020e, 180)

iv. *“Anion Exchange Membrane (AEM) – It is still a less mature technology with high potential. Only a few companies have commercialized it, with limited deployment.”* (IRENA, 2020c: 34)

Table 1: **Comparison of electrolysers** *(Source: adapted from IRENA, 2021b)*

	AEL	PEM	SOEC	AEM
Development status	Commercial	Commercial	Small scale pilot	Lab scale
Efficiency (system) [kWh/kgH_2]	50-78	50-83	45-55	Limited information
Lifetime [thousand hours]	60	50-80	<20	>5
Operating temperature [°C]	100-150°C	70-90°C	700-800°C	Limited information
Capital cost estimate for large stacks (stack only, >10MW) [USD/kWel]	270	400	>2,000	Limited information
Capital cost range estimate for the entire system, >10MW [USD/kWel]	500-100	700-1400	-	Limited information

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Of the installed global electrolyser capacity of 0.2 GW in 2020 (IRENA 2020e: 179), Europe has more than 40% of the share, followed by Canada with 9%, and China with 8% (IEA, 2021a: 116), while Europe has 60% of electrolysis manufacturing capacity and China 35%. A dedicated hydrogen infrastructure and network as well as supply chain will be necessary to support the global electrolyser capacity required for 2030 onwards (IEA, 2021a: 121).

The increase of electrolyser production will lead to the increase demand for minerals, mainly nickel and platinum group metals, which may, however, depend on the type of electrolyser technology. While AEL does not require precious metals, current designs use 800–1,000 t/MW of nickel. Even if AEL dominated the market by 2030, under the Net Zero Emissions by 2050 Scenario of IEA, this would translate into a nickel demand of 72 Mt, which is much lower than the amount needed for batteries. The catalysts in PEM electrolyser require 300 kg of platinum and 700 kg of iridium per GW. Therefore, if PEMs supplied the entire electrolyser production in 2030 under the Net zero Emissions Scenario, demand for iridium would significantly increase to 63 kt, nine times the current global production. However, it is expected that further recycling of electrolyser materials and the efficient use of minerals in electrolyser production may reduce the demand for both iridium and platinum by 10 % in the next few years. The AEM electrolyser, which does not require platinum, may advance in the meantime. PEM electrolyser cells can be recycled, which would further reduce the primary demand for these metals (IEA, 2021a: 121).

3.1.2 Green hydrogen cost

In 2020, green hydrogen cost accounted for around USD 2.6–6.7/kg (EUR 2.3–5.9/kg) (IRENA, 2020e: 183), which is 2–3 times more than blue and grey hydrogen. The cost of green hydrogen production is based on the cost of renewable power, the cost and performance of electrolysers, as well as the cost of green hydrogen transport and storage (IRENA 2020e: 182). Over the last ten years, the cost of green hydrogen has been reduced significantly due to reduced electrolyser costs and cheaper renewable power (IRENA, 2020a: 180). Hydrogen cost was USD 10–15 per kg in 2010, then, reduced to USD 4–6 per kg in 2020 (IRENA, 2020b: 10). Electrolyser costs are projected to fall a further 20–30% by 2030 and 60–70% by 2050 (IRENA, 2020c: 11). An analysis by the Hydrogen Council shows that the cost of electrolysis will continue to fall, and offshore wind-based electrolysis shows another 60% cost reduction from 2020 until 2030, as shown in Figure 3 below (Hydrogen Council, 2020: 23).

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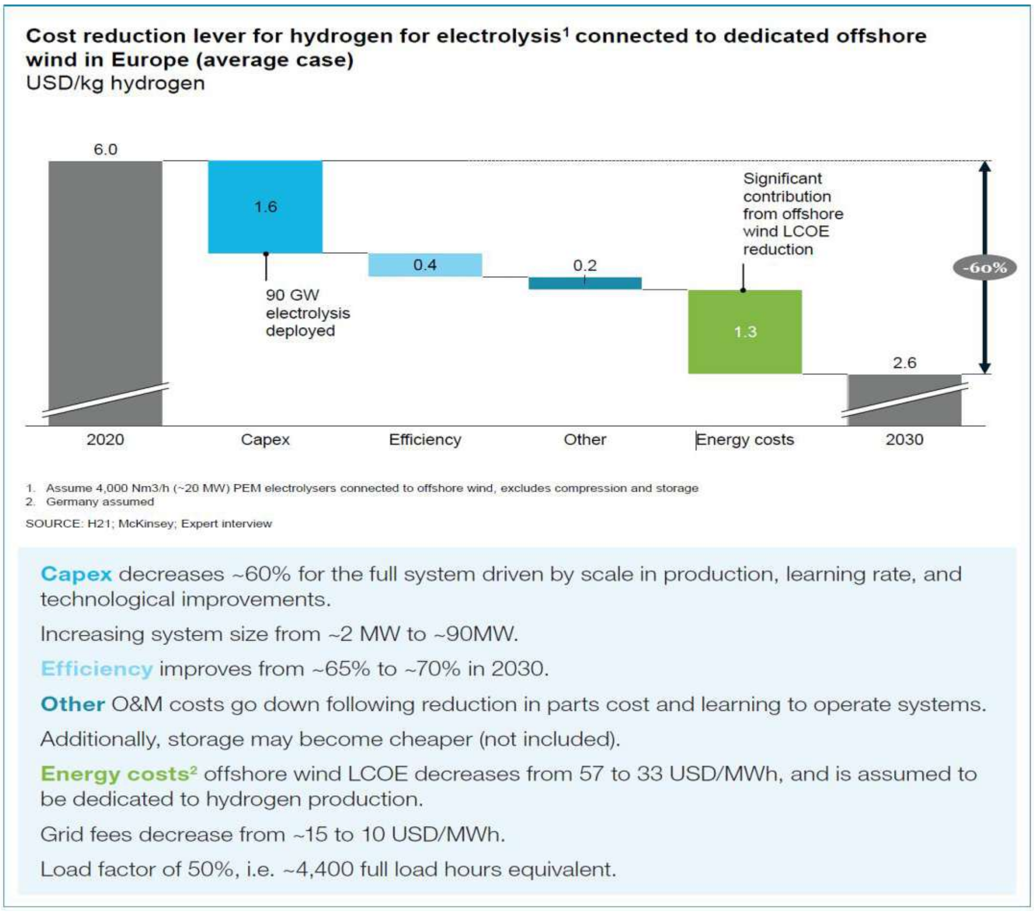

Figure 3: Projection of cost reduction for green hydrogen *(Source: Hydrogen Council, 2020)*

Main factors for continued cost reduction include the industrialization of electrolyser manufacturing (-25%), improvements in electrolyser efficiency, operations and maintenance (-10%), and the use of low-cost renewable power (-20%). Low-cost renewable power is region-specific and highly depends on access to renewable resources, mainly solar and wind (Hydrogen Council, 2020: 24).

As Figure 4 below shows, at some locations with favourable low-cost renewable electricity (from solar and wind), green hydrogen may become competitive with blue hydrogen by 2030, with green hydrogen production costs around USD 2.5–3/kg (EUR 2.2–2.7/kg) (IRENA, 2020c: 180).

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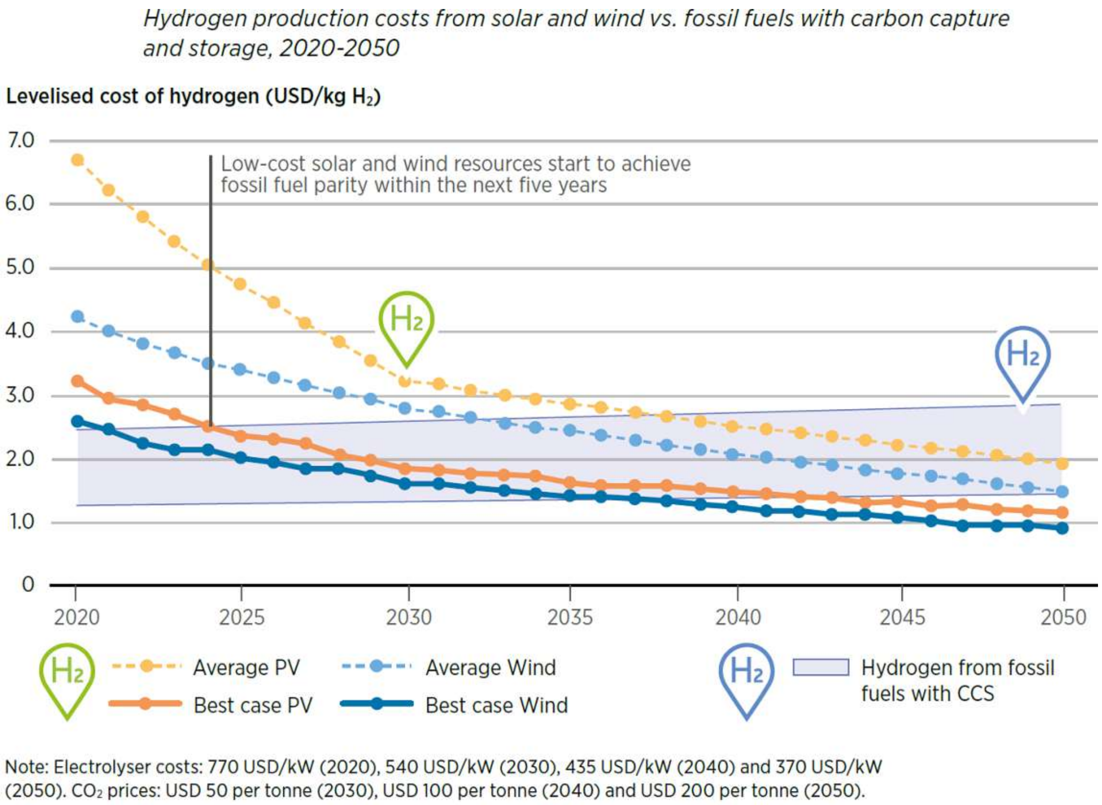

Figure 4: **Green hydrogen production cost, in comparsion with blue hydrogen** *(Source: IRENA Global Renewbles Outlook, 2020)*

The cost of electricity accounts for around 30-60% of the total cost of producing hydrogen, which varies depending on the cost of electricity, the capacity, load hours and location of the electrolyser (Ainscough, Peterson and Miller, 2014, cited by IRENA, 2019c: 15). The levelized cost of hydrogen is directly proportional to electrolyser load factors. Thus, lower electricity costs enhance cost-effectiveness and competitiveness of green hydrogen (IRENA, 2019c: 15).

In some countries and regions, hydrogen imports could be less expensive than domestic production, as Figure 5 below shows. For example, in Japan, domestic production of hydrogen using electrolysers and its distribution could cost around USD 6.5/kg H_2 (EUR 5.7/kg H_2) in 2030; hydrogen imported from Australia could cost around USD 5.5/kg H_2 (EUR 4.8/kg H_2). This opportunity would be similar in Korea and parts of Europe. Hydrogen imports could be more competitive by using ammonia directly in certain end-user. Hydrogen imports could help diversify energy sources and maintain energy security, especially for some energy-importing countries (IEA, 2019c: 67). For hydrogen exports, Africa has the potential to produce hydrogen (for both domestic use and export) around 500 Mt per year at less than

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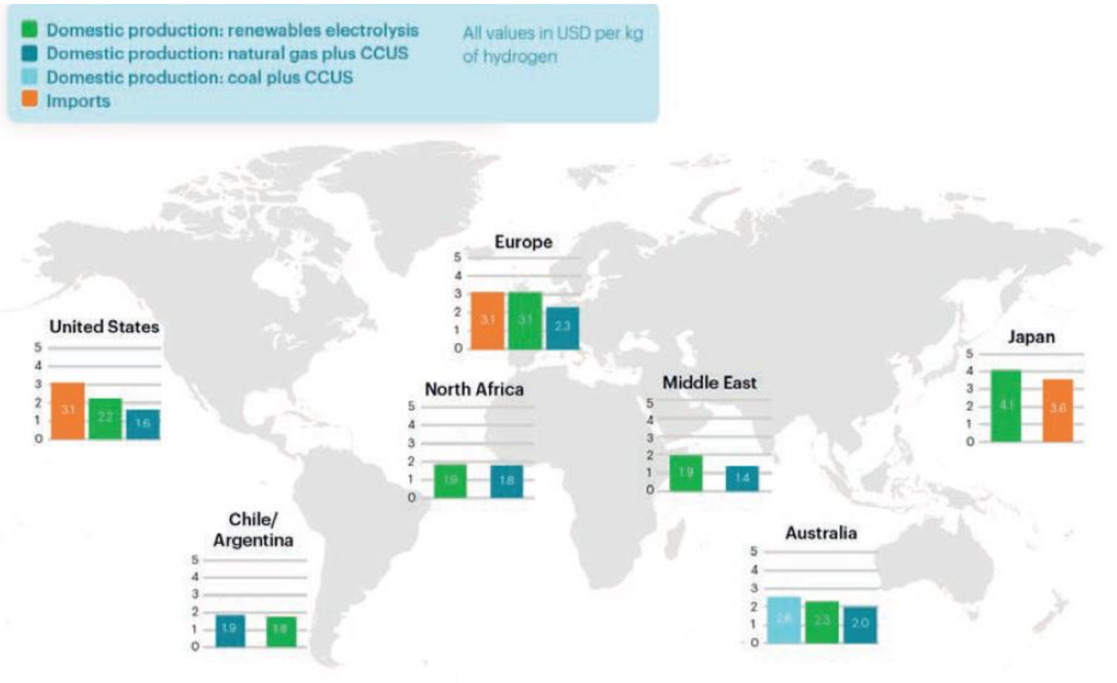
USD 2/kg (EUR 1.8.kg), and the Middle East could produce hydrogen combined with CCUS (IEA, 2019c: 188).



Notes: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area. Production cost reflects long-term potential (i.e. low CAPEX for wind and solar, see Chapter 2). Electrolysis considers dedicated wind and solar production.

Source: IEA 2019. all rights reserved.

Figure 5: Comparison of the long-term costs of domestic hydrogen production and hydrogen imports *(Source: IEA, 2019c)*

3.1.3 Green hydrogen infrastructure

Once compressed, liquified or converted to ammonia or liquid organic hydrogen carriers (LOHC), hydrogen can be transported or shipped for long distance through existing tanks and pipelines similar to natural gas. However, additional energy will be necessary for liquefaction and continuous cooling. Hydrogen can be stored in steel tanks or underground geological formations, such as salt caverns (IRENA, 2020b: 38).

For all types of hydrogen, dedicated infrastructure for transport and storage is missing. Hydrogen has so far been generated for on-site consumption. Globally, there are only about 5,000 km of hydrogen transmission pipelines (Hydrogen Analysis Resource Center, 2016, cited by IRENA, 2020b: 13). On the other hand, there are over three million km of pipelines for natural gas. Some of the natural gas infrastructure could be repurposed for hydrogen, while not all regions have existing infrastructure. On the other hand, synthetic fuels made from green hydrogen may be

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able to use existing tanks, pipelines, and other infrastructure, although it might need to be expanded (IRENA, 2020b: 13).

Hydrogen gas has been transported through natural gas pipelines over the last decades in several locations, including Belgium, France, Germany and the Netherlands (IEA, 2019b: 19). The existing natural gas infrastructure could transport hydrogen at much lower unit costs than when new dedicated hydrogen pipelines had to be built (IEA, 2019d: 589), although additional pipeline monitoring and maintenance measures would be necessary.

Hydrogen transport by pipeline is found to be more cost-effective than electricity transport by cable. In general, pipeline capacities (15-20 GW) are much larger than electricity cable capacity (1-4 GW). Pipeline hydrogen transport could help avoid electricity grid capacity constraints caused by integration of increasing renewable electricity production (van Wijk, 2021).

In general, the elements along the gas value chain that can tolerate the blending of hydrogen determine the national regulations for gas quality. Currently, most countries limit hydrogen concentrations in their natural gas network. Some countries allow a maximum of 2% blending and a few others between 4% and 6%, as Figure 6 below shows. Germany allows a maximum of 10%, but less than 2% if compressed natural gas (CNG) filling stations are connected to the network. There are some limitations in blending hydrogen due to the nature of some equipment in the network. According to European standards, the hydrogen content should be less than 1 % in control systems and seals of gas turbines (IEA, 2019c: 72). In 2019, there were 30 projects for blending hydrogen into natural gas networks globally at both the transmission and distribution levels (IEA, 2019d: 589).

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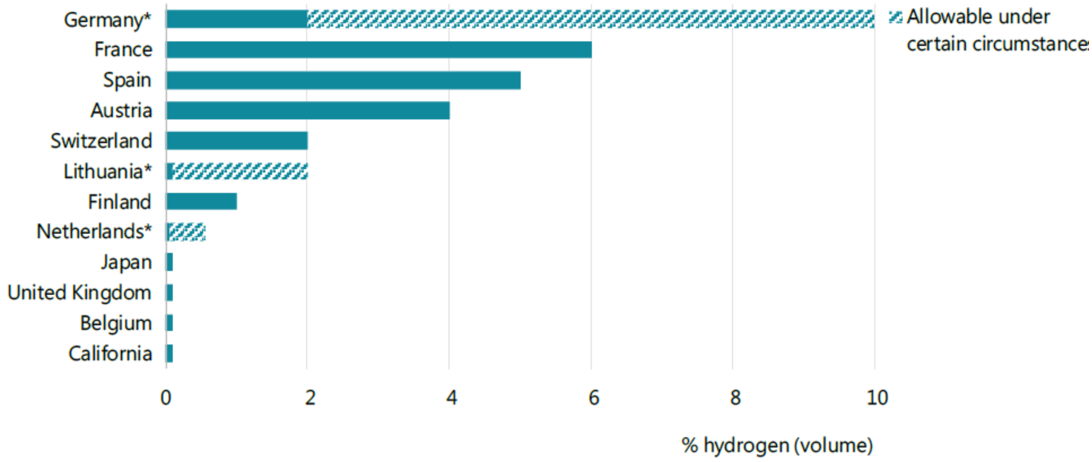

* Higher limit for Germany applies if there are no CNG filling stations connected to the network; higher limit for the Netherlands applies to high-calorific gas; higher limit for Lithuania applies when pipeline pressure is greater than 16 bar pressure.

Sources: Dolci et al. (2019), "Incentives and legal barriers for Power-to-Hydrogen pathways: An international snapshot", *Internation Journal of Hydrogen*; HyLaw (n.d.), *Online Database*; Staffell et al. (2019) "The role of hydrogen and fuel cells in the global energy system", *Energy and Environmental Science*.

Figure 6: Current limits on hydrogen blending in natural gas networks *(Source: IEA, 2019c)*

Since natural gas is internationally traded, harmonizing hydrogen blend limits across borders is necessary to support deployment. Standards should be revised, also taking possible variability in hydrogen blending levels over time into account. In Europe, in addition to the EC, several groups are examining standards for hydrogen blending. For example, the *HyReady,* a global industry project develops guidelines for transmission system operators (TSOs) and distribution system operators (DSOs) to introduce hydrogen to the grid, and the *HIPS-NET* , a group of 40 gas companies, explores a common hydrogen tolerance in the gas infrastructure (IEA, 2019c: 72).

Not only to ensure the safety of the gases in the pipeline, but also to promote the effort for decarbonisation, it is important to keep track of the amount of hydrogen injected into the grid and its carbon intensity. This accounting method, generally called a *guarantee of origin*, is essential if operators are paid a premium for supplying lower-carbon gas. In Europe, the *CertifHy,* a consortium of the certification bodies in Europe, developed hydrogen certification schemes and a central database of guarantees of origin for hydrogen. It has issued over 75,000 certificates since 2018 (IEA, 2019c: 72).

3.1.4 Green hydrogen end-use

Though there are various uses for green hydrogen and fuel cell technologies, this thesis focuses on the most promising green hydrogen applications in the following areas: industry, transport, heat, and power generation.

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i. Industry

Green hydrogen is currently used mainly in the chemical industry to manufacture ammonia and fertilizers, and the petrochemical industry to produce petroleum products (IRENA, 2020b: 6).

Currently grey and blue hydrogen, estimated approximately 36–720 tonnes per year, are used in the iron and steel industry (Fraile and others, 2015, cited by WB 2020: 76). Thus, steel production could use green hydrogen to replace natural gas and be a promising market for electrolysis and green hydrogen because of the high carbon emissions in the production process and the relative lack of viable alternatives.

These energy-intensive industries, i.e., the iron and steel industry, may in the future relocate to areas with sufficient and low-cost renewable energy resources (IRENA, 2020a: 30). It is expected that about 14 EJ of green hydrogen will be consumed in the industrial sector in 2050 (IRENA, 2020a: 181). In 2021, a 45 MW green hydrogen plant was opened in Berlevag, Norway, and is expected to produce green ammonia by 2024 (HAEOLUS, 2021).

ii. Transport

Hydrogen can be used in a fuel cell to produce electricity through a chemical reaction with oxygen, thus, can power FCEVs. According to the IRENA study, the transport sector is expected to be the second largest user of green hydrogen with 4 EJ consumed per year by 2050. Green hydrogen can be used in FCEVs, or shipping and aviation by producing synthetic fuels from hydrogen (IRENA, 2020a: 181).

The cost of FCEVs has decreased by at least 70% since 2006 (IRENA, 2020b: 10). The study conducted under the IEA Advanced Fuel Cells Technology Collaboration Programme estimates that there are a total of 34 804 fuel cell vehicles (FCVs) and 540 hydrogen refuelling stations (HRS) in operation globally by the end of 2020, as Figure 7 shows. Among FCVs, the highest share is passenger cars (25 392) which increased by 37% in 2020, compared to 69% in 2019. In 2020, South Korea became the first country to surpass 10,00 vehicles, followed by the USA (9,000) and China (8,000) (Samsun, et al., 2021: 6, 18, 36).

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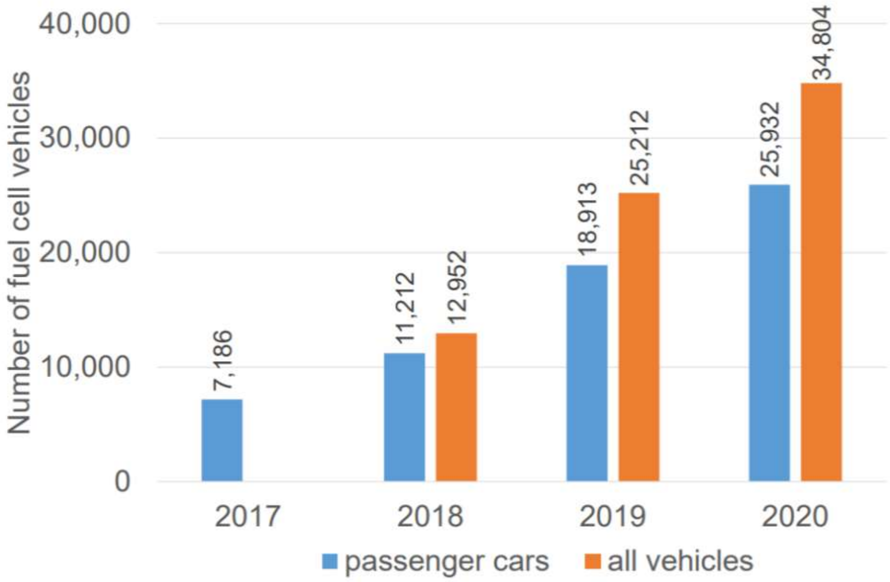

Figure 7: Numbers of fuel cell vehicles deployed globally for 2017-2022 *(Source: Samsun, et, al., 2021)*

The total number of HRS saw an increase of 15% in 2020, compared to 23% in 2019. The highest number with 137 was seen in Japan, followed by Germany (90), China (66) and the USA (46). It is worth noting that in Sweden, green hydrogen is supplied in all five HRS by the end of 2020 (Samsun, et al., 2021: 15, 36).

The Hydrogen Council foresees 10,000 HRS by 2030, to fuel around 4.5 million FCEVs globally (Hydrogen Council, 2021).

iii. Heating/buildings

In buildings, hydrogen can be blended with natural gas or used to produce synthetic methane, and injected into natural gas pipelines (IRENA, 2019b: 43).

Electricity and heat can be generated from hydrogen by fuel cells. Various fuel cell technologies are currently available for stationary power applications, achieving over 60% electric efficiency (IEA, 2019c: 152). However, current fuel cell stacks suffer from a shorter technical lifetime (5,000 to 10,000 hours of operation) than the lifetime of gas turbines (10,000 to 40,000 hours of operation). Furthermore, current stationary fuel cells have a smaller power output (up to 50 MW for the largest fuel cell power plants), making them most suitable for distributed generation (IEA, 2019c: 156). In 2018, the capacity of stationary fuel cells installed globally was around 1.6 GW, mostly run on natural gas, while around 70 MW run on hydrogen (IEA, 2019c: 153).

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Combined heat power (CHP) systems can efficiently heat the buildings while providing electricity. There are micro co-generation and fuel cell hydrogen demonstration projects, such as the *ENE-FARM* project in Japan, and the *ene.field* demonstration in Germany. This direct hydrogen use for heat production in buildings is more promising than hydrogen blending in existing natural gas networks due to several barriers related to cost, infrastructure, and policy design challenges (IEA, 2019c: 145).

iv. Power generation

Hydrogen can serve as (seasonal) storage of electricity generated from renewables (especially in summer), enabling the production and supply of clean electricity (in winter) (FCH JU, 2019: 50), and providing grid balancing services and buffering of congested renewable electricity. This role of hydrogen would contribute to managing intermittency and seasonal imbalances in the energy system.

In 2021, hydrogen was used for less than 0.2% of electricity generation. Recently hydrogen and hydrogen-based fuels can also be used in gas turbines, combined-cycle gas turbines (CCGTs) or fuel cells. Hydrogen-fired gas turbines and CCGTs could be a source of flexibility in electricity systems as the share of variable renewables increases.

Most of the current gas turbines can cope with 3–5% hydrogen (Mitsubishi heavy industries, 2021). In Fusina, Italy, a 12 MW CCGT has used hydrogen from a nearby petrochemical complex since 2010 (Goldmeer, 2019: 15), providing 60 million kWh per year to meet the needs of 20,000 households (ENEL, 2009). In Kobe, Japan, a 400 MW capacity hydrogen-fired CCGTs unit has distributed electricity (1.1MWe) and heat (2.8 watts thermal energy) to its adjoining premises since 2020 (Kawasaki, 2020).

3.2 Pros

i. Flexibility for storage and balancing variable renewable energy

Hydrogen can serve as a buffer to curtailed renewable energy and balance the grids. It can be stored in natural underground reservoirs for seasonal balancing, thus, can also balance intermittent renewable generation (IRENA, 2020a: 180).

Increasing variable renewable energy capacity provides an opportunity to produce hydrogen, using the excess renewable energy that would otherwise be curtailed, to keep power systems flexible and balance the grid. Unlike storage batteries,

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hydrogen can be stored on a large scale and for the long term, ensuring a reliable power supply when renewable generation is not sufficient, or prices are favourable to convert it back to power (Arias, 2019: 122). However, to be effectively used for seasonal energy storage, low-cost hydrogen is a prerequisite.

Hydrogen and hydrogen-based fuels can be transported over long distances from regions with abundant solar and wind resources (IEA, 2019c: 13). It can also be stored in compressed or liquefied form in natural or manmade structures, or mixed with other chemicals to produce liquid fuels or solids.

According to a study by the Det Norske Veritas Group, hydrogen transport via the gas network as well as hydrogen storage and use for electricity could be more beneficial than its industrial use, since the current electricity system capacity in Northern Europe is limited (Det Norske Veritas Group, 2017 cited by IRENA, 2019c: 25).

ii. Versatile in terms of supply and use

With current technologies, hydrogen can be used in various forms. It can be compressed as a gas or liquid and transported by gas infrastructure or ships. It can also be converted into electricity and methane to heat or power buildings, or provide feedstock for industries, and into fuel cells for transportations (IEA, 2019c: 13). This versatility of hydrogen provides various possibilities for hydrogen applications.

iii. Climate and environmental benefits

Green hydrogen contributes to decarbonization efforts, especially in the iron, steel, chemical and petrochemical industries. It can replace hydrogen produced from coal or natural gas in the production of direct reduced iron (DRI), while synthetic hydrocarbon feedstocks can replace primary petrochemicals, which could contribute to reducing CO_2 emissions by 30% in 2050.

The use of green hydrogen and other hydrogen-based synthetic fuels can be beneficial in the transport sector. The use of hydrogen and synthetic fuels could reduce CO_2 emissions by 22% in road freight, 25% in aviation, and 50% in shipping in 2050 according to IRENA (IRENA, 2020e: 52).

Hydrogen brings other environmental co-benefits by reducing air pollutant emissions (EC, 2020b: 12). It can play an important role in limiting nitrogen oxide (NOx) emissions, estimated at 7.9 Mt in Europe in 2019. In road transportation, which is responsible for approximately 40% of current NOx emissions, the substitution of

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regular vehicles by the projected hydrogen fleet in 2050 could reduce more than 0.5 Mt in NOx emissions (FCH JU, 2019: 55).

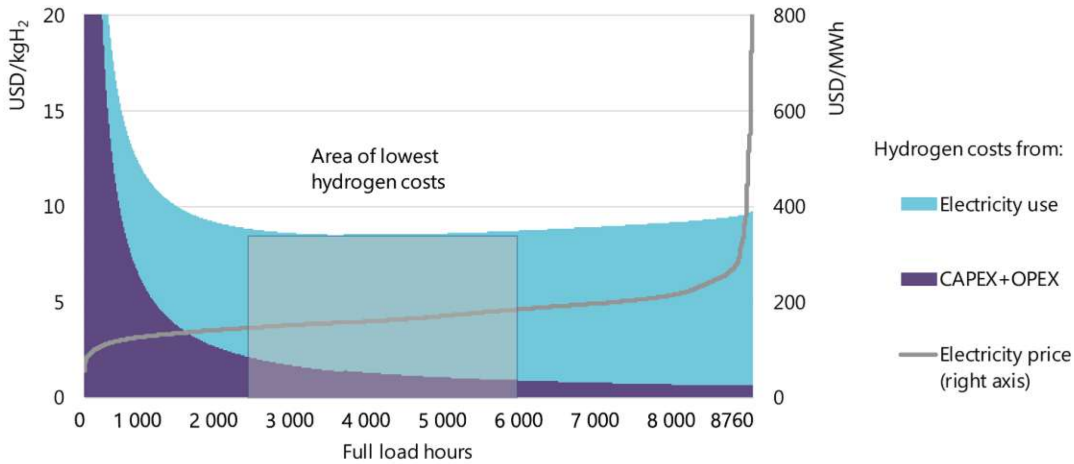
3.3 Cons

i. Cost of hydrogen production

For green hydrogen production, the cost of renewable electricity to operate the electrolysis is the largest cost component, followed by the cost of electrolysis facilities (IRENA, 2020c: 8).

According to IRENA, 85% of green hydrogen production costs can be reduced if the electricity cost to operate electrolyser as well as the capital expenditure (CAPEX) investment of electrolyser become inexpensive, and the performance of the electrolyser can be improved (IRENA, 2020c: 9).

When electrolysers use grid electricity for hydrogen production, the higher utilisation rate of electrolysers help to reduce the impact of CAPEX. However, operating an electrolyser unit at high full load hours of 3,000–6,000 and paying for the additional electricity could be cheaper than operating with surplus electricity at low full load hours, as shown in Figure 8 below (IEA, 2019c: 48).



Notes: CAPEX = USD 800/kWe; efficiency (LHV) = 64%; discount rate = 8%.
Source: IEA analysis based on Japanese electricity spot prices in 2018, JEPX (2019), *Intraday Market Trading Results 2018*.

Figure 8: **Hydrogen costs from electrolysis using grid electricity** *(Source: IEA, 2019c)*

Thus, it will not be possible to generate large quantity of hydrogen using inexpensive or non-dispatchable renewable electricity, if electrolyser operates only up to 10% of the time (IRENA, 2019c: 24).

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Electrolyser equipment is affected by technology choices. To achieve low-cost hydrogen production while satisfying demand requirements, an integrated design for various components is necessary (IRENA, 2020c: 35). Also, technological innovation is needed to further improve the performance of technology, including its efficiency and lifetime.

When considering the cost of electrolysis facilities, it is important to note that the supply of critical materials in electrolysers is mainly dominated by a few countries, as Figure 8 below shows. South Africa supplies over 70% of global platinum and over 85% of global iridium. Limited supplies of critical materials would strongly affect PEM electrolyser deployment, as PEM has limited short-term alternatives to replace these materials. SOEC electrolysers, although having more potential with higher efficiencies than PEM, would also be affected by a similar risk, since almost 95% of the supply for all SOECs' critical materials is currently supplied almost exclusively by China (IRENA, 2020c: 68).

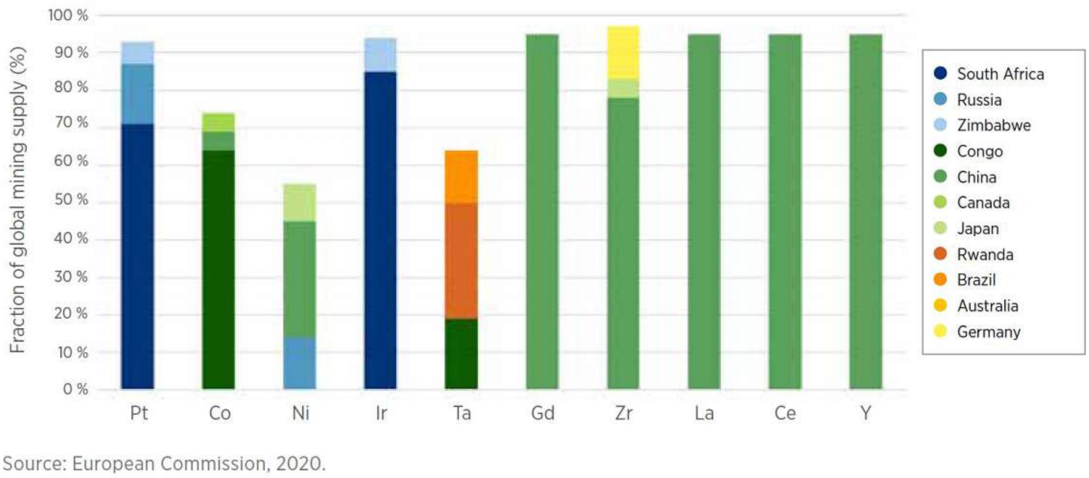

Figure 9: Top producers of critical materials in electrolysers *(Source: IRENA, 2020c)*

Scarce materials can become a barrier to electrolyser cost and scale-up. IRENA estimated that the iridium and platinum currently produced for PEM electrolysers will only provide 3–7.5 GW PEM electrolysers capacity per year, while the PEM electrolysers capacity will need to be around 100 GW per year by 2030 (IRENA, 2020c: 9). Thus, the use of such materials should be avoided, as already being implemented by some leading AEL manufacturers. Furthermore, the technologies to reduce the requirements for such materials in PEM electrolysers already exist. An

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emerging AEM electrolyser does not require scarce materials, but steal and nickel (IRENA, 2020c: 9).

ii. Lack of dedicated infrastructure

There is a lack of dedicated infrastructure for hydrogen transport and storage, as well as export and import. Hydrogen infrastructure is needed to move down the cost curve as green hydrogen production and demand increase.

Building on existing gas infrastructure, including salt caverns and pipeline systems, could provide huge energy storage volumes. However, there are limitations in hydrogen storage capacity and blending hydrogen into natural gas pipelines.

For FCEVs, refueling infrastructure should be adequate and strategically located. Hydrogen sales prices at HRSs will be determined by the number and the location of operational HRSs, the frequency of the HRSs used, and the quantity of hydrogen delivered to the HRSs (IEA, 2019c: 14).

iii. Limit in regulation for green hydrogen

Currently, hydrogen is not counted in energy statistics in almost all countries (IRENA, policy 2020b: 13). Hydrogen is produced mostly for on-site use or under direct arrangements between companies. Thus, a market for green hydrogen needs to be designed in a way that cross-border trading and market expansion are facilitated (IRENA, 2020b: 36). Significant government support is necessary, including financial incentives, standards and certification, and monitoring and tracking green hydrogen.

Valuing green hydrogen depends on guaranteeing origin certification and convertibility to carbon credits. Both processes are still under development, involving extensive regional and international debates (World Economic Forum, 2021).

iv. Efficiency and durability of electrolysis

Green hydrogen suffers substantial energy loss in its value chain. There are 30-35% energy loss at the hydrogen production through electrolysis, 23-25% energy loss at the conversion of hydrogen to other chemicals such as ammonia, and 40–50% energy loss at the use of hydrogen in fuel cells (IRENA, 2020b: 13). If hydrogen can be produced and used at its production site for clean products, such as ammonia, methanol, or DRI, these losses can be reduced (IRENA, 2019c: 21).

The electrical efficiency of electrolysis is around 63–73% for the AEL system, and 60% for the PEM system, while an optimistic efficiency is around 63–80%. Currently the efficiency of electorylsers is higher with partial loads. Thus, optimization and

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control strategies for electrolysers are necessary to improve their operating efficiency (FCH JU, 2018 cited by Yue et al., 2021: 13). Also, fuel cell and electrolyser components may suffer from electrical, mechanical, and thermal deformation, resulting in reduced performance. Current practice lowers the operating voltage of an electrolyser stack in a hydrogen production system by 0.4-5 μV per operation hour, with an electrolyser system durability of around 40,000 h, implying an up to 10% lower efficiency compared to the initial state (Schmidt O, et al., 2017, cited by Yue et al., 2021: 13).

The above issues may result in high operation and maintenance costs. To avoid unexpected shutdowns and component degradation, continuous efforts towards performance improvements are needed.

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4 Description, Assessment, Analysis and Discussion of the EU's and Japan's Hydrogen Policy

Japan spearheaded to publish a national hydrogen strategy in 2017. Among EU countries, France was the first to adopt its hydrogen strategy in 2018. In 2020, the Netherlands, Germany, and the EU adopted their respective hydrogen strategies, followed by Portugal and Spain. Their hydrogen strategies and renewable energy systems related policy measures support their GHG emission reductions under the nationally determined contributions (NDCs), as Table 2 below shows.

Green hydrogen is called *renewable hydrogen* or *clean hydrogen* in the EU, *CO_2-free hydrogen* (hydrogen produced by renewal sources or hydrogen produced by mostly imported fossil fuel plus CCS), or *clean hydrogen* in Japan. Currently, Japan has not provided a clear definition of CO_2-free hydrogen. Since 2017, when its Hydrogen Strategy was released, the definition of CO_2-free hydrogen included hydrogen produced with no CO_2 emission (METI, 2018c: 3). The discussion to define CO_2-free hydrogen has been ongoing since then.

Table 2: **Summary of NDC target, long-term target and relevant policy measures** *(Source: adapted from Fragkos et al., 2020: 5)*

	NDC target	Long-term target	Relevant policy measures
EU	At least 55% GHG emission reduction by 2030 compared to 1990 (July 2021)	Carbon neutral by 2050, compared to 1900, consistent with *European Climate Law* (July 2021) and *A Clean Planet for All Strategy* (November 2018)	The *Fit for 55 package* (July 2021) *Energy Efficiency Directive* (revised in July 2021) *A hydrogen strategy for a climate neutral Europe* (July 2020) *Renewable Energy Directive (RED II)* (revised in 2018) Strengthened *Emission Trading System* (ETS) ambitious CO_2 emission standards for various sectors
Japan	46% GHG emission reduction by 2030 relative to 2013 (April 2021)	Carbon neutral by 2050, announced under *Green Growth Strategy* (December 2020)	*Law Concerning the Promotion of the Measures to Cope with Global Warming (revised in May 2021)* *Renewable Energy Act* (revised in 2020) *Energy Efficiency Act* (revised in 2018) *Basic Hydrogen Strategy* (December 2017) The *Joint Crediting Mechanisms* The *Japan GHG Emission Reduction Certification Scheme (J-Credit)*

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4.1 EU policy

In December 2015, the 28 Member States of the EU signed and ratified the Paris Agreement *"to keep global warming well below 2°C above preindustrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C.*" (FCH JU, 2019: 4).

In accordance with the above, in December 2019, the EC announced the European Green Deal, a roadmap for achieving climate-neutrality in the EU by 2050. This ambition was set into the European Climate Law, announced in March 2020 and adopted in July 2021. In July 2021, the EC presented the so-called *Fit for 55 package* for the updated 2030 GHG emissions reduction target, at least 55% by 2030 (EC, 2022).

In 2019, most CO_2 emissions in the EU occurred in the power generation sector (33%), transportation (32%), and industrial heating and feedstock (15%). In 2019, final energy consumption in the EU was 30.9% by transport, 26.3% by buildings/households and 25.6% by industry (Eurostat site, 2021). To achieve the 2°C target, the EU needs to reduce its annual CO_2 emissions by about 80% in 2050 compared to the 2019 levels, reducing from approximately 3600 Mt to around 770 Mt per year (FCH JU, 2019: 54).

In 2020, hydrogen contributed less than 2% to the EU's energy consumption and was almost all produced from fossil fuels (EU, 2020b: 12) In the EU, 325 TWh of hydrogen become feedstock for refining, chemicals and metal processing every year (FCH JU, 2019: 48).

The EU Hydrogen Strategy

In 2002, the EC established a High-Level Working Group on Hydrogen (with 19 stakeholders from the research community, the industry, public authorities and end-users), and issued its vision document in 2003. Based on the recommendation of the Working Group, the EC launched the *European Hydrogen and Fuel Cell Technology Platform*, which developed the *Strategic Research Agenda* on hydrogen. The success of this platform led to the formation of the *Fuel Cells and Hydrogen Joint Undertaking* (FCH JU), a public-private partnership supported by the EC (IRENA, 2020b: 21).

In 2018, the EC published a long-term vision for a climate-neutral economy, which included enabling hydrogen produced from renewable sources with guarantees of origin to be counted against 2030 renewables targets. The EC also set up a

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Hydrogen Energy Network as an informal platform for exchange of best practices and latest developments of hydrogen among national experts of Member States. 28 Member States signed the Linz Declaration *Hydrogen Initiative,* promoting cooperation on sustainable hydrogen technology, together with around 100 businesses, organizations and institutions (IEA, 2019c: 21).

The EU Renewable Energy Directive II (RED II) (2018) increased the EU target for renewable energy sources consumption to 32% by 2030, requires renewable energy to make at least 14% of all transport sector fuels by 2030, and allows renewable hydrogen to be used by oil refineries in the production of conventional fuels (EU, 2018). This envisaged amount of hydrogen would be equal to a potential electrolyser market of up to several hundred MW per refinery for 85 refineries currently existing in Europe. However, there are no equivalent directives concerning chemical processes other than oil refining (Newborough et al., 2020: 21) In July 2021, as part of *the Policies Fit for Reducing Net GHG Emissions by at least 55% by 2030 Package,* the target was revised to 50% of green hydrogen consumption by the industry sector by 2030.

The EC adopted *a Strategy for Energy System Integration* in July 2020, which promotes hydrogen use especially where remote electrification or heating are necessary. Electrolysers are expected to play an essential role in an integrated energy system, coupled with offshore wind farms up to 450W, considering the EU becoming the global leader in offshore technology (EU, 2020b: 21). The Strategy states that 80% of gaseous energy use should be of renewable origin by 2050 (EC, 2020b: 8).

Together with the above strategy, in July 2020, the EC published *a Hydrogen Strategy for a Climate Neutral Europe,* which is part of the European Green Deal. The strategy sets clear electrolyser capacity targets of 6 GW by 2024 and 40 GW by 2030, which is supported by national targets from France (6.5 GW), Germany (5.0 GW), the Netherlands, Portugal and Spain (3.0–4.0 GW), as well as the renewable hydrogen production targets of 1 million tonnes per year by 2024 and 10 million tonnes by 2030. In addition, the EU will cooperate with southern and eastern neighbouring countries such as Ukraine and Morocco to build 40 GW of electrolyser capacity and import green hydrogen in the future. It is estimated EUR 220-340 billion will be needed for an additional 80–120 GW renewable power generation, and EUR 25–40 billion for electrolyser capacity by 2030 (IRENA, 2020b: 24). The EC's economic recovery plan, *Next Generation EU* announced in July 2020, highlights

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hydrogen as an investment priority to boost economic growth and resilience and create new local jobs. The total fund is EUR 750 billion for 2021–2023, a part of which is to be used for hydrogen (IRENA, 2020c: 23).

The Hydrogen Strategy recognizes that in a transitional phase, however, other forms of low-carbon (blue) hydrogen are necessary to replace existing (grey) hydrogen and kick-start an economy of scale of renewable (green) hydrogen. Based on various impact assessments, the EC plans to introduce EU-wide instruments for hydrogen deployment. The EC also proposes introducing minimum shares or quotas of renewable hydrogen for large hydrogen consumers or some end-users. Furthermore, the EC will introduce comprehensive terminology and a European certification system covering all renewable and low carbon hydrogen, based on full lifecycle GHG emission savings. These will be implemented by building on the existing ETS system and the *CertifHy* methodologies developed by industry initiatives, consistent with the EU taxonomy for sustainable investments. *Guarantees of origin* and sustainability certificates defined under the Renewable Energy Directive are expected to facilitate the most cost-effective production and EU-wide trading of renewable hydrogen (EC, 2020a: 5, 12).

The Hydrogen Strategy adopts a phased approach:

> Phase 1 (2020–2024): *"The EU aims to install at least 6 GW of renewable hydrogen electrolysers in the EU and the production of up to 1 Mt per year of renewable hydrogen, to decarbonise existing hydrogen production, for example, in the chemical sector and facilitating take up of hydrogen consumption in new end-use applications such as other industrial processes and possibly in heavy-duty transport."* (EC, 2020a: 5)
>
> *"The hydrogen supply would be mostly local to avoid the need for extensive infrastructure, while planning for infrastructure expansion. Some existing hydrogen production will be retrofitted with carbon capture."* (IRENA, 2020b: 24).
>
> Phase 2 (2025–2030): *"The EU aims to install at least 40 GW of renewable hydrogen electrolysers by 2030 and produce up to 10 Mt per year of renewable hydrogen. An additional 40 GW of capacity may be commissioned in the neighbouring regions."* (IRENA, 2020b: 24)
>
> *"In this phase, renewable hydrogen is expected to gradually become cost-competitive with other forms of hydrogen production, but dedicated demand-*

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side policies will be needed for industrial demand to gradually include new applications, including steel-making, trucks, rail and some maritime transport applications, and other transport modes. Renewable hydrogen will start playing a role in balancing a renewables-based electricity system by transforming electricity into hydrogen when renewable electricity is abundant and cheap and by providing flexibility. Hydrogen will also be used for daily or seasonal storage as a backup and provide buffering functions, enhancing security of supply in the medium term. The need for an EU-wide logistical infrastructure will emerge, and steps will be taken to transport hydrogen from areas with large renewable potential to demand centres located possibly in other Member States. The backbone of a pan-European grid will need to be planned, and a network of HRSs will need to be established. The existing gas grid could be partially repurposed for the transport of renewable hydrogen over longer distances, and the development of larger-scale hydrogen storage facilities would become necessary. International hydrogen trade can also develop, in particular, with the EU's neighbouring countries in Eastern Europe and Southern and Eastern Mediterranean countries." (EC, 2020a: 6)

Phase 3 (2030–2050): ***"****Renewable hydrogen technologies should reach maturity and be deployed at large scale to reach all hard-to-decarbonise sectors where other alternatives might not be feasible or have higher costs. Renewable electricity production needs to massively increase, as about a quarter of renewable electricity might be used for renewable hydrogen production by 2050."* (EC, 2020a: 7).

"E-fuels made from hydrogen would be used in various sectors, including aviation and shipping." (IRENA, 2020b: 24)

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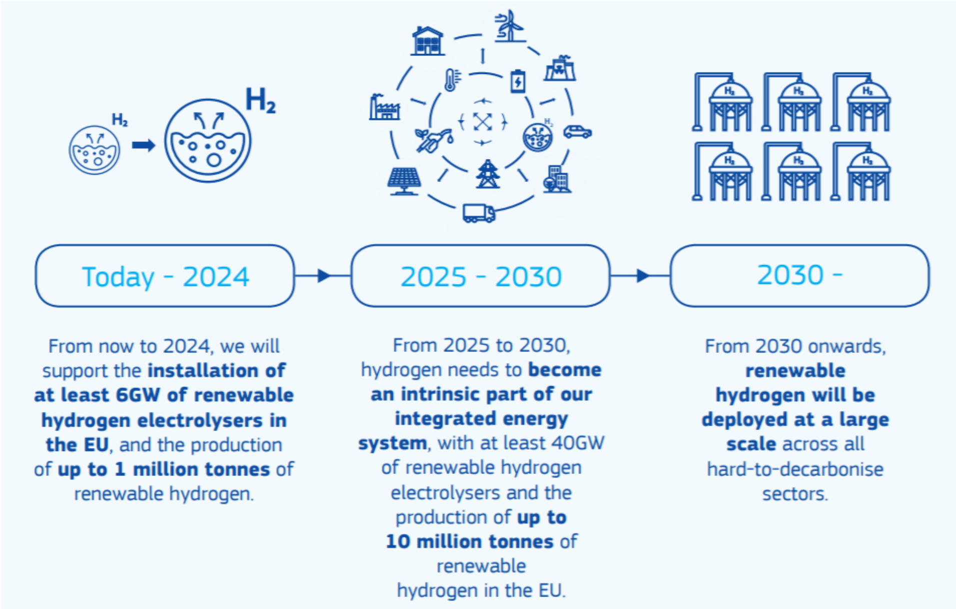

Figure 10: The path under the EU's Hydrogen Strategy *(Source: EC, 2020a)*

Most of the actions have already been translated into legislative proposals. Under the *Hydrogen and Decarbonized Gas Market Package* released in December 2021, it is proposed that no cross-border tariffs will apply for the dedicated hydrogen network in the future. Hydrogen can be transported after existing gas infrastructure are repurposed. Renewable and low-carbon hydrogen can be blended with natural gas up to a certain percentage, while the gas quality needs to be closely monitored. The package introduces an additional national network planning for hydrogen and an EU-side ten-year network development plan (EC, 2021a).

The Hydrogen Strategy aims for EU Member States to achieve a coordinated roll-out and ensure that the strategy fits within their overall national energy and climate plans of the EU strategy (IRENA, 2020b: 23). Since 2018, several countries have released their national hydrogen strategies. In this report, France, Germany, the Netherlands, Portugal, and Spain are highlighted for reference as they are some of the first to publish the hydrogen strategies, and their geography, climate and economy may be similar to some of the emerging economies and developing countries which may be considering green hydrogen adoption in the near future.

Renewable and low-carbon hydrogen are recognized as a strategic alternative energy carrier under the national energy and climate plans in most of EU Member States. National developments and experiences on their hydrogen plans are shared through the *Hydrogen Energy Network*, an informal group of EU energy policy experts established in June 2019.

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France was the first EU country to publish its *National Strategy for the Development for Decarbonized and Renewable Hydrogen in France* in 2018 with a hydrogen deployment plan for energy transition. In September 2020, the government released a second strategy that significantly upgrades the ambition with EUR 7 billion for 2020–2030, from EUR 150 million of public funding per year to EUR 700 million per year. The strategy aims at reaching an electrolyser capacity of 6.5 GW by 2030, and a 10% share of green and blue hydrogen in the industry sector by 2023 and 20-40% by 2028. The strategy has specific targets in the transport sector, namely 5,000 light-duty vehicles (LDV), 200 heavy-duty vehicles (HDV), and 100 HRSs (30 at the end of 2019) by 2023, and 20,000–50,000 LDVs, 800–2,000 HDVs, and 400–1,000 HRSs by 2028 (Hydrogen Europe, 2020: 75).

Germany published its *National Hydrogen Strategy* in June 2020 with a goal of 5 GW electrolysis production capacity by 2030 (i.e., 14 TWh of hydrogen production, provided by 20 TWh RES production) and 10 GW capacity by 2040. To facilitate the value chain development from production and distribution to end-users, EUR 9 billion of public funding has been provided: EUR 7 billion for market upscaling of hydrogen technology under the Future Package (Zukunftspaket) and EUR 2 billion for international partnerships. The strategy focuses primarily on the industry, whose demands could reach 80 TWh of hydrogen in steelmaking and 22 TWh in refining and ammonia production by 2050. Transport is another priority sector in the strategy (Hydrogen Europe, 2020: 76).

The Dutch Government published its *Government Strategy on Hydrogen* in April 2020, which aims to develop a 500 MW electrolyser capacity by 2025 and 3–4 GW by 2030. In the transport sector, the targets are to deploy 15,000 FCEVs, 3,000 HDVs, and 50 HRSs by 2025. By 2030, the FCEV fleet is expected to increase to 300,000, and a minimum blending rate of 14% of sustainable fuel is expected in aviation fuel (Hydrogen Europe, 2020: 78).

The Portuguese government adopted its *National Hydrogen Strategy* in August 2020. Portugal plans to attract EUR 7–9 billion of investments, 15% from the government and 85% from the private sector. By 2030, hydrogen should account for 5% of the country's final energy consumption, 2–2.5 GW of electrolyser capacity are expected to be installed, and a 10–15% ratio of hydrogen in natural gas networks will be achieved. In the transport sector, hydrogen will account for 5% of road transport fuel consumption, and 50–100 HRS will be built. Hydrogen will account for 5% of energy consumption in the industrial sector (Hydrogen Europe, 2020: 78).

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The Spanish government released its *National Hydrogen Roadmap* in July 2020. EUR 1.5 billion public funding will be provided for 2021–2023 and it aims to mobilize close to EUR 9 billion public and private investments for 2021–2030 to develop the hydrogen sector, with the target of 4 GW of electrolyser capacity and 25% integration share of green hydrogen in the industrial hydrogen mix by 2030. In the transport sector, the targets are 150–200 buses and 5,000–7,500 light-duty vehicles (LDV) and heavy-duty vehicles (HDV) for freight transport, and 100– to 150 HRSs (Hydrogen Europe, 2020: 80).

Hydrogen Roadmap Europe

In January 2019, the FCH JU published the *Hydrogen Roadmap Europe*, which was developed based on the inputs from 17 leading European industrial actors, presenting a pathway for the large-scale development of hydrogen and fuel cells until 2050. It indicates that by 2050, hydrogen could provide up to 24% of the total energy demand, corresponding to 2250 TWh of energy in the EU and the United Kingdom (UK), as Figure 11 below shows (FCH JU, 2019). The roadmap presents quite ambitious prospects, namely that by 2030, the hydrogen demand in the EU and the UK will be 665 TWh or 16.9 MT, which is more ambitious than the one in the EU Hydrogen Strategy, producing 10 MT of renewable hydrogen by 2030.

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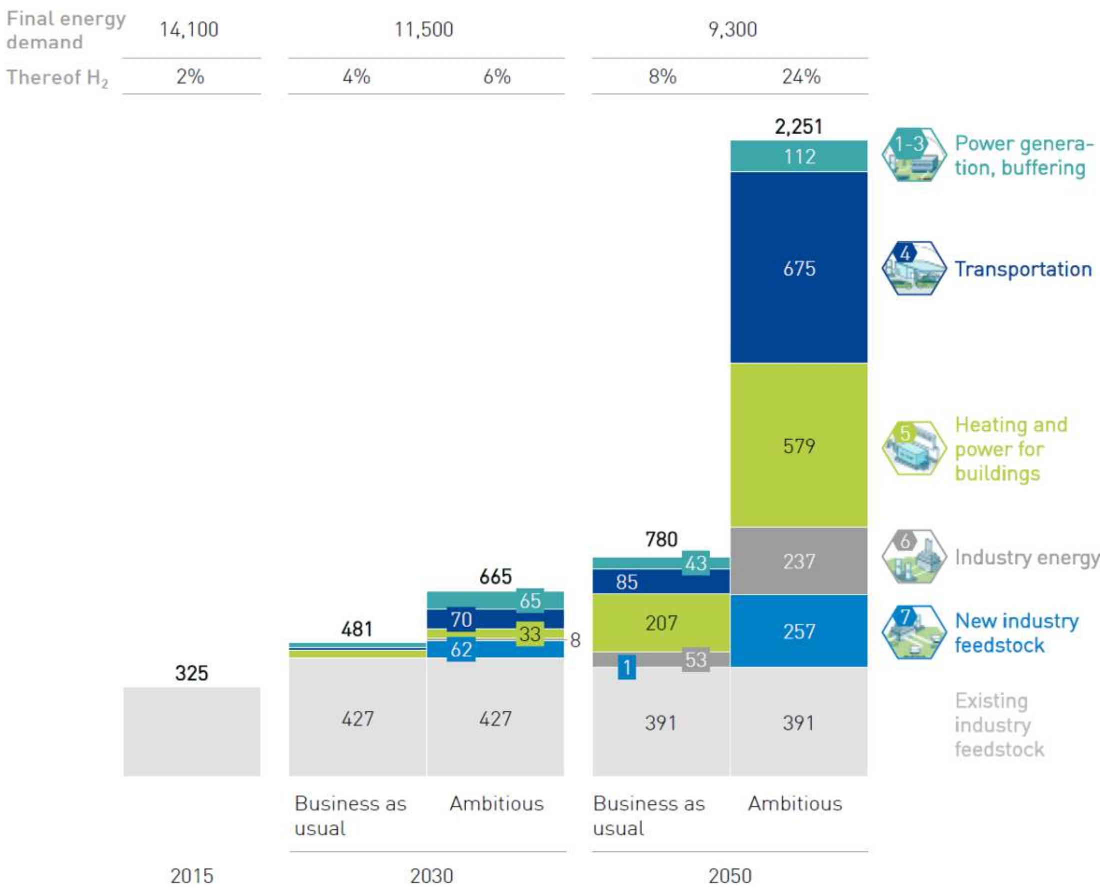

Figure 11: Potential hydrogen production in Europe in 2030 and 2050 (TWh) *(Source: FCH JU, 2019)*

The roadmap proposes the following milestones:

> *"Transport: by 2030, FCEVs could account for 1 in 22 passenger vehicles and 1 in 12 of light commercial vehicles (LCVs) sold, a total of 3.7 million fuel cell passenger vehicles and 500,000 fuel cell LCVs.*
>
> *Buildings: hydrogen could replace an estimated 7% of natural gas (by volume) by 2030, and 32% by 2040, which are equal to approximately 30 TWh in 2030 and 120 TWh in 2040.*
>
> *Industry: a transition to one-third ultra-low carbon hydrogen production by 2030 is expected to be achieved in all applications, including refineries and ammonia production.*
>
> *Power system: the at-scale conversion of "surplus" renewables into hydrogen, large-scale demonstrations of power generation from hydrogen, and renewable-hydrogen generation plants could also take place by 2030. Hydrogen could be supplied from a mix of ultra-low-carbon sources, both*

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electrolysis and steam methane reforming (SMR)/autothermal reforming (ATR) with carbon capture and storage (CCS) are expected to be dominant" (FCH JU, 2019: 9).

4.1.1. EU's challenges and opportunities

4.1.1.1. Challenges

i. Hydrogen production and cost

According to a study by Lux et al., to decarbonize the European energy system by 2050, renewable hydrogen demand will be about 1536–1953 TWh H_2, leading to marginal hydrogen production costs of over EUR 110–130/MWh H_2. This increase in electricity demand for hydrogen production will require electrolysers with a capacity of more than 798 GW_{el}, an additional 766 GW_{el} of wind power and 865 GW_{el} of solar power to be installed by 2050 (Lux et al., 2020: 8, 15).

In 2021, the cost of green (electrolysis with renewable electricity), blue (grey hydrogen plus CCS) and grey (from natural gas by SMR) hydrogen in Europe is EUR 2.5–5/kg, 2/kg and 1.5/kg, respectively (European Parliament, 2021: 3) Considering solar and wind conditions in Europe, the cost of renewable hydrogen production is estimated from EUR 3.5 per kg (from solar photovoltaics (PV) in southern Europe) to EUR 6.5 per kg (from onshore wind in northern Europe) (Hydrogen Europe, 2020: 30).

According to the European Hydrogen Backbone, in the EU and the UK, hydrogen demand is expected to be 2300 TWh (2150–2750 TWh) by 2050, corresponding to 20–25% of EU and UK final energy consumption by 2050. The potential for domestic green hydrogen supply from dedicated renewables in the EU and the UK is estimated at 450 TWh in 2030, 2100 TWh in 2040, and 4,000 TWh in 2050, as Figure 12 below shows. This projection already takes into account the increasing demand for renewable electricity for direct consumption, available land, environmental considerations and set-up costs. However, it has to be noted that achieving this potential will largely depend on public acceptance of new renewable installation beyond currently planned expansion (European Hydrogen Backbone, 2021: 5).

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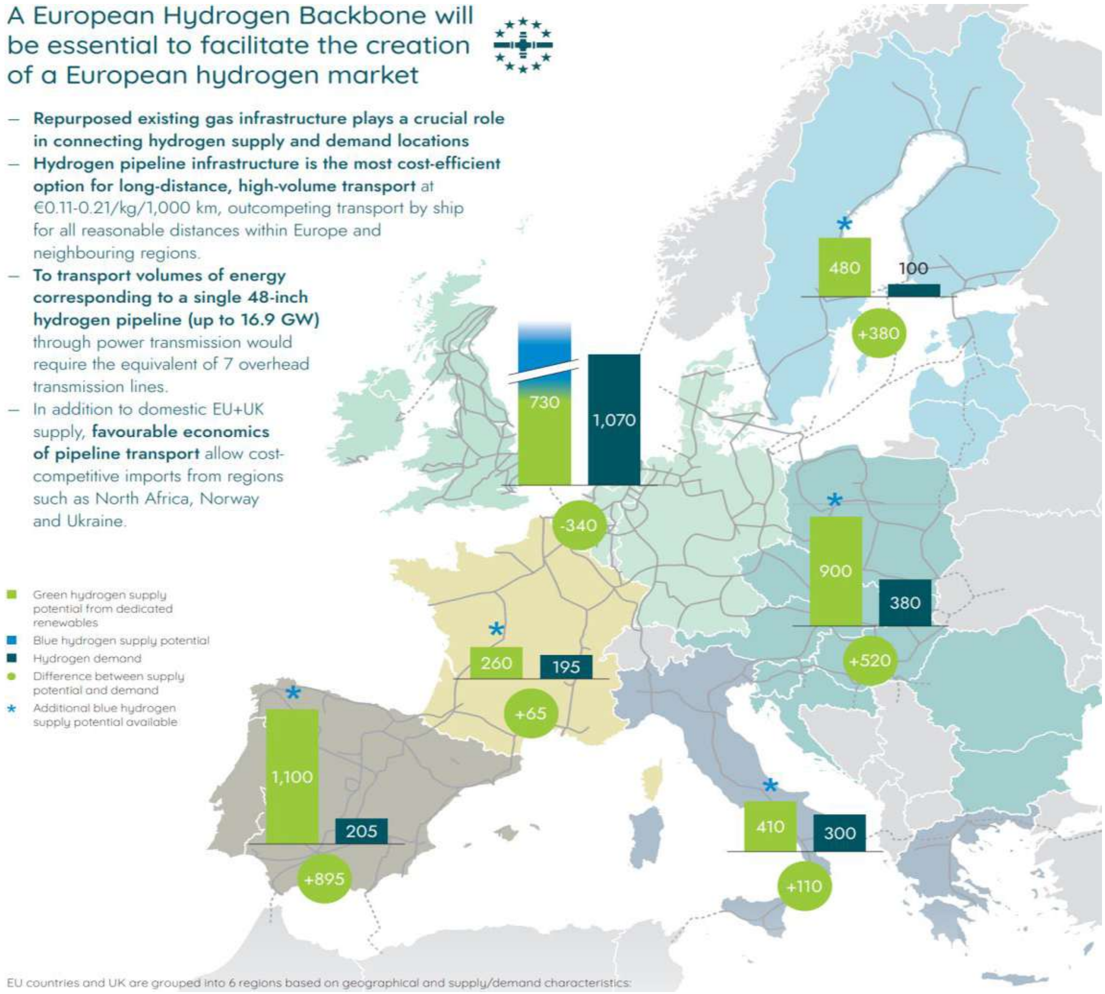

Figure 12: Hydrogen supply potential in Europe *(Source: European Hydrogen Backbone, 2021)*

Over the last few years, operational electrolysis capacity in Europe has increased significantly, from 90 MW in 2019 to 135 MW as of October 2021 (Hydrogen Europe, 2021: 51). According to an analysis by Tracteble et al., 2.8 GW of electrolyser capacity is expected in Europe by 2025 (IRENA, 2019d: 19). To meet the increasing demand for electrolysers, the EU has researched on the recovery and recycling of noble metals from electrolysers so that the need for key raw materials used in electrolyser stacks could be reduced, as well as their costs and environmental impact. The FCH JU sets clear targets for critical raw material use in electrolysers under their *HyTech Cycling roadmap for recycling and dismantling strategies and technologies for within FCH technologies* (IRENA, 2021a: 36).

ii. Infrastructure

In Europe, only a few hydrogen pipelines exist, namely in Belgium (600km) and Germany (400km) (European Parliament, , 2021: 2).

Hydrogen can employ existing gas networks across the EU to integrate renewable and low-carbon gases. In some cases, repurposing gas networks for hydrogen applications may provide a cost-efficient solution, including transporting renewable hydrogen from offshore renewable electricity parks. While hydrogen may be blended with natural gas into the existing gas networks to a certain extent during a transitional phase, dedicated infrastructures for storage and transportation of large-scale hydrogen would be needed. The EC will assess the expansion of HRS as part of the revision of the Alternative Fuels Infrastructure Directive and the Regulation on the Trans-European Networks for Transport (TEN-T) guidelines (EU, 2020b: 18).

For hydrogen storage, Europe already has substantial capacities. Its gas network has a capacity of 36 billion m³ and could store up to 100 TWh of hydrogen, assuming 10% blending. Its salt caverns have a capacity of 18 billion m³ and could store about 40 TWh of hydrogen, assuming an available capacity of 80% (FCH JU, 2019: 22).

iii. Policy and regulatory framework

While the EU established overall frameworks for hydrogen deployment, frameworks are still missing for hydrogen trading and supply, including certifications. Also, all hydrogen relevant legislation, such as the Renewable Energy Directive (RED II), the Energy Efficiency Directive, the Energy Taxation Directive, the ETS, and the EU Gas and Electricity Directives, still need to be aligned (Hydrogen Alliance, 2021: 8) and their revisions are currently being discussed at the EC.

Concerning green hydrogen certification, current *guarantee of origin* schemes are voluntary and have several schemes across the EU, covering different scopes with different references and thresholds, such as CertifHy (EU), RED II (EU), and TÜV SÜD (Germany), all of which have various environmental attributes. This complicates the green hydrogen certification, thus, an EU-wide harmonized *guarantee of origin* scheme is necessary (STRATS Advisors, 2021) To address this challenge, the EC is launching an EU-wide database to certify the carbon footprint of hydrogen and other low-carbon fuels in a harmonised way and revising the REDII to count green hydrogen as a renewable fuel under the RED II (Euractive, 2021).

To promote green hydrogen uptake, fiscal incentives, such as lower tax rates and tax relief for consumers who use green products, such as green steel and green fertilizer, for green goods should be considered (IRENA, 2021a: 31). One example is in a form of CAPEX subsidies for renewable hydrogen projects or facility owners to

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support their innovation and decarbonision effort. Austria, Belgium, Bulgaria, Finland, Germany, and the Netherlands will implement such CAPEX subsidies (Hydrogen Europe, 2020: 98).

Within the EU, applicable taxes and levies, including carbon pricing, are not applied homogeneously across energy carriers and sectors, creating distortions towards the use of specific carriers. In many EU Member States, taxes and levies on electricity are higher than for coal, gas, or heating. Aligning the taxation of energy products and electricity within the EU environment and climate policies is necessary (EU, 2020b: 14, 16). To avoid double taxation of energy products, including hydrogen, the Energy Taxation Directive is being revised (IEA, 2021a: 39).

To foster a transparent, efficient, and competitive market for renewable hydrogen, the EU considers the use of Carbon Contracts for Difference (CCfD). This is a long-term contract with a public counterpart that would compensate the investor by paying the difference between the CO_2 strike price and the actual CO_2 price in the ETS. This mechanism in a way remunerates electrolysers for the services provided to the energy system, thus, supporting initial deployment and scale-up of renewable hydrogen (EU, 2020a: 13, 14).

For hydrogen transport and infrastructure, harmonized technical and safety requirements and standards for hydrogen infrastructure are necessary. There is a lack of synergies between the Trans-European Networks for Energy (TEN-E) and Trans-European Networks for Transport (TEN-T), especially for shipping. The EU hydrogen strategy envisages the revision of TEN-E, the internal gas market legislation, TEN-T and the Alternative Fuels Infrastructure Directive to secure an efficient hydrogen supply chain, as well as the development of common quality standards, certification, and verification methodologies (EU, 2020a: 15).

For the gas grid, one of the critical issues is the maximum legal or safely acceptable hydrogen concentration in the natural gas distribution or the transmission network. Germany allows a legal concentration of hydrogen in transmission networks at 10%, the highest in the EU. Figure 13 below presents the maximum share of hydrogen allowed in transmission networks (Hydrogen Europe, 2020: 97).

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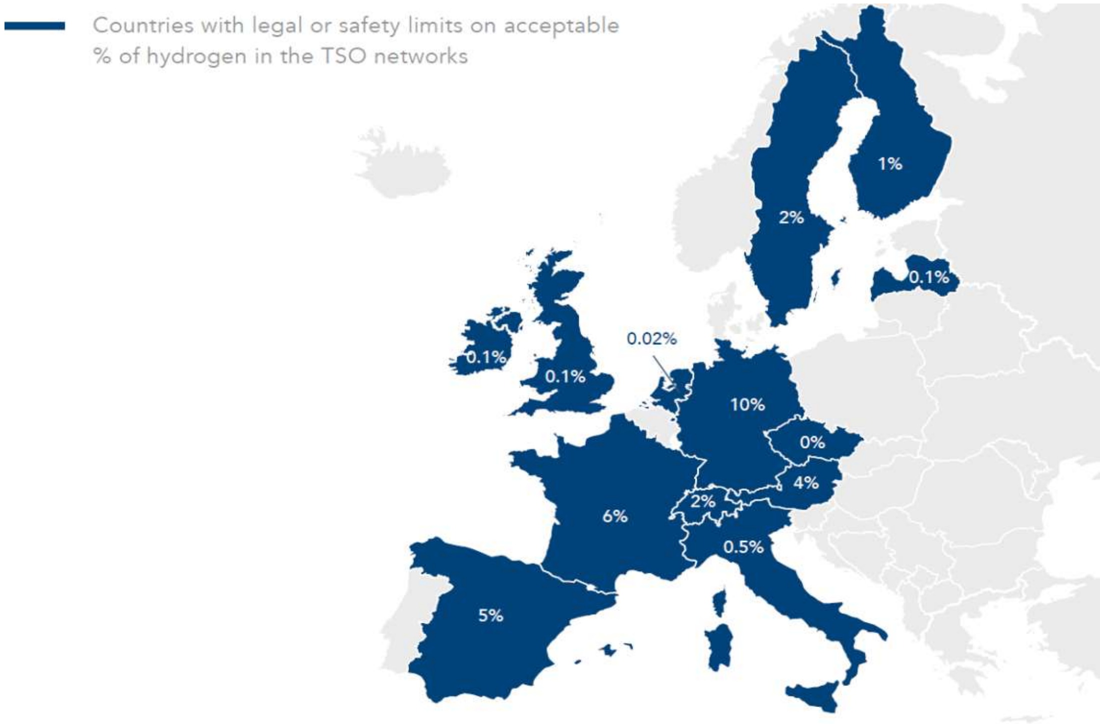

Figure 13: Hydrogen concentration allowance in transmission networks in Europe *(Source: Hydrogen Europe, 2020)*

The EU Hydrogen Strategy considers applying the existing rules for the electricity and gas markets, such as access to trading points and standard product definitions, for a fair and open hydrogen commodity market. The strategy also suggests the necessity of third-party access rules, rules on grid connection by electrolysers, and simplified administrative procedures (EU, 2020a: 16). These issues were already addressed under the *Hydrogen and Decarbonized Gas Market Package* released in December 2021.

4.1.1.2. Opportunities

Hydrogen trade

Hydrogen trade between countries in Europe is foreseen as promising opportunities, utilising the existing cross-border gas pipelines or building a new dedicated hydrogen pipeline. Hydrogen and electricity trade between countries could help smooth low-carbon energy supplies and help match low-cost supplies with demand.

In 2019, 107,000 tonnes of hydrogen, around 1% of total hydrogen consumption in Europe, was exported by EU countries to other EU countries and externally. Over 90% of all hydrogen trade in EU countries were among Belgium, France and the Netherlands, where Air Liquide owns, operates and transports excess hydrogen to

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be used as feedstock from one chemical plant to another through its interlinked hydrogen network in these countries. (Hydrogen Europe, 2020: 17).

Imported green hydrogen might be competitive with local production, depending on the location and availability of low-cost renewable energy. By 2030, hydrogen production in North Africa from dedicated renewable electricity might have import costs as low as USD 4.7/kg H_2 (EUR 4.1/kg H_2) for over 500 Mt H_2 per year, compared to USD 4.9/kg H_2 (EUR 4.3/kg H_2) from renewable electricity in Europe. Also, grey or blue hydrogen could be imported from the Middle East at competitive costs as low as USD 2/kg H_2 (EUR1.76/kg H_2) as ammonia, or USD 2.3/kg H_2 (EUR 2.3/kg H_2), if cracking produced pure hydrogen. With the energy trade with Africa and the Middle East being one of the pillars of European neighbourhood policy, the EU supports energy infrastructure investments in these regions (IEA, 2019c: 191).

4.1.2. EU plans, actions and financial support

Considering some important aspects, such as industrial competitiveness and its value chain implications for energy systems, the EU already has the solid basis for an incentivizing and supportive policy framework for scaling up renewable hydrogen, notably with the REDII and the ETS. Numerous instruments and financial resources are available to boost hydrogen deployment, such as the *Next Generation EU* and the *2030 Climate Target Plan* (EU, 2020a: 13).

4.1.2.1. Plans and actions

As of 2019, 56 hydrogen projects, worth EUR 215 million, are ongoing with support from FCH JU and other funding sources (FCH JU, 2019: 24).

i. Production

In 2020, 1.5–2.3 GW of new renewable hydrogen production projects were under construction or announced, and an additional 22 GW of electrolyser projects were envisaged (EU, 2020a: 8). Some of the ongoing projects are as follows:

In Innsbruck, Austria, Europe's largest 3.2 MW pressurized AEL was installed under the *Demo4grid* project funded by the FCH JU to demonstrate balancing grid services and production of green hydrogen for industrial purposes at the food retail company MPREIS in December 2021. FC trucks for MPREIS will be refuelled via an HRS directly at the food production centre from early 2022 onwards (Demo4grid, 2021). Also, under the *H2future project* funded by the FCH JU, Siemens, together

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with steelmaker Voestalpine and utility provider Verbund, has been supplying a 6MW PEM electrolyser at the Linz steelworks since 2019, the largest green hydrogen electrolyser plant as of 2021 (H2future, 2021).

In France, in January 2021, Total and Engie initiated the *Masshylia project*, which will be the largest renewable hydrogen production site in the Alpes-Cote d'Azur south region, France. 100MW solar will be connected to a 40MW electrolyser to produce 5 tonnes of green hydrogen per day for biofuel production at Total's la Mede biorefinery. This project is supported by the French government and the *Important Project of Common European Interest* (IPCEI) innovation fund (Totalenergies, 2021).

In Germany, under the *REFHYNE project* funded by the FCH JU, a 10 MW PEM electrolyser plant (1300 tonnes of hydrogen per year) started operation at Shell's Rhineland refinery in Wesseling in July 2021. It is powered with 100% renewable electricity and used for processing and upgrading products at the refinery site (REFHYNE, 2021).

VNG and a few other companies plan to connect a 40 MW wind power to 35 MW electrolysers near its chemical industry site, including up to 59 million cubic meters of hydrogen storage (approximately 150 million kWh of energy, providing the heat for 20,000 households annually (IRENA, 2019c: 11).

Since 2013, the Audi e-gas plant in Werlte, Germany, has a 6MW AEL electrolyser capacity to convert electricity from offshore wind into hydrogen, which is then used in chemical synthesis and CO_2 from a biomethane plant to produce SNG (IEA, 2019a: 57).

In the Netherlands, under the Djewels project funded by FCH JU, the largest electrolysis unit in Europe, a 20 MW electrolyser (providing 3,000 tons of green hydrogen per year) for green methanol production at Delfzijl is planned to be increased to 100 MW (Djewels, 2021).

In Spain, under the Basque Hydrogen Corridor, green hydrogen production by electrolysis (112 MW) from waste (recovery of 126,000 t per year of waste) and e-fuel production from green hydrogen and captured CO_2 (8,000l/day) are being implemented (FCH JU Hydrogen Valley site, 2021).

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ii. *Infrastructure*

In 2019, several large-scale demonstration projects were underway. First power-to-gas (e.g., wind-to-hydrogen) pilot sites are in operation or being built across Europe, for example, in Germany, the UK, Italy, Spain, the Netherlands, Denmark, and the North Sea for offshore wind (FCH JU, 2019: 24).

The *European Hydrogen Backbone* initiative, launched by a consortium of 29 European gas infrastructure companies in 2020, aims to establish an 11 600 km long pipeline by 2030, to be extended to 39 700 km by 2040, comprising mainly 122cm diameter pipelines, each having a transfer capacity of 13 GW of hydrogen (European Hydrogen Backbone initiative, 2021), as shown in Figure 14 below. Also, several IPCEI projects are under development, involving groups of EU countries, whose governments aim to achieve cross-border solutions for producing, distributing and using renewable hydrogen at scale by 2030 (Newborough et al., 2020: 19).

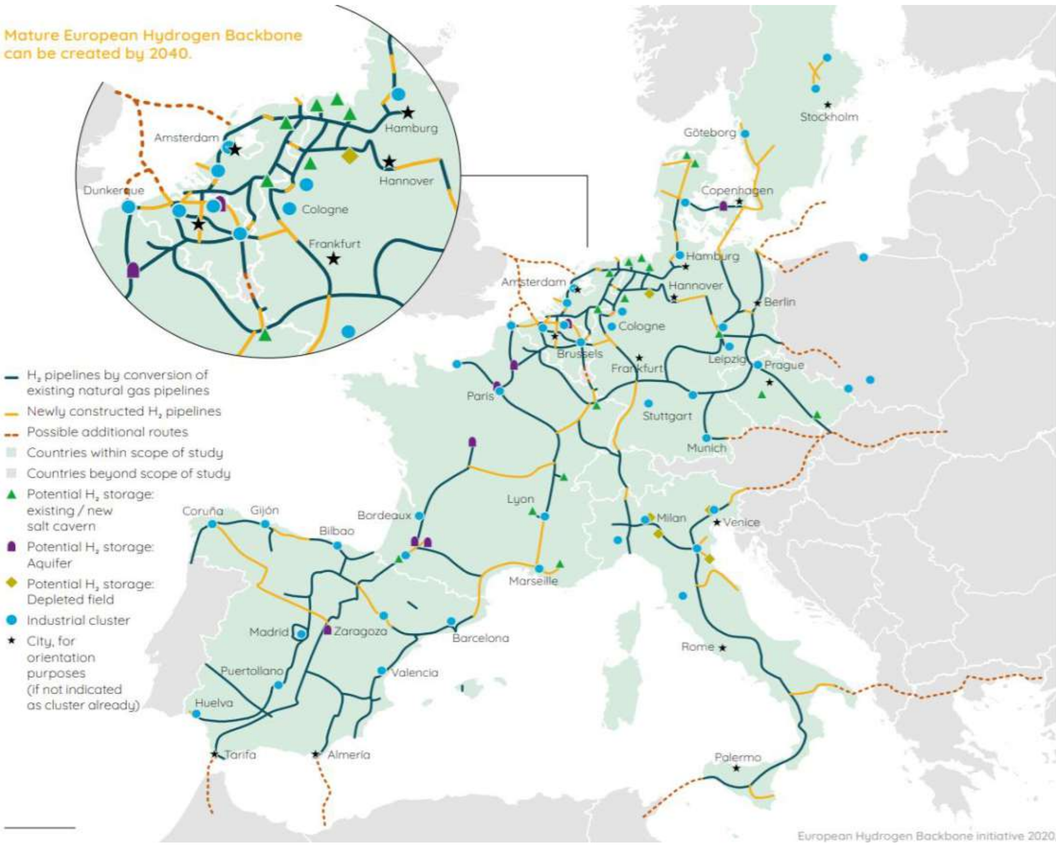

Figure 14: The proposed European hydrogen transmission backbone *(Source: European Hydrogne Backbone, 2020)*

To realise this target, significant upgrades to gas networks are necessary. The Netherlands has upgraded its gas infrastructure from low-calorific gas (from Groningen) to high-calorific gas (from Norway and LNG) and reflected the cost of upgrading the network in the prices (FCH JU, 2019: 35). This change requires upgrades to infrastructure very similar to those necessary for a hydrogen network (FCH JU, 2019:35)

Under the *GRHYD demonstration project* in France and Germany, renewable hydrogen is blended up to 20% into the natural gas network. Under the *HyDeploy project* in the UK, hydrogen is blended up to 20% into the gas network (FCH JU, 2019: 36).

iii. End-use

In Europe, hydrogen technology exists in most segments and is ready for deployment. In the short term, transport and heating have a high protentional for adoption, and industry feedstock and power generation in the long term (FCH JU, 2019: 46).

Industry

Projects in Austria, Finland, Germany, and Sweden are testing variations of DRI to replace coking coal with hydrogen, producing carbon-free steel (FCH JU, 2019: 43).

In Salzgitter, Germany, the *GrlinHy2.0 project* aims to produce hydrogen from high-temperature SOEC (0.72 MW) for steel annealing processes. By the end of 2022, it is expected to be operational for at least 13,000 hours, producing a total of 100 tons of green hydrogen at an electrical efficiency of a minimum of 84% lower heat value (GrlinHy2.0, 2021).

In Spain, *Fertiberia* and *Iverdorla* companies blend hydrogen produced by solar PV-powered electrolysis for ammonia production, to be operational in 2021 (20 MW). ArcelorMittal committed to building a DRI unit using hydrogen produced directly from renewable sources (IEA, 2021a: 186).

Transport

The FCH JU has supported numerous FCEV demonstration and deployment projects, including taxis, delivery vans, buses and refuse trucks. This support contributed to accelerating the deployment of fuel cell taxis in Europe, most notably in Paris (100), the Hague (40), Copenhagen (10) and London (50). Madrid has announced plans to deploy 1,000 vehicles. Several European countries, including France, the Netherlands, Portugal, and Spain, set FCEV targets in their hydrogen strategies, in total expected to be about 415,000 FCEVs by 2030 (IEA, 2021a: 75).

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In parallel, most of the EU countries have provided supports such as provision of CAPEX support for HRSs, purchase subsidies and registration tax benefits for FCEVs (Hydrogen Europe, 2020: 92).

By the end of 2020, there are over 2600 FCEVs (over 90% LDV, and about 130 fuel cell buses), and around 165 HRSs operational in Europe (IEA, 2021a: 75). As of March 2021, there were 41 HRs, 375 FC vehicles, 21 buses and 325 forklifts in France; 90 HRs, 951 FC vehicles, 79 buses and 162 forklifts in Germany; and 11 HRs, 390 FC vehicles, eight buses, and 22 trucks in the Netherlands (IPHE, 2021: 3).

For fuel cell trains, since 2018, hydrogen fuel cell passenger trains have driven over 180,000 km in Germany. A hydrogen passenger train in Austria started operations in 2020 (IEA, 2021a: 71). Furthermore, in 2022, the world's first fleet of 14 green hydrogen trains will begin operating on Germany's Lower Saxony network. Fueled by green hydrogen, each train is expected to reduce CO_2 emissions by 700 tonnes per year. The trains will be refueled from one of the world's largest electrolyser HRSs connected to wind power, located in Bremervoerde, with the station being constructed (Hydrogen Europe, 2021: 106).

In the Northern Netherlands, the first region officially designated as a *Hydrogen Valley* by the EU, *the Green Planet* in Pesse, is established. It is a multifuel station providing fuels for all passenger and cargo transportation. It is one of the largest HRSs in Europe, supported by regional, national and European funds. The Dutch provinces Groningen and Drenthe already operate 30 hydrogen buses (Hydrogen Europe, 2021: 71, 79).

In Spain, the *Green Hysland project* will generate, distribute, and use at least 3,000 tonnes of renewable hydrogen locally per year, coupled with a 26.4 W PV plant and a 10 MW electrolyser on the island of Mallorca (Green Hysland, 2021). Green hydrogen will supply fuel to a fleet of FC buses and FC rental vehicles, heat and power for commercial and public buildings, auxiliary power for ferries and port operations (FCH JU, 2021c).

For the maritime sector, Sweden and Norway have explicit targets for hydrogen based fuels. The EC is developing a strategy to set CO_2 reduction targets, especially from large ships. Shipping may be incorporated into the European ETS from 2023 onwards (IEA, 2019c: 139).

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Heating/buildings

Using fuel cells for providing stationary power is becoming common, at least for niche applications. Fuel cells have also been designed for Micro-CHP applications providing power for residential, commercial, and light industrial buildings. Seven countries in the EU and the UK provide CAPEX support for Combined Heat and Power CHP stationary power fuel cell applications (Hydrogen Europe, 2020: 96). Under the *ene.field project* for 2012–2017, over 1,000 micro-CHP fuel cell systems for residential and commercial buildings were installed in 11 countries. In Germany, over 750 units were installed, owing to the support provided by the *KfW 433 programme*, which provided grants and output-related subsidies of up to EUR 3,000 for units with a capacity of 250 W to 5 KWe, in new and existing buildings (IEA, 2019c: 145).

Power generation

Hydrogen could serve as a storage of renewables-generated electricity, while balancing and buffering renewable electricity. Some notable projects on power generation from green hydrogen are listed as follows:

In Hobro, Denmark, the *HyBalance project*, funded by FCH JU, Air Liquide and a few other companies, has delivered 120 tonnes of hydrogen, 60 tonnes to industrial customers and 60 tonnes to HRSs and FC taxis in Copenhagen since 2018. A 1.2 MW PEM electrolyser connected to wind power has balanced the electricity grid (HyBalance project, 2021).

In France, Saillant sur Vienna, the *HYFLEXPOWER project*, funded by *Horizon 2020*, was launched by a consortium of *Siemen*s and other companies in May 2020. It demonstrates the world's first integrated *power to hydrogen to power* cycle, with a 12 MW CHP plant powered by green hydrogen produced by a PEM electrolyser.

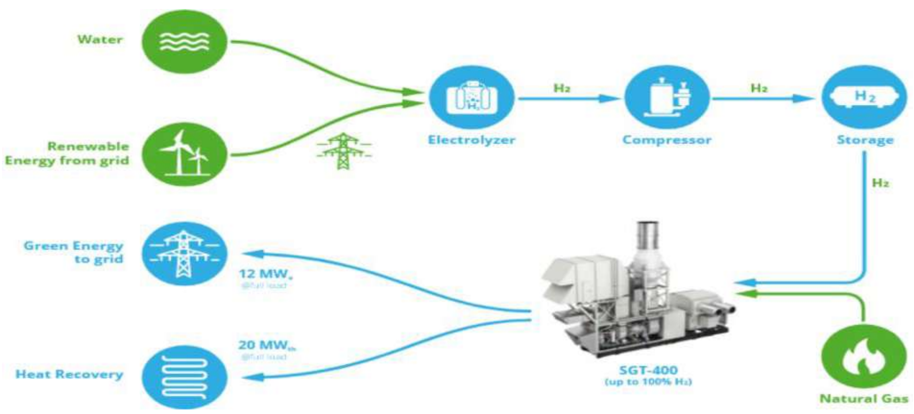

Figure 15: HYFLEXPOWER project overview *(Source: Hyflexpower, 2021)*

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The *REMOTE project* funded by *Horizon 2020* demonstrated the effectiveness of two fuel cell-based H_2 energy storage solutions (one integrated P2P system, one non-integrated P2G+G2P system) through three demonstration sites supplied by renewable electricity in Greece, Norway, and Spain (REMOTE project, 2021).

4.1.2.2. Financial support

According to the EU Hydrogen Strategy, from 2020 to 2030, investments in electrolysers could be around EUR 24–42 billion. Additionally, EUR 220–-340 billion would be necessary to connect 80–120 GW of renewable generation capacity to the electrolysers. Approximately EUR 11 billion would be required to upgrade the current natural gas plants with CCS. EUR 65 billion will be required for hydrogen transport, distribution and storage and HRS networks. From 2020 to 2050, investments in hydrogen production are expected to be around EUR 180–470 billion in the EU (EC, 2020a: 7).

The EU has supported R&D and innovation on hydrogen value chain through collaborative projects and joint investments, such as Horizon 2020 (2014–2020) and the FCH JU from 2014 onwards (European Parliament, 2021: 5). The European Investment Bank (EIB) also provided significant investments for the uptake and roll-out of hydrogen projects over the last decade. These efforts have contributed to developing various technologies for hydrogen and HRSs as well as improving relevant regulations for hydrogen deployment in the EU (EC, 2020a: 17).

According to the technology readiness level as well as its degree of bankability, different funding and financial instruments are available, and project proponents can combine funds to help overcome bottlenecks and enhance synergies with various funding sources. Figure 16 below shows some examples of funding and financing sources for projects. For (R&D) and demonstration to deployment of technology, funding such as *Horizon Europe* and *Just Transition Fund* can be utilised. For demonstration to deployment, in addition to funding, financial instruments with risk sharing components are available, such as *Innovation Fund* and *InvestEU.* For deployment and scale up, loans via the EIB, national or commercial banks can be utilised.

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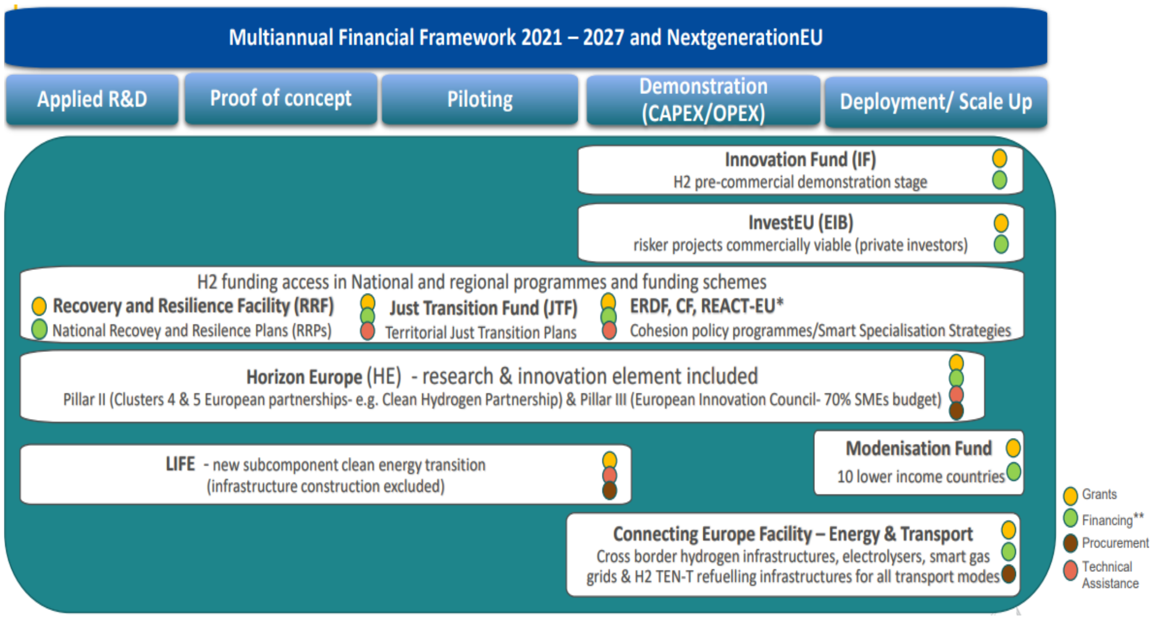

Figure 16: An example of combination of funding *(Source: EC, 2021b)*

In 2021, the EU established the *Hydrogen Public Funding Compass,* where, as a single entry point, stakeholders can identify public funding sources both by the EU and Member States for hydrogen projects. This website is expected to facilitate the efficient and effective use of the fund, as well as attract additional investment towards hydrogen deployment (EC, 2021b: 8).

The *ETS Innovation Fund*, around EUR 10 billion polled by the revenue from EU ETS to support low-carbon technologies for 2020–2030, could also facilitate the first-of-a-kind demonstration of innovative hydrogen-based technologies, possibly leading to significant GHG emission reduction (EU, 2020: 18). The fund can be accessible through regular calls for fund proposals, which are published at the *EU Funding and Tenders portal*.

The EC promotes collaboration in R&D and innovation among Member States as mandated under the *Strategic Energy Technologies Plan* priorities. Synergies with financial instruments, such as the *ETS Innovation Fund* or the *European Structural and Investment Funds (ESIF),* will bridge first-of-a-kind demonstration projects and present diverse opportunities for renewable or low-carbon hydrogen across the EU. Two of five ESIF funds, the *European Regional Development Fund* and the *Cohesion Fund*, with an additional amount provided under the new initiative *REACT-EU,* support the green transition, including hydrogen deployment. The EU commits and has extensively been working with its Member States, regional and local authorities, the industry and other stakeholders to support innovative solutions in renewable and low-carbon hydrogen. The *Just Transition Fund* with Euro 65–75 billion for 2021–2027 to alleviate the socio-economic impact of the transition towards a climate neutral economy in the most affected regions, such as the coal regions in transition, could also support a smooth transition and necessary investment for hydrogen use in the industry. Both *Connecting Europe Facility Energy* and *Connecting Europe Facility Transport* provide funding for dedicated hydrogen infrastructure, and carbon capture projects (EU, 2020a: 19).

As part of the EC's recovery plan published in May 2020, a temporary instrument of *Next Generation EU*, including the Strategic European Investment Window of the *Invest EU programme* (formerly known as *EFSI*) and the *ETS Innovation Fund*, will enhance funding support and fill the gap for investment in renewables energy, which have been affected by the COVID-19 crisis since early 2020.

The *European Clean Hydrogen Alliance*, launched in July 2020 with over 1500 stakeholders, pools resources to achieve further cost reductions and competitiveness in hydrogen and its applications (EU, 2020a: 18). The hydrogen alliance builds on the successful industrial mobilization of the *European Battery Alliance* (EBA), which is a consortium of the stakeholders of the battery value chain, supported by the EC and EIB (EC, 2021c).

The *Clean Hydrogen Partnership* was launched in November 2021, building on the success of the FCH JU. It is part of a EUR 22 billion package of industrial partnerships and supports R&D and demonstration of hydrogen technologies for their market readiness.

The *IPCEI,* established in March 2018, follows up the recommendations identified in the Hydrogen Strategy. IPCEI supports large integrated hydrogen and hydrogen fuel cell projects which will contribute to decarbonization efforts in the EU (EU, 2020: 8). Currently there are eight ongoing IPCEI projects across 17 EU countries including 43 GW of renewable generation for green hydrogen production (Hydrogen Europe, 2020: 31).

To support the project proponents to develop financially sound and viable hydrogen projects, advisory service and technical assistance are provided under the *Cohesion Policy*, the *EIB Advisory Hubs* or *Horizon Europe*. The *Hydrogen Valleys Partnership* already facilitates cooperation between European regions that plan to develop the production and utilisation of hydrogen. Especially in carbon-intensive regions, the *Interregional Innovation Investment Instrument* and the *European*

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Regional Development Fund support the development of innovative hydrogen value chains (EU, 2020a: 18).

For neighbouring regions, the *EU Stabilisation and Association Agreements with the Western Balkans*, and the *Association Agreements with Neighbourhood Countries*, provide the political framework for these neighbouring countries (Western Balkans and Ukraine) to participate in joint hydrogen research and development programmes with the EU. The existing regional sectorial international cooperation fora such as *Energy Community* and the *Transport Community* will also support the promotion of clean hydrogen (EU, 2020a: 20).

To tap into the opportunity for a renewable hydrogen trade with neighbouring regions, the *European Neighbourhood Instrument* supports energy infrastructure investments in Africa and the Middle East with over EUR 15 billion for 2014–2020. Under the *Africa–EU Energy Partnership*, one of the energy security objectives is doubling electricity interconnections and African gas exports to the EU by 2020 compared to 2010. The EU already imports around 12–14% of its gas demand from North Africa, mainly Algeria. However, it must be examined whether these gas pipelines could be repurposed cost-effectively to carry hydrogen while their shares are only a few percent (IEA, 2019c: 191).

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4.2. Japan's policy

On 25 October 2020, Japan announced a new GHG emission reduction target, with 46% by Fiscal Year (FY) 2030 and to zero by FY 2050, from the FY 2013 level. These targets were revised upwards from their previous commitment made at the Paris Agreement, to cut GHG emissions by 26% by 2030 and 80% by 2050. The government's target is a reduction by 25% in the transportation sector, by 39% in the residential sector and by 40% in the commercial sector in 2030 from the FY 2013 level. In 2019, total CO_2 emissions were 1029 Mt, to which the industry sector contributed 37,4% (384 Mt), the transportation sector 20% (206 Mt), and the commercial sector 18.8% (193 Mt) (MoE, 2021a).

Japan is heavily dependent on energy imports, mainly from the Middle East, which accounted over 85% of its total primary energy supply (TPES) in 2019 (IEA, 2021c). Beyond energy efficiency efforts, the most viable option to improve energy self-sufficiency for Japan has been nuclear power, which accounted for 4% of TPES in 2019 (MoE, 2021a). Still, most of its plants have been temporarily shut down after the Fukushima nuclear accident in 2011.

In 2012, the feed-in-tariff (FIT) scheme for renewable energy was introduced to subsidize the installation of renewables, including solar PV for 10–20 years, wind for 10 years, and geothermal for 15 years (METI, 2012). In 2020, renewable energy accounted for 20.8% of all electricity generated in Japan, compared with 18.5% in 2019 (ISEP site, 2019). By 2030, the government plans to increase the share of renewable energy to 36–38% of all electricity generated as the primary power source, and the share of hydrogen to 1%, according to the *6th Strategic Energy Plan* published in October 2021 (METI, 2021c: 12).

In December 2013, a *Council for a Strategy for Hydrogen and Fuel Cells,* an expert group from the industry, academia and the government to promote the use of hydrogen, was established by the Ministry of Energy, Trade and Industry (METI). In June 2014, that council published the *Strategic Roadmap for Hydrogen and Fuel Cells* and revised it in 2016 (METI, 2019c: 2).

In April 2016, the *National Energy and Environment Strategy for Technological Innovation towards 2050* was published by the *Council for Science, Technology and Innovation*. The strategy identifies promising technical fields, such as hydrogen, to significantly reduce GHG emissions by around 2050 (METI: 2019b: 44).

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The Basic Hydrogen Strategy

In December 2017, the *second Ministerial Council on Renewable Energy, Hydrogen and Related Issues* was held, and the *Basic Hydrogen Strategy* was published. The strategy indicates the pathway driving innovation building a *hydrogen society* and achieving full-scale deployment of hydrogen by 2050 (METI, 2019c: 45). Japan focuses on the end-use in the fields of power, transportation, residential, heavy industry and potentially refining. The country plans to increase hydrogen import and spearhead hydrogen end-use technologies, especially in mobility (Hydrogen Europe, 2020: 81). The strategy includes the development and utilisation of both CO_2-free hydrogen from renewable sources or from fossil fuels plus CCS in its plans and stresses the necessity of competitive cost (Nagashima, 2020: 6).

According to the strategy, by 2030, Japan aims to reach 1 GW of power capacity based on hydrogen, corresponding to an annual hydrogen consumption of 0.3 Mt H_2, increasing to 15–30 Mt H_2 (15–30 GW) in the long term (METI, 2019c: 20). To achieve this by 2030, commercial-scale supply chains need to be established to procure 300,000 tons of hydrogen per year, with hydrogen costs of JPY 3/kg (EUR 0.024 /kg) and hydrogen supply costs around JPY 30/Nm³ or about JPY 334/kg (EUR 0.24/Nm³ or EUR 2.7/kg). Japan aims to reduce hydrogen costs to JPY 2/kg (EUR 0.016 /kg) and hydrogen supply costs to JPY 20/Nm³ (1.6 EUR/Nm³) by 2050, allowing hydrogen to become cost-competitive with LNG power generation when environmental cost adjustments are incorporated. Also, Japan aim at reducing hydrogen power generation costs to JPY 17/kWh (EUR 0,14/kWh) by 2030.

After 2030, the target is to procure between 5 and 10 million tonnes of hydrogen per year (amounting to between 15 and 30 GW in power generation capacity), which will significantly depend on the consumption for hydrogen power generation to replace gas power generation. According to the Institute of Applied Energy, the hydrogen demand in Japan is expected to reach 53 Mtoe (0.22 trillion Nm³) in 2050, which would make a 13% share of the TPES (Arias, 2019: 14).

Around 2040, a CO_2-free (blue and green) hydrogen supply value chain is expected to be fully established (METI, 2017b: 3).

The strategy proposed ambitious targets, especially in mobility:

- HRSs (160 in 2020), to 320 by 2025; and 900 by 2030
- FCVs (3800 in 2020); to 200,000 FCEV by 2025; and 800,000 by 2030

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- Fuel cell buses (91 in 2020) to 1200 by 2030
- Fuel cell forklifts (250 in 2020) to around 10,000 by 2030

Figure 17 below summarizes the above targets and other key targets envisaged under the strategy from 2017 and 2030 to around 2050.

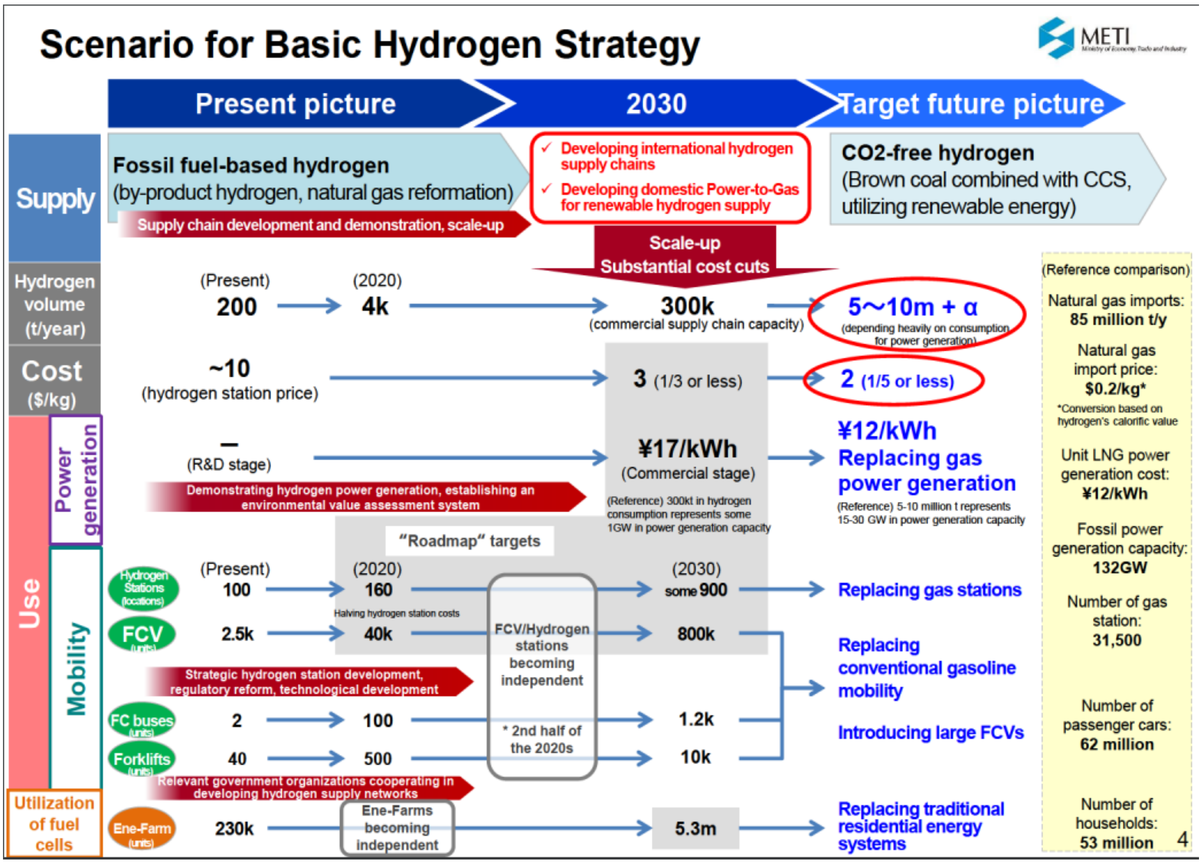

Figure 17: Overview of the Japan Basic Hydrogen Strategy *(Source: METI 2017a)*

To reduce the cost of electrolysers, the 2019 strategy outlines steps for improvement of AEL and PEM technologies. The government will support the development of a technology to lower the unit cost for water electrolysis systems from JPY 200,000/kW (EUR 1552/kW) in 2021 to JPY 50,000/kW (EUR 383 /kW) by 2030 in order to achieve cost competitiveness. By around 2032 when the FIT system for renewable energy projects will expire, Japan aims to reduce the cost of green hydrogen to become competitive with that of imported hydrogen (METI, 2019c: 14).

The strategy aims to commercialize thermal power using hydrogen by 2030 through the development of combustion technology and the availability of hydrogen fuel. A 15–30 GW of hydrogen generation capacity is required to make hydrogen

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commercially viable, compared to LNG. Japan consumed around 50 million tons of LNG in 2018 in power generation, representing 35% of the total power supply in 2018 (Nagashima, 2020: 19).

The strategy aims at improving the efficiency and extending the life cycle of commercial and industrial fuel cell systems, achieving an efficiency over 55% by 2025 and over 65% by 2050, and a durability from 90,000 hours in 2017 to 130,000 hours by 2025, with a system cost of JPY 300,000–500,000/kW (EUR 2300–3900/kW) and power generation costs of JPY 17–25/kWh (EUR 0.14–0.19/kWh) by 2025. It aims to realise grid-parity in these sectors, combining the utilisation of exhaust heat by 2025 by developing fuel cell stack technologies for getting higher efficiencies and power densities and eliminating the cause of degradation (METI, 2017a: 29).

To achieve these targets, Japan encourages to further improve power generation efficiency for solid oxide fuel cells (SOFCs) and the fuel heat utilisation factor for polymer electrolyte fuel cells (PEFCs). Japan will also explore other markets for stationary fuels in other regions, such as Europe, where the heat demand is high, and promote the adoption of fuel cells for commercial and industrial scale. From 2030, Japan aims to deploy pure hydrogen fuel cell co-generation systems using CO_2-free hydrogen (METI, 2017a: 29).

For prospective hydrogen import, carrier technologies (storage and distribution of hydrogen), fuel cells and electrolysers have been identified as the main R&D priorities since 2014 (Nagashima, 2020).

The Strategic Roadmap for Hydrogen and Fuel Cells

In March 2019, the *Council for a Strategy for Hydrogen and Fuel Cells*, an expert group of the government, the private sector, and academia, published the third version of the *Strategic Roadmap for Hydrogen and Fuel Cells.* (METI, 2019c: 2). The first version was published in 2014.

The roadmap recognises the necessity of blue hydrogen production and utilisation through brown coal gasification during the transition phase in the early 2020s and expects that hydrogen technologies will become commercially viable by 2030. The roadmap set specific targets for green hydrogen in terms of electrolyser costs of JPY 50,000/kW (EUR 383/kW), efficiency (70% or 4.3 kWh per normal cubic metre [Nm³]) and production costs (EUR 3.0/kg) by 2030 (METI, 2019c: 9).

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For industrial processes and heat utilisation, the use of CO_2 free hydrogen is considered in the future while targeting JPY 20–30/Nm³ (EUR 0.15–0.23/Nm³) for the cost of hydrogen (plant delivery) by 2030 (METI, 2019c: 36).

Figure 18 below summarizes the key targets envisaged under the roadmap for the period from 2025 to 2030. The targets for 2030 in the roadmap are same as the ones in the Hydrogen Strategy published in 2017, but the additional interim targets of 2025 and other concrete measures to achieve these targets under the roadmap and the strategy are specified.

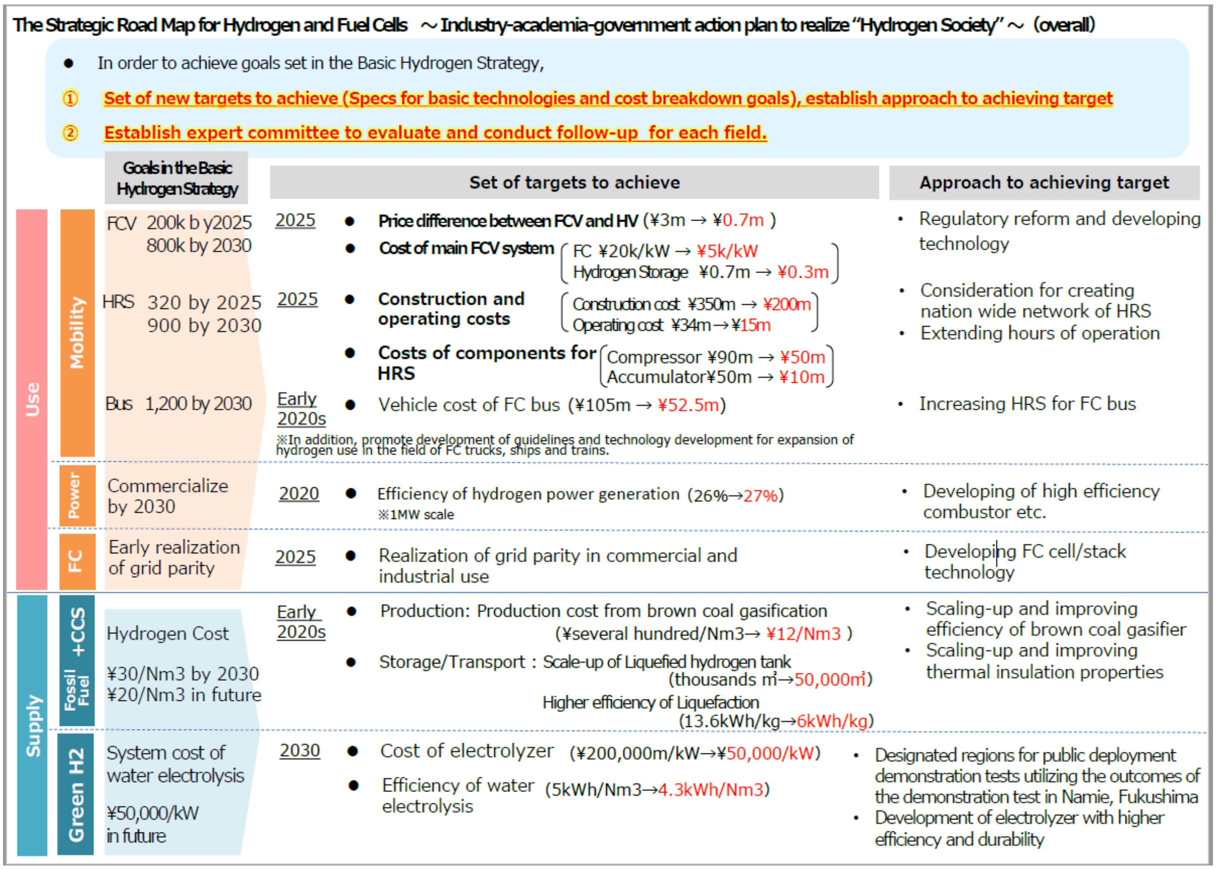

Figure 18: Overview of the Japan Strategic Roadmap for Hydrogen and Fuel Cells *(Source: METI, 2019c)*

Based on the evaluation of the R&D projects, which was supported by the New Energy and Industrial Technology Development (NEDO), the Hydrogen and Fuel Cell Strategy Council formulated the Strategy for Developing Hydrogen and Fuel Cell Technology in September 2019, which identified ten technological development items in three areas, namely (i) fuel cell technology, (ii) supply chain and (iii) water electrolysis and others, which are to be prioritized towards achieving the targets set in the Roadmap for Hydrogen (METI, 2019d: 5).

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The government published the *Green Growth Strategy through Achieving Carbon Neutrality in 2050* in December 2020, which includes timelines and specific targets to expand hydrogen use to 3 Mt in 2030 and 20 Mt in 2050 from 2Mt in 2021, with a public investment plan of JPY 310 billion (EUR 2.39 billion) to build a large-scale hydrogen supply chain, and JPY 80 billion (EUR 617 million) to increase the capacity of electrolysers (IEA, 2021a: 180), which come from the *Green Innovation Fund* established at NEDO with JPY 2 trillion for 2021–2030 (METI, 2021a). The Green Growth Strategy also supports further investment, job creation and upskilling and reskilling of workers.

4.2.1. Japan's challenges and opportunities

4.2.1.1. Challenges

i. Hydrogen cost

The main challenge for deployment of hydrogen in Japan are the high procurement and supply costs. The government has been supporting the built-up of a supply chain for importing CO_2-free hydrogen from renewable sources or fossil fuels plus CCS under demonstration projects. The cost of imported hydrogen will be critical to meet the increasing demand for hydrogen, particularly in the power generation sector.

The Asia Pacific Energy Research Center and the Institute of Energy Economics in Japan estimates that, by 2030, the sales price of hydrogen needs to be lower than USD 16-27 cents/Nm³ (EUR 0.14–0.24/Nm³) to be cost-competitive with coal-fired power, USD 17–22 cents/Nm³ (EUR 0.15–0.19/Nm³) with LNG, and USD 44–53 cents/Nm³ (EUR 0.39–0.47/Nm³) with oil. To become competitive with the cost of thermal power generation, CO_2-free hydrogen must be imported at below USD 17 cents/Nm³ (EUR 0.15/Nm³). In 2018, the retail price of hydrogen at HRSs in Japan was about JPY 100/Nm³ or USD 90 cents/Nm³ (EUR 0.76/Nm³). Domestic hydrogen is more expensive than hydrogen produced from imported fossil fuels with CCS. The high levelized cost of renewable energy in Japan (JPY 14.1/kWh for wind energy in 2020) has contributed to the higher cost of domestic hydrogen production (Nagashima, 2018: 65, 67).

According to IEA's estimate for Japan's industrial sector in 2030, importing hydrogen produced with renewable resources in Australia would be around USD 5.5/kg H_2 (EUR 4.86), of which conversion, transportation and reconversion costs are around

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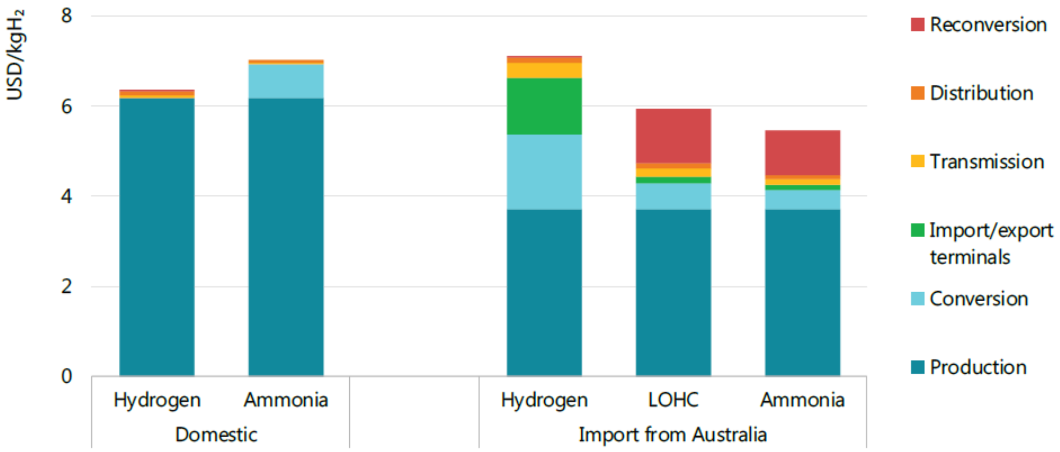
USD 1.5/kg (EUR 1.3/kg), corresponding to 30–45% of the full cost of hydrogen. This imported hydrogen from Australia will be cheaper than hydrogen produced in Japan (USD 6.5/kg) (EUR 5.7/kg), as shown in Figure 19 below. In the figure, it was assumed that hydrogen was produced by electrolysers connected to renewable energy facilities with excess power generation in Australia and transported as ammonia or LOHC to the end-users in Japan (IEA, 2019c: 82).



Notes: Assumes distribution of 100 tpd in a pipeline to an end-use site 50 km from the receiving terminal. Storage costs are included in the cost of import and export terminals. More information on the assumptions is available at www.iea.org/hydrogen2019.
Source: IEA analysis based on IAE (2019), "Economical Evaluation and Characteristic Analyses for Energy Carrier Systems" and Reuß (2017), "Seasonal storage and alternative carriers: A flexible hydrogen supply chain model". All rights reserved.

Figure 19: Comparison of the estimated cost of hydrogen produced in Japan and hydrogen produced via electrolysis and imported from Australia in 2030 *(Source: IEA, 2019c)*

Another factor contributing to the higher cost of hydrogen is the high cost of renewable energy. In 2020, the government introduced tender-based pricing for solar and wind energy, though the bidding prices are still two to three times higher than in Europe (Nagashima, 2020: 10).

The *Association of Hydrogen Supply and Utilization Technology*, established by 49 energy and engineering companies in 2009, also supports hydrogen cost reduction by proposing a new industry standard category based on fuelling capacity for FCVs and HRSs (Arias, 2019: 49).

ii. Policies and regulations

As of 2021, hydrogen is not defined as a non-fossil fuel derived energy source under the *Energy Supply Structure Intensifying Act*, which promotes the use of renewable and non-fossil fuel energy sources. The government plans to include hydrogen as a non-fossil fuel derived energy source and identifies the methodology to properly

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evaluate the amount of CO_2 emissions of hydrogen in its life-cycle (METI, 2021b: 70), for which one of the options is to include hydrogen, ammonia and CCUS under the green electricity certificate and the *J-Credit Scheme,* which are currently used to certify the GHG emissions reduction from renewable energy (Nagashima, 2020: 14). In 2020, the Ministry of Environment (MoE) published the guidelines for the life-cycle assessment of the hydrogen supply chain and the tool for calculating the GHG emission reduction of hydrogen supply chains (MoE, 2020a). However, the application of these guidelines and tools is voluntary.

One of the factors affecting the slow pace of hydrogen deployment is that currently, there are no laws specific to the use of hydrogen, but various laws are applicable. Hydrogen is regulated as a type of high-pressure gas under the *High Pressure Gas Safety Act*, with standards for large-scale chemical plants with high explosive risks. In addition, several other regulations, such as construction-related regulations and environmental regulations, are also applicable. In the case of FCVs, these are governed under the *Road Vehicle Act*, but hydrogen container and other accessories under the *High-Pressure Gas Safety Act*. FCV manufactures need FCVs and hydrogen containers certified separately under these different acts.

Table 3: Major regulations and regulatory bodies for hydrogen in Japan *(Source: CMS legal, 2021)*

Regulatory Body	Role
Industrial and Product Safety Policy Group, Commerce and Information Policy Bureau, Ministry of Economy, Trade and Industry	• Administers the High Pressure Gas Safety Act.
Water and Air Environment Bureau, Ministry of Environment	• Administers the Air Pollution Control Act, Noise Regulation Act, and the Vibration Regulation Act.
Ministry of Land, Infrastructure and Transport and Tourism	• Administers the Road Vehicle Act, the Road Act and the Building Standards Act.
Fire and Disaster Management Agency, Ministry of Internal Affairs and Communications	• Administers the Fire Services Act.
Each prefecture	• Handles permission and notification under the High Pressure Gas Safety Act.

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These intricate regulations have affected slowing hydrogen deployment as well as increasing the cost of hydrogen production and HRS in Japan (Nagashima, 2020: 18).

In addition to these regulations, hydrogen suppliers and end-users are also required to meet standards, such as Japan Industrial Standards, ISO TC197 Hydrogen Technologies and High Pressure Gas Safety Association standards, and are recommended to meet the guidelines set by the *Associations of Hydrogen Supply Utilization Technology* and the *Japan Petroleum Energy Center*.

Since 2007, the government has reviewed and revised the regulations to scale up HRSs and reduce hydrogen costs. Based on the inputs provided by the municipalities, prefectures, or the Fuel Cell Commercialization Conference of Japan, comprised of over 80 fuel cell related companies, associations and research institutes, METI has proposed and implemented the revisions in the fuel cell and HRS related regulations. In 2021, the revisions included the integration of the regulation of hydrogen containers and accessories into the *Road Vehicle Act*; lifting the limits of pressure for accumulators (from 82 to 87.5 MPa); easing the technical standards of the HRS surrounding walls; increasing the temperature limit (from 40 to 45°C) in the hydrogen containers at HRSs; and improvements of the administrative process for the use of spare parts in case of equipment failure or repair. Expected to be implemented in 2022 or later, all the revisions would contribute to lower HRS construction and operation costs (METI, 2021b: 60). In 2020, the CAPEX of HRS was JPY 310 million (EUR 2.41 million) and annual operating expenditure (OPEX) JPY 33 million (EUR 257,000). The government aims to reduce them to JPY 200 million (EUR 1.5 million) and JPY 15 million (EUR 115,000) by 2025, respectively (Fuel Cell Commercialization Conference of Japan, 2020: 3). In parallel to these reviews and revisions, NEDO conducts the verification of these revision items and provides the data and results with METI (METI, 2021b: 60).

METI provides subsidies for FCV and HRS construction, accounting for JPY 25 billion (EUR 194 million) in 2020. For HRSs, the subsidy is up to 60–70% of CAPEX and OPEX. The subsidy is mainly channelled through *Japan H_2 Mobility (JHyM)*, a consortium of Japanese automakers, infrastructure developers and investors that develop and operate HRSs (METI, 2021d: 13).

For 2015–2019, the MoE provided subsidies with a total budget of JPY 220 million (EUR 17 million) for up to 30% of CAPEX for HRSs with electrolysis connected to renewable power sources. The requirement for subsidies was to operate the HRSs

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with 100% renewable hydrogen. However, in 2019 the Board of Audit of Japan published that 80% of the beneficiaries supplied only about 45% of renewable hydrogen to operate HRSs. Based on this, the MoE decided to end the subsidy for HRSs from 2021 onwards (Board of Audit of Japan, 2019). The MoE further explored that the necessary electricity to produce one kg of hydrogen was initially estimated at 73 kWh/kg, while the actual was 75–1,430 kWh/kg, which is 1.5–4.8 times more than the estimate. These were affected by the outside temperature and the hydrogen supply amount at the HRSs. The ministry concluded that more data would be necessary to estimate the renewable hydrogen amount to operate HRSs and will continue working with relevant stakeholders to improve the subsidy scheme (MoE, 2020b).

Another factor affecting slowing hydrogen deployment is that, as seen in the case of the subsidy provided by MoE, some schemes were set with ambitious or strict targets. Except for subsidies, there are no further incentives to adopt hydrogen in the energy market. Still, numerous issues need to be resolved to scale up hydrogen deployment in Japan.

iii. Infrastructure and transport

In Japan, there is a lack of extensive hydrogen infrastructure, transport and storage. Due to the mountainous topography, the natural gas network is limited with about 253,000 km, compared to Germany with 530,000 km (Nagashima, 2018: 41).

Concerning the blending of hydrogen in the existing gas pipeline, only the safety assessment has been conducted, while the feasibility assessment is planned to be conducted in the future. For synthetic methane, ammonia, methylcyclohexane (MCH), the existing pipeline and storage facility can be used immediately. The Central Research Institute of Electric Power Industry study revealed that when blended into the gas pipeline with up to 10%, methane is estimated to have a CO2 reduction of up to 19 times more than hydrogen. The Japanese gas associations assume that the utilisation of synthetic methane would be the most viable option in the short- to medium-term, while LOHC could be an option in the long term (Central Research Institute of Electric Power Industry, 2019: iii). For limited local or new pipelines, dedicated hydrogen pipelines may be considered in the future (Tokyo Gas, 2021: 12).

Since 2019, the MoE has supported projects to verify the feasibility of blending renewable hydrogen into the natural gas network at eight different sites in Japan.

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For hydrogen import and transportation technology, MCH and liquefied hydrogen (LH2) were selected for pilot projects on long-distant shipping. The technology for MCH long-distance shipping and storage have already been established, but the expansion of the MCH facility and improvement in MCH process efficiency are still necessary. The technology for LH2 shipping and storage also needs to be further developed, while the technology for extraction of hydrogen from LH2 is already verified (METI, 2016: 10).

As of February 2018, the capacity of the LNG storage facility is 19 million kilolitre, and LNG underground storage is 7.2 million kilolitres. The Engineering Association of Japan estimates that the necessary additional storage capacity would be about 2 million m³ (Engineering Association, 2019: 49, 66).

4.2.1.2. Opportunities

Technology development and innovation

In 2020, the number of patents relating to hydrogen technologies in Japan was 103,853, while 90,107 were in the US, and 256,960 in China. Out of the patents, 48,000 are related to fuel cells, which were supported mainly by NEDO research projects, with 16,752 in the US and 16,689 in China (Hikima, et al., 2020: 12).

In 2019, 676 patent families for hydrogen technologies were registered, out of which Europe (30%) and Japan (25%) had the highest shares (IEA, 2021a: 172).

Japan has taken the lead in proposing international standards, such as hydrogen safety requirements and performance testing methods. They include ISO/TC197 (Hydrogen Technologies), ISO/TC265 (standardization in the fields of CO_2 collection, transportation, and storage), IEC/TC105 (Fuel Cell Technologies) and UN/GTR13 (Global Technical Regulation on Hydrogen/Fuel Cell Vehicles).

Japan also plans to strengthen the cooperation with the industry, academia and investors, as well as the cooperation under multilateral frameworks and partnerships on hydrogen, aiming to enhance information exchanges, joint investigations and joint R&D with other front runners in hydrogen supply chain development, including the EU, France, Germany, and the USA (Hydrogen and Fuel Cell Strategy Council, 2019: 42).

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4.2.2. Japan's plans, actions, and financial support

4.2.2.1. Plans and actions

Japan focuses on the deployment of hydrogen by using existing infrastructure. Thus, there are many ongoing projects in places with demand and supply of hydrogen on the same or nearby sites. Considering the prospect of energy source diversification and energy security enhancement, some projects include hydrogen imported and used at industrial plants located at the port.

i. Production

The Hydrogen Strategy set the target of hydrogen cost at JPY 30yen/ Nm^3 by 2003, and JPY 20/ Nm^3 by 2040–2050. The Hydrogen Roadmap envisages establishing the complete hydrogen supply chain by imported renewable hydrogen (METI 2019b: 5). The government supports the improvement of electrolyser technology and R&D Demonstration and Deployment (RDD&D) on imported hydrogen.

As part of the reconstruction and recovery efforts after the nuclear accident in 2011, *Fukushima Hydrogen Energy Research Field*, the world's largest, started operation in Namie, Fukushima Prefecture, in March 2020. The 100 MW AEL electrolyser connected to a 20 MW solar PV can produce up to 900 tons of hydrogen a year and will be used to fuel 560 FCVs or 150 households per day, and to support factory operations (Toshiba, 2019: 12).

Since September 2021, the *Yamanashi Hydrogen project*, a P2G facility of a 1.5 MW PEM electrolysis connected with a 21 MW solar PV system, has been operational. Hydrogen stored in a tank is used in fuel cells to produce electricity in times of low solar infeed. Hydrogen can also be compressed for transport for LPG customers or injected into the nearby customer pipelines for use in pure hydrogen fuel cells and boilers (Yamanashi Prefectural Enterprise Bureau, 2019: 22).

Under the *Advanced Hydrogen Energy Chain Association for Technology Development project*, supported by NEDO, 210 Mt hydrogen are produced annually in Brunei from natural gas, converted into LOHC, and shipped to Japan since December 2019. 100 Mt MCH hydrogen annually has been supplied to the adjacent power plant since January 2020 (Advanced Hydrogen Energy Chain Association for Technology Development, 2020).

The *Hydrogen Energy Supply Chain Pilot Project*, an initiative of the Australian and Japanese governments, began operations in January 2021, under which 160 tonnes of coal (Lignite) with CCUS are converted into 3 tonnes of hydrogen for liquefaction and shipping to Japan, as Figure 20 below shows. The brown coal gasification/hydrogen purification demonstration facility achieved a target purity of 99,999% in February 2021. The world's first liquefied hydrogen carrier left Japan to Australia in December 2021 and returned with LH2 to Japan in February 2022 (Hydrogen Energy Supply Chain Pilot Project, 2021).

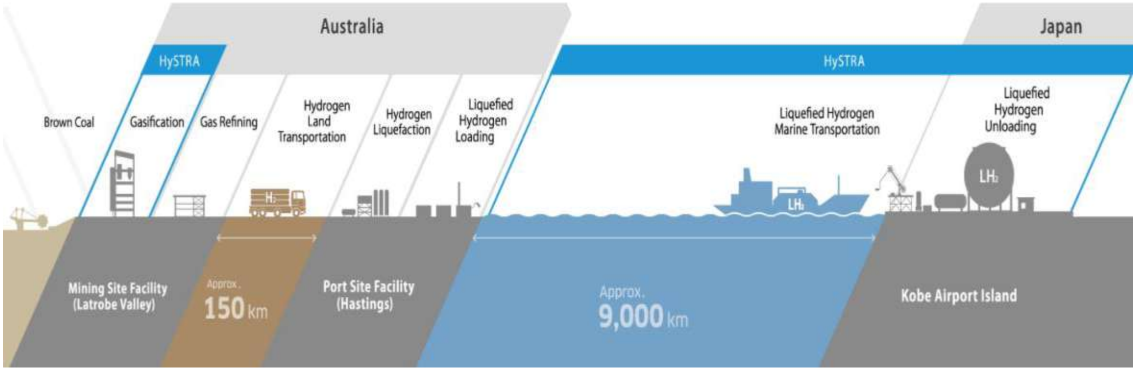

Figure 20: Hydrogen Energy Supply Chain Pilot Project overview *(Source: Hydrogen Energy Supply Chain Pilot Project, 2021)*

i. End-use

Industry

In 2018, the JGC Holdings Corporation announced the successful demonstration of synthesizing green ammonia with renewable hydrogen and electricity generation at a demonstration plant for power generation through gas turbines fuelled by this synthesized ammonia. This project is supported by the *Strategic Innovation Programme* under the Cabinet Office (JGC, 2018). Based on this success, in 2021, the JGC launched a new project to upscale green ammonia production with 100 MW AEL connected with renewable power supported by the *Green Innovation Fund* (JGC, 2021).

Transport

In 2020, 4,300 fuel cell cars, 100 fuel cell buses and 137 HRSs were operational in Japan, the highest number in the world. By 2030, Japan aims to have 800,000 passenger LDVs, 1200 buses, 10,000 forklifts and 1,000 HRSs, with the latter being revised from 900 as part of Japan's Green Growth Strategy published in December 2020 (JHyM, 2021). To support the targets for FCEV adoption set under the Hydrogen Strategy, the government supports reducing the cost of HRSs, fuel cells and hydrogen storage systems to make FCEV cost-competitive with hybrid EVs.

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In 2021, the manufacturer Toyota launched the *Woven City project*, providing 2000 inhabitants with PV and hydrogen fuel cells for stationary use and transport. ENEOS, a gas company, produces green hydrogen from renewable energy and operates HRSs in the Woven City (Toyota Woven City, 2021).

In 2019, the Panasonic factory in Shiga started a demonstration to supply CO_2-free hydrogen with photovoltaic power generation connected to electrolysis, as well as a 500 kW ENE-FARM, to fuel cell forklifts and operation within the factory (Panasonic, 2021: 11).

Heating/buildings

In fuel cell applications, Japan was the first to market a micro-cogeneration system for residential use at *ENE-FARM* in 2009. Its electricity output of 700-1,000 W, with a power generation efficiency of 53%, and a CO_2 emission reduction of 1.3 tons per year, can supply a part of the power and heating demand of a household. More than 350,000 units were installed as of March 2021. The price has been reduced to JPY 800,000 (EUR 6,500) for a standard polymer electrolyte fuel cell (PEFC) from 0.3 to 1 kW, and to JPY 1 million (EUR 8130) for a standard solid oxide fuel cell (SOFC) which achieved a period for recovering the investment of between 7 and 8 years by 2020, and of 5 years by 2030 (METI, 2019c: 32). ENE-FARM subsidies were eliminated in early 2020 for PEMFCs and in early 2021 for SOFCs as they reached maturity.

Fuel cell application in the industry started in 2017. The government supports the reduction of system costs from JPY 1.8 million/kW (EUR 14,000/kW) in 2019 to JPY 500,000 (EUR 3900) by 2025 to improve durability and efficiency over 65% (METI, 2019c: 36).

At the HARUMI FLAG residential complex in Tokyo, pure hydrogen fuel cells provide electricity for streetlights and air conditioning units with a total power output of 30 kW, with a power generation efficiency of 53%, and a rated energy conversion efficiency of 56% (Panasonic, 2019).

The Asahi Quality and Innovations Company conducted the verification of SOFC power generation with subsidies provided by MoE. A hybrid 1 MW SOFC system combined with a micro gas turbine initially used LNG as fuel. The system has been operational and fuelled by biogas generated from the waste treatment process in the beer factory in Ibaraki, Japan. The system generates 1.6 million kWh per year and 1,000 tonnes of CO_2 reduction (Asahi Group Holdings, 2020).

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Power generation

Since November 2017, a P2G hydrogen energy demonstration project in Hokkaido, initiated by Toyota Tsusho Corporation and a few other companies with NEDO fund, has been in operation. The hydrogen produced by the electrolyser, connected to a 2.2 MW wind farm, reacts with toluene to produce MCH, which is delivered to the user's site, where it is separated into hydrogen and toluene by a dehydrogenation system, with the regenerated hydrogen being mixed with LPG to produce heat using a mixed-fuel boiler (Toyota Tsusho, 2017).

In 2018, Kawasaki Heavy Industries and the Obayashi company announced a success in the world's first demonstration of electricity and heat supply using 100% hydrogen to an urban area in Kobe. The 1 MW hydrogen turbine system supplied 2800 kW heat to a hospital and a sports facility, and 1100 kW electricity to an exhibition centre and incineration facility (NEDO, 2018).

4.2.2.2. Financial support

Since 2012, nearly EUR 1.32 billion has been provided for R&D, demonstration and deployment of hydrogen programmes, primarily by METI, MoE, Ministry of Education, and Ministry of Land, Infrastructure, Transport and Tourism. The fund has been channelled through NEDO which oversees national programmes on new technology development, including hydrogen RDD&D (Arias, 2019).

Since 2014, the *Strategic Innovation Programme* under the Council for Science, Technology and Innovation, the Cabinet Office, has provided financial support to the projects in 12 areas, addressing the most important social issues facing Japan. Hydrogen is covered under the Energy Carriers theme. The fund is provided directly from the Cabinet Office to promote cross-ministerial collaboration. For 2014–2017, JPY 32.5 billion (EUR 253 million) and for 2018–2022, JPY 28 billion (EUR 218 billion) were allocated (Cabinet Office, 2020).

As Table 4 below shows, the total government budgetary support for R&D and subsidies for hydrogen technologies, clean mobility and HRS are increasing annually, with approximately JPY 69.81 billion (EUR 543 million) in 2021, JPY 83.6 billion (EUR 650 million) in 2020, and JPY 71.4 billion (EUR 555 billion) in 2019 (METI, 2020a: 10). For 2009–2020, the subsidies for ENE-FARMs, accounting for up to about 25% of the equipment and installation cost, were provided by METI, MoE and local governments (Fuel Cell Association, 2020). For all FCVs, the national subsidy has been provided by METI and MoE, depending on the car model, which is up to about 25% of the retail price. Additionally, all prefectures and municipalities also offer subsidies of up to 50% of the national one, depending on their budget. This support would bring the cost of the FCV to about 60% of the retail price of around JPY 6.4 million (EUR 49 800) in 2021 (Next Generation Vehicle Promotion Center, 2021).

Table 4: **Budget of METI for hydrogen and fuel cell related technologies for FY 2017–2021** *(Source: Author, with data form METI, 2021)*

Items/activities	**FY Budget in JPY billion**				
	2017	**2018**	**2019**	**2020**	**2021**
Hydrogen supply chain development in Fukushima as part of recovery efforts Imported hydrogen supply chain development including transport, storage and utilisation	4.7	9.4	20.74	14.6	15.33
CO_2-free hydrogen production technology via methane	0	0.9	1.4	0	0
Clean energy vehicle subsidy (includes FCV, EV, hybrid vehicle, green diesel vehicle	12.3	13	14	20	20
HRS establishment and operation subsidy	4.5	5.7	10	13	12
ENE-FARM and fuel cell including industrial use, subsidy	9.36	8.9	5.82	0	0
R&D on scaling up of HRS	0	2.4	2.99	3	3.6
HRS safety regulations and standards improvement	0	0.6	0.64	0	0
R&D on hydrogen use in steel and chemical production process for decarbonization	0	3	4.5	18	4.5
Demonstration of decarbonization in industrial process, especially at factories and ports using hydrogen	0	0	0	0	7.85
R&D on fuel cell for cost reduction and improvement durability and efficiency	3.1	2.9	4	7.5	0
R&D on CCS technology development including research on CO_2 storage	9.9	11.5	7.31	7.5	6.53
Total (JPY billion)	**43.86**	**58.3**	**71.4**	**83.6**	**69.81**
Total (EUR million)	**341.36**	**453.75**	**555.71**	**650.66**	**543.33**

In 2021, METI allocated approximately JPY 70.7 billion (EUR 550 million) for subsidies and projects for RDD&D hydrogen, FC and HRS, and MoE allocated JPY 6.58 billion (EUR 51 million) for hydrogen projects focusing on decarbonization (MoE, 2021b: 6). Under the *Green Growth Strateg*y published in December 2020, NEDO established the EUR 21 billion *Greene Innovation Fund* for 2021–2031, out of which JPY 699 billion (EUR 5.39 billion) is allocated for the hydrogen programme. The state-owned *Japan Oil, Gas and Metals National Cooperation* also supports

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some projects, focusing on R&D on CCS and supply chain development for blue hydrogen and blue ammonia (Japan Oil, Gas and Metals National Cooperation, 2021).

After commercial viability has been proved in the demonstration phase, the projects can seek funding from the state-owned *Japan Bank for International Cooperation* (JBIC), which provides policy-based finance and supplements private sector financial institutions. Based on the Hydrogen Strategy adopted in 2017, JBIC revised its regulations to expand the areas of investment for export. Accordingly, hydrogen production, transportation, supply, and utilisation have been included for the provision of funding for investment (JBIC, 2020: 6). Since 2019, the state-owned *Nippon Export and Import Insurance Agency* (NEXI) launched loan insurance for green innovation to offer preferential credit risk premiums for environment and climate projects including hydrogen, fuel cell, CCUS and renewable energy. By 2025, NEXI committed to underwrite insurance for a total of JPY 1 trillion (EUR 7.78 billion) (NEXI, 2019).

For industry-academia-government partnerships, the *Fukuoka Strategy Conference for Hydrogen Energy* was founded in August 2004 to lead the multi-stakeholder partnership to realize a hydrogen society. It is the largest in Japan with 862 partners as of 2021, led by Kyushu University, and supports RDD&D and human resources development for the hydrogen programme (f-suiso, 2022).

The *Fuel Cell Cutting-Edge Research Centre Technology Research Association*, a consortium of five FC companies and six academia institutions established in April 2010, hosts forums for governments, private sectors and research institutes to discuss the challenges in FC technologies and applications and identify possible solutions which could be further researched and developed under projects supported by NEDO (METI, 2021b: 54).

In February 2018, *Japan H2 Mobility (JHyM)* was established by a consortium of 11 Japanese automakers (26 in 2021), infrastructure developers and investors. It consolidates efforts of stakeholders to develop HRSs nationwide with financial resources from financial institutions that are part of JHyM. The latter closely works with the government and supports the standardization of equipment related to HRSs, optimization of FCV driver usability, and the deregulation of industry standards for HRSs. For 2018–2021, JHyM established 80 HRSs, about 50% of which are operational (METI: 2021b, 57).

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5 Strategy Comparison and Synthesis of a Suitable Policy Approach

5.1 Comparison of Hydrogen Strategies in the EU and Japan

The hydrogen strategies of the EU, selected EU countries and Japan provide overall targets and measures on the future role of (green) hydrogen in their national energy systems and economies. Both started from fundamental RDD&D on hydrogen and adopted a phased approach to integrating hydrogen into their energy systems as follows:

1. Scaling up and laying the market foundations (–2030),
2. Large-scale adoption and market expansion (2030–2050), and
3. Full deployment and application of hydrogen (2050-).

Both recognize the necessity of using low-carbon (blue) hydrogen to replace existing hydrogen and create an economy of scale of green hydrogen in the transitional phase until around 2030. The prioritization of the sector to integrate green hydrogen is linked to GHG reduction targets.

At the EU level, these actions proposed under the hydrogen strategy have swiftly been translated into legislative proposals, which greatly help to create a favourable environment for investment in hydrogen infrastructure, and to develop a competitive hydrogen market. In addition, many EU countries published or plan to publish their hydrogen strategies, noting the critical role of hydrogen in their energy and climate strategy and programme.

The EU hydrogen roadmaps developed by FCH JU with input from 17 European industrial actors, and Japan's roadmap developed by the expert group of the government, private sector and academia translated the visions into concrete, quantified targets and action plans.

The EU has been working to create an enabling regulatory environment through the revision and update of relevant regulations, standards, and certification to foster a fair and transparent hydrogen market. As the EU strategy suggests, setting minimum shares or quotas for green hydrogen could help accelerate its adoption. In this aspect, Japan needs to accelerate its effort on the regulatory development for hydrogen.

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Furthermore, both strategies provide substantial support and commitment for investment in the entire hydrogen supply chain, from R&D, infrastructure, production facilities, and end-use applications. Especially financing for early movers would be critical to mitigate the investment risks of the private sectors. The EU provides a wide variety of funding mechanisms as well as other support tools, such as CCfD. Japan also provides funds from several ministries and JBIC and investment protection from the Nippon Export and Import Insurance agency.

Table 5 below provides a comparison of the Hydrogen Strategies of the EU, selected EU countries and Japan.

Table 5: **Comparison of hydrogen strategies and deployment targets** *(Source: adapted from IEA, 2021a, and Maestre, et al., 2021)*

Country	Key document/ act, year	Deployment targets (2030)	Public investment committed
EU	*A hydrogen strategy for a climate-neutral Europe*, July 2020	40 GW electrolyser with additional 40 GW in neighbouring regions for hydrogen import	EUR 3.77 billion by 2030
France	*National Strategy for the development for decarbonized and renewable hydrogen in France*, September 2020	6.5 GW electrolyser 20-40 % green and blue hydrogen 20,000–50,000 FC LDV 800–2,000 FC HDV 400–1,000 HRSs	EUR 7.2 billion by 2030
Germany	*The National Hydrogen Strategy*, June 2020	5 GW electrolyser	EUR 9 billion by 2030
Netherlands	*National Climate Agreement*, June 2019 *Government Strategy on Hydrogen*, April 2020	3–4 GW electrolyer 300,000 FC cars 3,000 FC HDVs	EUR 70 million per year
Portugal	*National Hydrogen Strategy*, May 2020	2–2.5 GW electrolyser 10–15% hydrogen blend in gas network 5% hydrogen share in final energy consumption 50–100 HRSs	EUR 1–1.3 billion
Spain	*National Hydrogen Roadmap*, October 2020	4 GW electrolyser 25% green hydrogen as commodity and energy carrier 5,000–7,000 FC LDVs-HDVs 15–200 FC buses 100–150 HRSs	EUR 1.5 billion until 2023
Japan	*Basic Hydrogen Strategy*, December 2017 *Green Growth Strategy*, October 2020 and June 2021 (revised)	0.3 Mt hydrogen consumption per year 800,000 FCEVs 1,200 FC buses 10,000 FC forklifts 900 HRSs	JPY 699.6 billion by 2030 (EUR 5.74 billion)

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For the production of green hydrogen, it appears essential to increase electrolyser capacity as well as to improve its efficiency, bring down the cost of renewable energy, and establish dedicated infrastructure for hydrogen transport and storage. However, for all countries, the missing amount of green hydrogen production to meet their future demands, as well as to fully achieve their 2050 decarbonization targets may need to be carefully examined and complemented by other means. Reducing the cost of electrolysers is also crucial, although there is uncertainty on their sufficient supply, including the availability of their raw materials. Both the EU and Japan would need to continue their efforts to further reduce the cost of green hydrogen production, electrolysers, as well as renewable energy. To complement future hydrogen demand, Japan considers hydrogen imports from other countries with low renewable energy costs and fewer land-use constraints as one of its priorities. Hydrogen imports may enhance Japan's energy security in the longer term, although dealing with the growing international competition on hydrogen would need to be addressed. To transport and store hydrogen, a dedicated and extensive infrastructure, including connection to the grid and using gas pipelines, is necessary. In both the EU and Japan, adequate infrastructure is still missing and being developed.

France, the Netherlands, Portugal, Spain, and Japan set demand targets in specific sectors in their strategies, which would help give signals to the respective industries, and foresee hydrogen imports and necessary international collaboration (Material Economics, 2020: 12).

For the industrial sector, hydrogen application is mainly considered for energy-intensive processes, especially in steelmaking, chemicals, refining, methanol and ammonia. It has significant potential to decarbonize the industrial sector, so that substantial technological development in this area is foreseen. Japan focuses on hydrogen utilisation in the steelmaking and chemical industries.

For the transport sector, as the most immediate and potential hydrogen application, many governments prioritize certain subsectors, primarily focusing on medium- and heavy-duty transport.

For heating and power generation, hydrogen could contribute to cope with grid imbalances and to decarbonise heating and cooling supply in buildings, which has already been implemented in Japan and considered in Germany and the Netherlands.

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Both the EU and Japan have strong partnerships among their respective stakeholders, governments, industries, and academia. Stakeholders jointly set clear, long-term, and holistic targets for decarbonization pathways for major sectors and segments which would be key to achieving the set goals. Governments support multi-stakeholder partnerships and platforms, in the case of the EU both at EU-wide and national levels. The close cooperation and collaboration of stakeholders has accelerated the development of supply chains and scaled up investments for green hydrogen.

In the case of the EU, a strong cooperation across the Member States has already been achieved to realize the successful deployment of hydrogen, guided by their overall policy framework, such as the European RED II. This cooperation on hydrogen deployment has been building on existing systems, such as the *ETS* and *CertifHy* methodologies, and establishing European guidelines, standards and certification. The EU also created diverse RDD&D funding programmes through various channels, not only for EU Member States, but also for neighbouring countries, which help in advancing the development and deployment of the technology in the whole region.

The EU has already been working on ensuring the alignment of efforts and strategies on green hydrogen across countries and regions through coordination and continuous knowledge exchange, as seen in the established partnerships and forums, such as the *Clean Hydrogen Alliance* and the *Clean Hydrogen Partnership*. All this has contributed to streamlining activities related to hydrogen trade (IRENA, 2021a: 33).

5.2 Synthesis of a Suitable Policy Approach

Based on the analysis of the hydrogen strategies, roadmaps, plans and actions of the EU and Japan, it is clear that establishing comprehensive policies and regulations with concrete targets and measures, along with an enabling environment, is crucial to integrating hydrogen in the entire energy system and overall climate actions.

A suitable pathway towards the adoption of green hydrogen could be concluded as follows:

1. Support and promote RDD&D and conduct economic, social, and environmental impact assessments to identify drawbacks and highlight benefits and added values. Knowledge and information should be

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continuously shared with relevant stakeholders to achieve sustainable advancements and support innovation. RDD&D will help to identify barriers and their enabling measures, priority areas and sectors for investment and support. These preparation activities may also be assisted by regional or international (climate) finance mechanisms and institutions.

2. Develop national hydrogen strategies and roadmaps with short-, medium- and long-term actions, along with concrete targets and milestones on high priority research areas and applications, and implementation measures for hydrogen demand and supply. These identify the future role of and demand for hydrogen in the decarbonization of the energy system and the whole economy. This, then, sets the level of ambition a country should envisage for the hydrogen uptake, while providing a valuable reference for market and technology development, private investment, and project finance (IRENA, 2021b: 8). Green hydrogen's role in the national energy system and climate action needs to be specified. Clear and proper definition of the roles and responsibilities of relevant hydrogen stakeholders in strategies and roadmaps will ensure the smooth implementation of the envisaged actions.

3. Provide substantial financial support for the entire green hydrogen chain, which could mitigate investment risks, accelerate deployment of hydrogen and support creating hydrogen demand. Financial incentives through lower taxes for green products, CAPEX subsidy provision, or lower grid fees for green hydrogen and related technology, while ensuring to avoid double taxation for energy products, will help to promote green hydrogen. As the EU exhibits good examples of financial support, providing funding, financial instruments, and loans according to the technology readiness level and its degree of bankability, multilateral, regional and national financial mechanisms and institutions will also play critical roles in this regard.

4. Establish a hydrogen infrastructure to kick-start green hydrogen application. As seen in the case of the EU and Japan, fuel cells may have immediate applications in certain areas of hydrogen use, especially in the transport sector. Governments will need to remove barriers and adapt regulations for expanding HRS networks, while supporting the increase of hydrogen supply and development of hydrogen infrastructure. As in the case of the EU and Japan, consortiums or initiatives of automobile manufacturers and gas companies could also accelerate the expansion of hydrogen infrastructure.

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For green hydrogen transport, adequate infrastructure, pipelines and storage capacity is needed, especially where local power generation is not able to meet the demand and could be prioritized for an efficient hydrogen economy. In the transition period, existing infrastructure could be utilised and upgraded for hydrogen, where feasible, while the development of new dedicated hydrogen infrastructure will still be necessary.

5. Establish an enabling policy and regulatory framework. Depending on the available energy resources in the country, some countries may need to consider the use of grey hydrogen or blue hydrogen to bridge towards green hydrogen application in the process of their decarbonization efforts. Governments will need to establish or revise associated policies and regulations on energy, the environment, and industries, including certification, standards, and guidelines on safety and technology, which would help incentivize the industry to join the hydrogen market and ensure fair competition. As seen in the EU, actions envisaged under the hydrogen strategy should be translated into legislative measures.

   Furthermore, governments need to classify and recognize green hydrogen, in particular its contribution to GHG emission reductions, in official energy statistics. Also, governments will need to ensure that standards for safety, international trade and technology adoption, for example, for HRS and storage sites, based on national or international norms, are in place and are properly applied to the use of hydrogen and its carriers.

   A *guarantee of origin*, as developed and improved further by the EU, will help to differentiate and value green hydrogen. Discussions on standards and certification of green hydrogen have been ongoing at various national and regional organizations, such as TÜV SÜD and the EU. Thus, interested countries could take advantage of the already accumulated information and knowledge shared by those platforms.

   Introducing quotas and minimum shares of green hydrogen for large hydrogen consumers or specific end-use sectors may help to accelerate the adoption of green hydrogen.

6. Develop skilled personnel. Japan included human resources development for the hydrogen programme in its hydrogen strategy. For countries where

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hydrogen is new, training and reskilling of skilled personnel is essential to ensure safe production, storage, transport, and use of green hydrogen.

Throughout the process towards green hydrogen adoption, strong collaboration and coordination in projects and investments among relevant stakeholders, namely, governments, industries, private sectors, academia and financial institutions is critical. Also, public support for renewable power expansion is necessary, taking into account the social and environmental impact.

Several multilateral initiatives and platforms on hydrogen such as the *Hydrogen Initiative*, the *International Partnership for Hydrogen and Fuel Cells in the Economy* (IPHE), and the *Mission Innovation,* have been promoting R&D, knowledge and information sharing, facilitating collaboration among stakeholders, and supporting investment in green hydrogen projects (IPHE, 2021: 5). These actions have contributed to and will continue improving electrolyser technologies, reducing green hydrogen costs. This international cooperation is crucial and will pave the way for future international green hydrogen supply chains and trades, as well as set international standards and certification on green hydrogen.

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6. Conclusions

Green Hydrogen is a promising option as an energy carrier by providing flexible and long-term storage that will help to diversify energy sources, thereby enhancing energy security, especially for countries such as Japan, which is prone to natural disasters and highly dependent on energy imports.

For green hydrogen adoption, the availability of inexpensive renewable power and electrolysers, efficient and flexible performance of electrolysers, lower cost and availability of its transport and storage infrastructure, and the availability of a sufficient number of skilled personnel are fundamental. All these aspects need to be covered under hydrogen strategies, plans and actions, and an enabling policy framework with concrete financial instruments must be established when countries envisage green hydrogen adoption. Strong collaboration and partnership among national stakeholders (government, industry, academia, and investors) are vital. Regional coordination and support, as seen in the EU, and international cooperation appears similarly advantageous and necessary to accelerate green hydrogen adoption and deployment.

The EU and Japan both started from fundamental RDD&D on hydrogen, which has lasted over a decade and continues. Both hydrogen strategies have integrated hydrogen into their national energy systems in phases, indicating short-, medium- and long-term actions with concrete targets and measures and substantial financial commitment. Both recognize the necessity of using low-carbon (blue) hydrogen to replace existing hydrogen and create an economy of scale for green hydrogen in the transitional phase, until around 2030. Existing multilateral partnerships and initiatives also support their actions and accelerate electrolyser technology improvements and green hydrogen uptake. Where applicable, the regional level cooperation, as seen in the EU, facilitates countries to achieve a coordinated deployment of green hydrogen within countries of the region. Each country has a different base for policies and actions, depending on social, economic, and political priorities, as well as available resources and infrastructure. Lessons learnt and (early identified) best practices from the hydrogen strategies of the EU and Japan provide useful perspectives for countries that may consider adopting green hydrogen in the near future.

Countries where renewable energy resources are affordable and sustainable, and where higher renewables shares in their energy mixes have been or will be

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achieved, will have a higher potential in adopting green hydrogen. Long-term forecasts expect that green hydrogen costs could be lower than USD 2.00/kg (EUR 1.76/kg) by 2030 in countries with adequate renewable resources, such as China, the Middle East and Africa (IEA 2019c: 188). China, India, Egypt, Namibia, and South Africa have already started green hydrogen projects. Locations that are remote from electricity grids, countries with available gas network, and areas with sufficient renewable resources or extreme seasonal renewable variability may have great potential for green hydrogen adoption (World Bank Group, 2020: xviii).

To assess the green hydrogen potential in emerging economies and developing countries could be one of the areas for future research. As the number of large-scale electrolyser projects is increasing globally, identifying a way to support and diversify electrolyser manufacturers to facilitate fair balancing, accommodating supply and demand for critical minerals which are used in electrolyser equipment, and promoting recycling of electrolyser materials and parts could also be areas for further research.

With the right policies put in place, in the near future, green hydrogen could become one of the most reliable and affordable energy carriers for some countries and contribute to achieving climate change goals and environmental benefits altogether.

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List of abbreviations

AEL	Alkaline electrolysis
AEM	Anion exchange membrane electrolysis
BEV	Battery electric vehicle
CAPEX	Capital expenditure
CCfD	Carbon contracts for difference
CCGTs	Combined-cycle gas turbines
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
CHP	Combined head power
CNG	Compressed natural gas
CO_2	Carbon dioxide
DRI	Direct reduced iron
DSOs	Distribution system operators
EBA	European Battery Alliance
EC	European Commission
EIB	European Investment Bank
EJ	exajoules
ETS	Emission trading system
EU	European Union
EUR	Euro (An exchange rate of JPY 100 = EUR 0.76, as of December 2021, has been applied.)
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
FCV	Fuel cell vehicle
FIT	Feed-in-tariff
FY	Fiscal Year – of Japan, which is from April of one year to March of the following year
GHG	Greenhouse gases
G2P	Gas to power
H_2	Hydrogen
HEV	Hybrid electric vehicle
HDV	Heave-duty vehicle
HRS	Hydrogen refueling station
IEA	International Energy Agency
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IRENA	International Renewable Energy Agency
kg	Kilogram
JBIC	Japan Bank for International Cooperation
JPY	Japanese yen
LCA	Life cycle assessment
LCV	Light commercial vehicle
LDV	Light-duty vehicle
LNG	Liquefied natural gas
LH2	Liquefied hydrogen
LOHC	Liquid organic hydrogen carrier

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METI	Ministry of Economy, Trade and Industry of Japan
MoE	Ministry of Environment of Japan
Mt	Million tonnes
NDC	Nationally determined contributions
NEDO	New Energy and Industrial Technology Depelopment Organization of Japan
NEXI	Nippon Export and Import Insurance Agency
NH_3	ammonia
Nm^3	Normal cubic meter
NO_X	Nitrogen oxides
OPEX	Operating expenditure
PEFC	Polymer electrode fuel cell
PEM	Polymer electrolyte membrane
PV	Photovoltaics
P2G	Power to gas
P2P	Power to power
R&D	Research and development
RDD&D	Research and development, demonstration and deployment
RED II	Renewable Energy Directive - agreed in June 2018, revised in December 2018
SMR	Steam methane reforming
SOFC	Solid oxide fuel cell
t	Tonne(s)
TPES	Total primary energy supply
TEN-E	Trans-European Networks for Energy
TEN-T	Trans-European Networks for Transport
TSOs	Transmission system operators
TW/GW/MW/kW	Terawatt hour, gigawatt, megawatt hour, kilowatt hour (unit of power, 1 Watt = 1 J per s)
TWh/GWh/MWh/kWh	Terawatt hour, gigawatt hour, megawatt hour, kilowatt hour (unit of energy, 1 Wat—hour = 3600 J)
UK	United Kingdom
USA	United States of America
USD	United States Dollar (An exchange rate of USD 1 = EUR 0.88, as of December 2021, has been applied.)
VRE	Variable renewable energy

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