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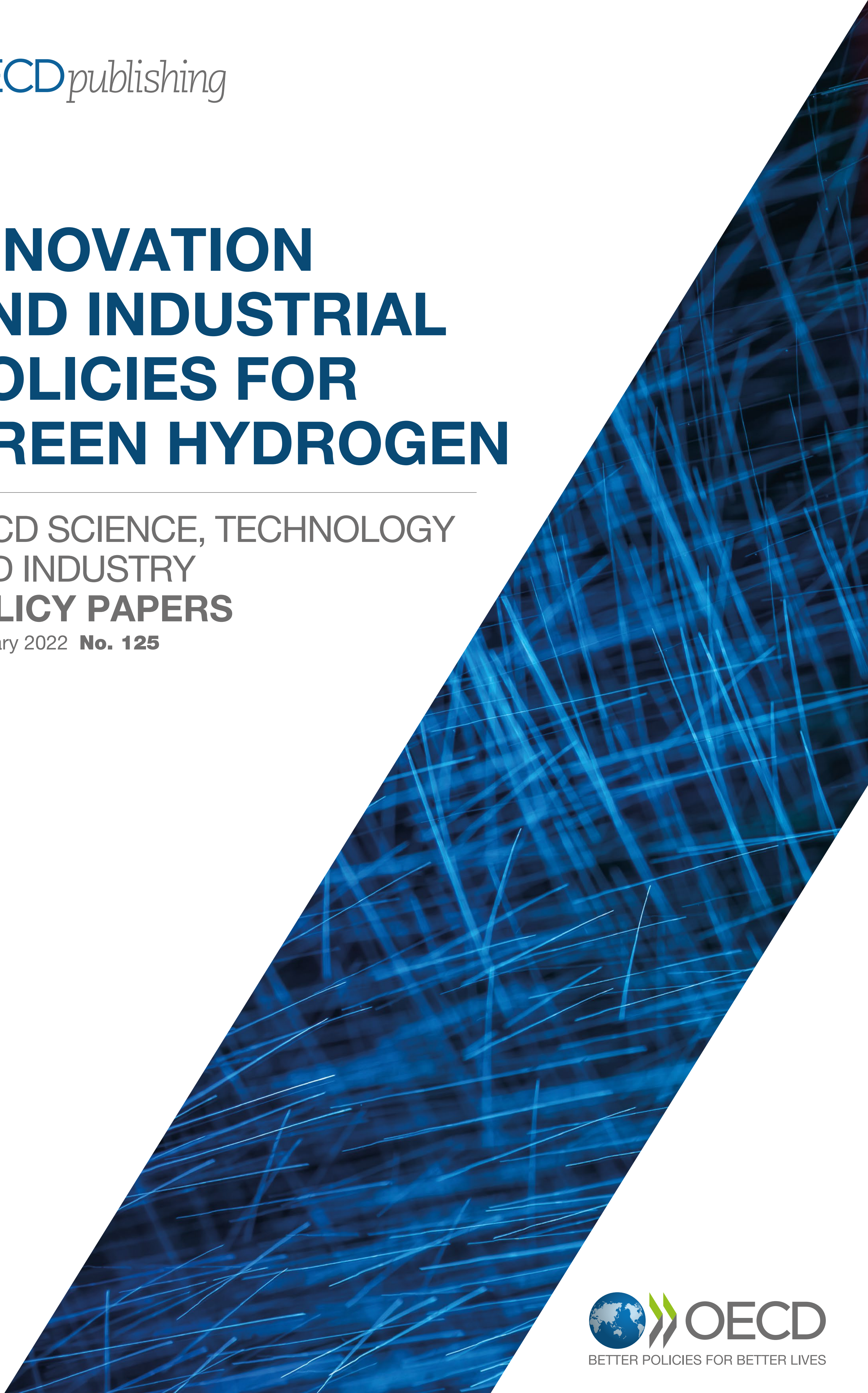

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Innovation and Industrial Policies for Green Hydrogen

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This paper examines the current development of hydrogen technology in the manufacturing sector and the industrial policies enacted to support it across countries. In addition to continued R&D efforts, governments can already lay the ground for the deployment of green hydrogen by implementing five types of policies: 1) supporting R&D and demonstration for green hydrogen to bring down the cost of electrolysers and make them competitive; 2) increasing the supply of renewable electricity; 3) reducing the cost gap between green hydrogen and brown technologies through a comprehensive policy package, such as carbon pricing and the phasing out of inefficient fossil fuel subsidies; 4) reducing uncertainty, for instance by promoting international standardisation, hydrogen infrastructure, and sound regulatory standards; and 5) considering blue hydrogen as a short-term option to facilitate the transition to green hydrogen.

Keywords: hydrogen, decarbonisation, technology support, industrial policy

JEL Codes: L52, O38, Q54, Q55, Q58

Executive summary

The recent commitments to carbon neutrality by 2050 have put the spotlight on the critical role that hydrogen can play to achieve net-zero targets. Production of hydrogen from water and renewable electricity through electrolysis (green hydrogen) can contribute to reducing emissions through four channels. First, hydrogen is already a feedstock for a number of chemical products and green hydrogen can make this production carbon-neutral. Second, hydrogen is a promising alternative to fossil fuels for high-temperature industrial processes in hard-to-abate sectors such as steel production. Third, hydrogen is necessary for the development of fuel-cell vehicles and can also, in specific circumstances, reduce emissions in the built environment by replacing natural gas. Finally, hydrogen can be used to store energy produced from intermittent sources, thereby supporting the supply of low-cost renewable electricity.

Most net-zero emission scenarios agree that hydrogen will play a pivotal role in decarbonisation at the 2050 horizon. However, in 2021, the production of green hydrogen is still about 3 times more expensive than grey hydrogen (made out of natural gas through steam reforming), even under the most favourable conditions. Major cost reductions – and the rapid deployment that they would induce – are realistic in the next 10-20 years, but will crucially depend on massive improvements in the cost of electrolysers (through R&D and large-scale demonstration projects) and on the availability of large volumes of cheap renewable electricity. These investments, in turn, depend on ambitious public policies.

Against this backdrop, a number of countries have published National Hydrogen Strategies, which contain ambitious hydrogen production targets at the 2030 horizon. These targets are a significant improvement with respect to today's virtually inexistent green hydrogen production, but are still far from the necessary deployment at the 2050 horizon. Some longer-term objectives (until 2050) could provide more certainty to investors.

Moreover, these targets mostly rely more on financial support for the deployment of new large electrolysers than on direct support for innovation. Between 2008 and 2019, several countries increased public RD&D spending on hydrogen, but others cut public spending on RD&D by more than half. The focus of public support at the deployment stage transpires in firms' recent filings of intellectual property rights: while patenting activity on hydrogen production technologies is growing at a very slow pace, the number of hydrogen trademarks recently took off, suggesting that companies are focusing on commercialisation rather than on innovation, and anticipate a growing hydrogen market pulled by government subsidies.

Even if some countries perform better (Denmark, Germany and Austria appear as the countries with the highest specialisation in hydrogen patents for the period 2015-19), the global stability in the number of hydrogen patents casts doubt on the capacity to develop the hydrogen-related technologies and to achieve the cost reductions that are needed to make green hydrogen competitive. In addition, the share of young firms in hydrogen patents is declining. However, young firms are found to produce on average more radically novel hydrogen innovations than established firms.

In this context, countries willing to support hydrogen should follow these five policy priorities:

- Ensure greater support for R&D in green hydrogen and demonstration projects. Targeted R&D support instruments are required, as horizontal R&D support cannot stimulate innovation in technologies characterised by significant uncertainty. Large-scale demonstration projects are also needed to reduce costs through

economies of scale, economies of scope and learning-by-doing. Financial instruments (including public loans or guarantees and government venture capital) could efficiently de-risk demonstration projects and crowd in private money. Ensuring that knowledge can flow across firms and that newcomers can benefit from publicly funded R&D and demonstration projects is particularly important as the hydrogen sector is singularly concentrated. Ensuring sound competition and low barriers to entry is therefore another essential element of green hydrogen industrial policies. Cooperation and coordination between countries is also needed to favour knowledge diffusion.

- Ensure a sufficient supply of renewable energy where possible, and encourage the creation of an international hydrogen market. Making green hydrogen competitive will require a significant decrease in the cost and a significant increase in the supply of renewable electricity. Countries endowed with low renewable energy resources should therefore consider importing green hydrogen from countries with abundant renewable energy. Agreeing on common international standards would reduce investors' uncertainty and facilitate the creation of such an international market for hydrogen.
- Establish clear carbon price trajectories to provide investors with the right incentives. Adequate carbon pricing would make green hydrogen more competitive, contribute to a cost-efficient decarbonisation, and could provide revenue to finance R&D support to green hydrogen. Deployment subsidies might be needed, on top of carbon pricing, to cover the price difference with fossil fuel-based alternatives in the medium run, but a combination of strong R&D support and clear carbon pricing trajectories could well be sufficient. Carbon Contracts-for-Difference (CCfD), which are experimented in Germany and consists in forward-contracts on the price of abated greenhouse gases, can decrease uncertainty for investors.
- Reduce uncertainties for investors through regulatory action and standardisation. Strong government signals are required regarding the potential role of green hydrogen, infrastructure investments – often a pre-requisite for the adoption of hydrogen – and regulatory standards (e.g. on guarantees of origin, hydrogen purity, equipment specifications, blending into the gas grid). Low-carbon hydrogen certificates similar to the ones currently in place on the renewable energy market could be introduced.
- Consider blue hydrogen as an interim solution to facilitate the transition to green hydrogen. Blue hydrogen (produced from natural gas with carbon capture) should be considered only as a short-term option. On the one hand, blue hydrogen may help the transition from fossil fuels to green hydrogen by decarbonising the existing production of grey hydrogen, by facilitating the emergence of a growing hydrogen market and by decarbonising early on some industrial sectors, as well as transportation. On the other hand, blue hydrogen suffers from important drawbacks as it is not completely carbon neutral, it may compete with green hydrogen, and carbon storage requires affordable and secure storage options. All in all, the case for supporting blue hydrogen will depend on country and industry characteristics.

Table of contents

Executive summary 4

1. Introduction 7

2. The role of hydrogen to achieve carbon neutrality 9

3. Technological and economic feasibility for hydrogen to fulfil its role 13

4. Global hydrogen innovation 20

5. Comparison of hydrogen policy developments across main hydrogen economies 30

6. Hydrogen policies: what can governments do now? 43

Endnotes 49

References 50

Annex A. Most important hydrogen policy documents in different countries 53

Tables

Table 3.1. Characteristics of a typical green hydrogen project for ammonia production 13
Table 5.1. Public RD&D spending on hydrogen and fuel cells by country 31
Table 5.2. Planned hydrogen capacity in main economies (until 2040) 33
Table 5.3. Largest planned hydrogen projects in the world (until 2040) 33
Table 5.4. Hydrogen targets in main hydrogen economies 35
Table 5.5. Hydrogen Instruments in main hydrogen economies 37
Table 5.6. Hydrogen infrastructure priorities in main hydrogen economies 39
Table 5.7. Hydrogen standards in main hydrogen economies 41
Table 5.8. International cooperation on hydrogen in main hydrogen economies 42
Table 6.1. Most important sources used in international comparison section 53

Figures

Figure 2.1. Global hydrogen and hydrogen-based fuel use in the IEA Net Zero Emission Scenario 11
Figure 2.2. Role of different technologies in emission reductions in the Netherlands between 2015 and 2050 12
Figure 3.1. Green hydrogen electrolyser cumulated cash flows for different scenarios 14
Figure 3.2. Expected future cost reductions for green hydrogen 16
Figure 4.1. Number of annual patent filings in different hydrogen technologies, 2004-19 22
Figure 4.2. Number of trademarks related to hydrogen, 2004-18 23
Figure 4.3. Top hydrogen innovation countries 24
Figure 4.4. Main owners of hydrogen trademark by country, 2014-2018 24
Figure 4.5. Relative technology advantage in hydrogen technologies, 2004-08 and 2015-19 26
Figure 4.6. Trademarks specialisation toward hydrogen, 2014-18 26
Figure 4.7. Concentration of patenting activity in hydrogen, 2015-2019 27
Figure 4.8. Concentration of hydrogen-related trademarks (2014-2018) 28
Figure 4.9. Share of young firms in hydrogen patents, 2004-19 28
Figure 4.10. Average originality index of hydrogen patents, 2010-15 29
Figure 5.1. Public RD&D spending in OECD countries on hydrogen and fuel cells, 2004-2019 30

1. Introduction

The recent commitments to carbon neutrality by 2050 have put the spotlight on the critical role that hydrogen can play to achieve net-zero targets. Production of carbon-free hydrogen from renewable electricity (green hydrogen) through water electrolysis – a technology first developed in 1888 – or of low-carbon hydrogen through nuclear electricity, biomass, or fossil fuels with carbon capture and storage can contribute to reducing carbon emissions through four main applications (IEA, 2019[1]). First, it is a promising alternative to fossil-fuel for high-temperature industrial processes, which are frequent in hard-to-abate sectors such as steel production. Second, hydrogen is necessary for the development of fuel-cell vehicles, not only cars but also heavy vehicles, ships and airplanes, and can also play a role to reduce emissions in the built environment. Third, hydrogen is a feedstock for a number of chemical products (e.g. ammonia) and perhaps for future synthetic fuels. Finally, the rapid increase in the supply of low-cost renewable electricity does not only make the large-scale production of green hydrogen possible, it can also be further enhanced by the deployment of hydrogen, which can store energy produced from intermittent renewable electricity sources. More generally, green hydrogen is attractive because it can contribute to a wide range of policy objectives, such as energy security, reduced local air pollution, economic development and energy access.

However, unlocking the potential of carbon-free or low-carbon hydrogen requires facing the double challenge of decarbonising current hydrogen production and scaling up volumes. At present, global hydrogen production amounts to a mere 90 Mt, and over 90% of this production uses carbon-emitting sources (coal and natural gas) (IEA, 2021[2]). In order to make a meaningful contribution to climate neutrality, available scenarios suggest that global hydrogen production needs to reach 500 Mt in 2050 and the proportion of this hydrogen produced using carbon-free or low-carbon processes needs to increase from 10% to over 90% (IEA, 2021[2]). The production costs of green hydrogen also need to fell sharply (by around 75%) in order to become economically competitive with high-carbon sources (Hydrogen Council and McKinsey & Company, 2021[3]; IRENA, 2020[4]). The competitiveness of hydrogen-based solutions will also depend on the cost of fossil fuels, which will be affected by global demand and supply factors, but also by public policies, including carbon prices.

Against this backdrop, many countries have adopted National Hydrogen Strategies over the last two years, which lay out targets and policy instruments to reach those. These strategies are motivated both by the desire to seize an important decarbonisation opportunity and to give domestic firms a potential competitive edge in the future hydrogen economy.

The objective of this paper is to analyse the role that industrial policies – and particularly innovation and technology adoption policies – can play to accelerate the deployment and use of low-carbon hydrogen. Although hydrogen has an important role to play in many sectors – including transportation – the paper mainly focuses on the manufacturing sector, where few alternatives to hydrogen currently exist to achieve deep decarbonisation, in particular for high temperature processes. In line with the IEA's net-zero emissions scenario, the paper also focuses mostly on green hydrogen as the source of decarbonised hydrogen with the greatest deployment potential in the coming decades. The paper describes the main technological and economic bottlenecks for the green hydrogen revolution to take place; provides an empirical description of the current hydrogen innovation and diffusion landscape based on patent and trademark data; reviews countries' National Hydrogen Strategies and analyses the set of existing policy instruments in place (including targets, infrastructure programmes, standards and international cooperation instruments); and offers recommendations for policy makers on the most pressing policy actions that are required.

This paper is closely related to the economic policy literature on decarbonisation strategies. Building on the growing interest in new industrial strategies (OECD, forthcoming[5]), several papers discuss the policy mix to reach net-zero emissions, or more generally to effectively reduce carbon emissions (Tagliapietra and Veugelers, 2020[6]; Altenburg and Rodrik, 2017[7]; Rodrik, 2014[8]).

This paper also builds on the literature describing the advancement of hydrogen technologies and the remaining engineering and economic challenges (IEA, 2019[1]; Hydrogen council, 2020[9]; IRENA, 2020[4]; Hydrogen Council and McKinsey & Company, 2021[3]). Some of these papers also provide policy recommendations to develop and deploy hydrogen technologies (IRENA, 2020[10]; Griffiths et al., 2021[11]; McWilliams and Zachmann, 2021[12]; IEA, 2021[13]; Anderson et al., 2021[14]; OECD, 2021[15]).

After summarising this literature in sections 2. and 3. , this paper complements the existing evidence with a landscape of hydrogen patents and trademarks filings and a review of National Hydrogen Strategies and policy measures in 11 countries. Based on this new evidence, it puts forward five policy priorities:

- Ensure greater support to R&D in green hydrogen (particularly for production processes at low technology readiness levels) and demonstration projects
- Ensure a sufficient supply of renewable energy where possible, and encourage the creation of an international hydrogen market
- Use carbon pricing and carbon price trajectories to provide investors with the right incentives
- Reduce uncertainties for investors through regulatory action and standardisation
- Consider blue hydrogen as an interim solution to facilitate the transition to green hydrogen.

The outline of the paper is as follows. Section 2. starts by explaining the role that hydrogen can play to achieve carbon neutrality based on a review of recent studies. Section 3. describes the technological and economic feasibility of green hydrogen to fulfil this role, and identifies avenues to reduce its production costs. Section 4. presents an overview of the global green hydrogen innovation and diffusion landscape based on patent and trademark data. Section 5. provides a detailed analysis of countries' hydrogen policies and targets, as outlined in the different National Hydrogen Strategies. Section 6. concludes with policy recommendations.

2. The role of hydrogen to achieve carbon neutrality

Hydrogen is a promising technology with great potential to decarbonise the economy, especially in industry, transportation, buildings, and electricity generation. There are four main ways through which hydrogen can contribute to carbon emissions reductions.

First, hydrogen can reduce emissions by replacing fossil fuels as an energy carrier in energy-intensive production processes, such as high-temperature heating. In fact, hydrogen is the only technology known so far that can decarbonise some hard-to-abate processes in heavy industry (e.g. iron and steel production, cement, chemical sector), needed to achieve very low emission levels.

Second, hydrogen can also replace fossil fuels in the transportation sector. Fuel-cell vehicles may be more efficient than batteries to decarbonise heavy transport.

Third, hydrogen is already being used as an input into industrial processes in several sectors including refining (to purify oil by removing sulphur), iron and steel (to remove oxygen from iron ore to produce iron), and chemicals (as a feedstock in ammonia and methanol production).

Fourth, hydrogen is often mentioned as a solution to store energy produced out of electricity, thereby saving renewable energy in peak hours that could otherwise be lost. Therefore, hydrogen can also help to deal with high levels of variability in renewable electricity production, by storing this energy into hydrogen, and thereby accelerating the large-scale deployment of renewable electricity. Nevertheless, several studies claim that the conversion factor of the power-to-hydrogen-to-power chain is low: 25% to 35% depending on the assumptions (Ademe, 2020[16]; France Stratégie, 2021[17]). A 25 % conversion factor means that one needs an input of 4GWh of electricity to retrieve 1GWh at the end of the cycle. Some argue that this option, if not well suited to provide short-term flexibility to the electricity system, could be useful for long-term seasonal storage (McWilliams and Zachmann, 2021[12]).

However, large differences exist in the amount of CO_2 emitted between different ways of producing hydrogen. Virtually all of the existing industrial uses of hydrogen today are supplied using fossil fuels (IEA, 2019[1])[1] which is known as “black” (using coal), “brown” (using lignite) or “grey” (using natural gas) hydrogen. The two main existing alternatives are “blue” hydrogen (low-carbon) and “green” hydrogen (zero carbon). Blue hydrogen is still produced from natural gas but a significant part of the associated carbon emissions are removed via Carbon Capture and Storage (CCS), while green hydrogen uses electricity produced from renewable energy sources to break down water into hydrogen and oxygen through the process of electrolysis, and thereby does not emit CO_2 (IEA, 2020[18]).

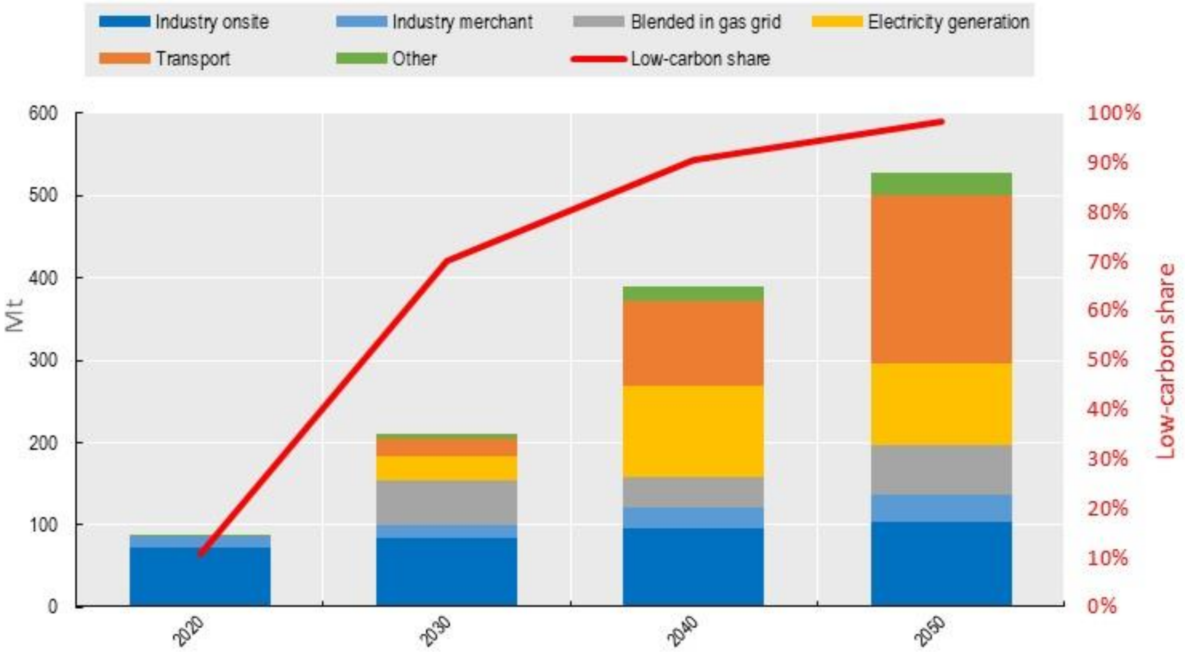
To reduce carbon emissions, it is important that the production of hydrogen becomes low-carbon and ideally zero-carbon. This can take place thanks to the deployment of blue or, ideally, green hydrogen, but other low-carbon or fully decarbonised hydrogen production processes exist. For example, electrolysis can be powered by nuclear energy, which is sometimes referred to as purple hydrogen. The production of hydrogen from biomass coupled with CCUS has the interesting potential of leading to net negative emissions, which could be helpful to compensate residual emissions in hard-to-abate sectors in a net zero emissions scenario. [2]

While a possibility to transition away from fossil fuel-based (grey) hydrogen is to (at least transitorily) associate it with carbon capture and storage (CCS) technologies (referred to as blue hydrogen production), there are uncertainties surrounding the potential greenhouse gas emission reductions that blue hydrogen can achieve. Emissions savings with current CCS technologies are estimated at 60-85% relative to natural gas (Committee on Climate Change, 2018[19]) and, in some countries, fugitive methane emissions associated with the mining, transport, storage, and use of the natural gas needed to produce the hydrogen and power carbon capture could increase the greenhouse gas footprint of blue hydrogen (Howarth and Jacobson, 2021[20]). Therefore, this study focuses on green hydrogen as the only scalable solution compatible with carbon neutrality in the long-run, although blue hydrogen can be considered in the short-run and is discussed in subsection 6.5.

Hydrogen is widely recognised as a key technology to achieve carbon neutrality in 2050. Figure 2.1 shows the role of hydrogen in the IEA's Net Zero Emission Scenario (IEA, 2021[2]). Global hydrogen use needs to increase spectacularly from 90 Mt in 2021 to more than 200 Mt in 2030 and more than 500 Mt in 2050. The proportion of this hydrogen being low-carbon (green or blue hydrogen) needs to increase from 10% in 2020 to 70% in 2030 and to more than 90% in 2050. In 2030, about half of this low-carbon hydrogen should come from electrolysis and the other half from coal or natural gas with CCS. The largest increases in use of hydrogen are expected to take place in the transportation and electricity generation sectors, while hydrogen is now almost exclusively used on-site in the chemical, iron and steel and refinery sectors.

While Figure 2.1 shows that global hydrogen use needs to increase rapidly, this required increase is slightly smaller for industry for which we already observe a large hydrogen use. What is needed in industry, however, is to replace the currently used fossil fuel-based hydrogen by green or blue hydrogen. Another peculiarity of the industrial sector compared with other hydrogen applications is that, for the most part, hydrogen will be produced on site, rather than being produced in larger quantities centrally and then distributed. This feature has important policy implications for the hydrogen revolution, in particular as regards the required hydrogen infrastructure.

Figure 2.1. Global hydrogen and hydrogen-based fuel use in the IEA Net Zero Emission Scenario

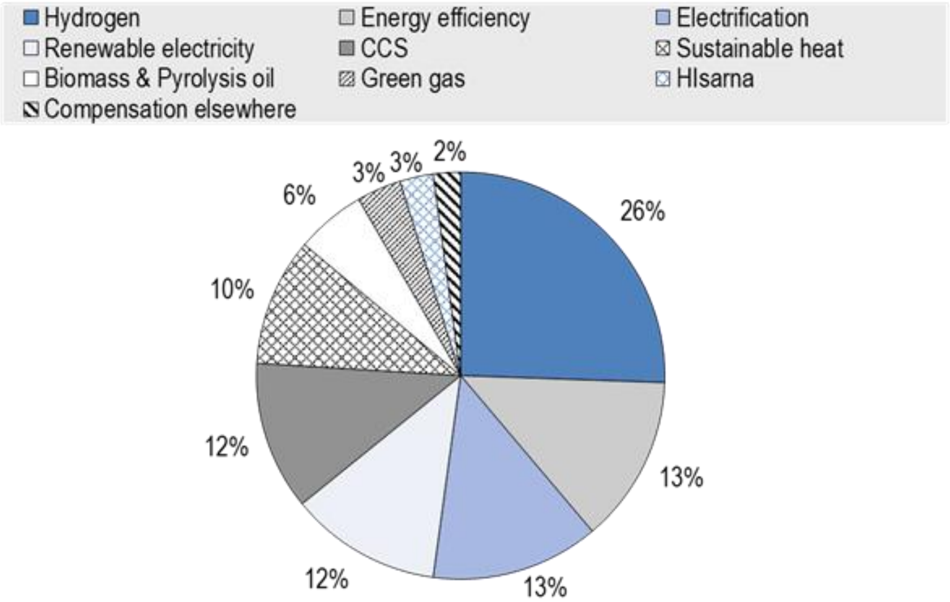


Note: Includes hydrogen, but also ammonia and synthetic fuels produced out of hydrogen.
Source: (IEA, 2021[2])

The major role that hydrogen will play to achieve a net-zero economy is confirmed by other scenarios. For example, the zero-emissions scenario for 2050 by the Energy Transitions Commission (2020[21]) expects hydrogen to account for 15-20% of final energy demand in 2050. In this scenario, hydrogen production needs to reach 500-800 Mt in 2050 (slightly more than in the IEA scenario), of which most will be produced from electrolysis. With 40 EJ in 2050, hydrogen would become the most important final direct source of energy after electricity (264 EJ), particularly for heavy industry.

The role of hydrogen may be even greater in particular countries or regions specialised in heavy industry. For example, Figure 2.2 presents a scenario on the role of different technologies in emission reductions in four key manufacturing sectors of the Netherlands between 2015 and 2050 (Anderson et al., 2021[14]). It shows that hydrogen accounts for 25% of the emission reduction, which is much more than the other sources of emissions reductions, such as energy efficiency, electrification of heat processes and renewable electricity. In this scenario, hydrogen becomes the most important energy carrier after electricity for the Dutch manufacturing sector, with 119 PJ of energy in 2050. The role of hydrogen is particularly important in the chemical and refinery sectors.

Figure 2.2. Role of different technologies in emission reductions in the Netherlands between 2015 and 2050



Note: 4 manufacturing sectors: chemical sector, metallurgy, refineries and food-processing. The contribution of "Renewable electricity" corresponds to the abatement of the 2015 scope 2 emissions, which would be overturned by completely shifting to renewable electricity sources by 2050. The contribution of "Electrification" corresponds to additional electricity needed to reach the carbon neutrality objective in 2050, assuming that this additional electricity is also renewable and carbon-neutral. HIsarna is a a direct reduced iron process for steelmaking.
Source: Anderson et al. (2021[14]), based on Berenschot (2020[22]).

Finally, hydrogen itself (because it is inflammable and explosive, although less than gasoline), and CCS in the case of blue hydrogen, may come with safety risks. It is unclear how the public opinion will weight these risks when hydrogen starts to play a more important role in the future. This possibility of opposition against hydrogen from citizens may put an additional risk on not reaching the full potential that the production and use of hydrogen may have, and thereby contributes to the other risks and uncertainty that may already put a brake on investments now.

3. Technological and economic feasibility for hydrogen to fulfil its role

This section first demonstrates that green hydrogen falls short of being competitive with fossil-fuel based alternatives, even in countries which significantly support the green transition. It then describes the expected cost trajectory of green hydrogen production, and the two main avenues to reduce costs: cheaper electrolysers, and cheap and abundant renewable electricity.

3.1. The current high costs of green hydrogen: The example of ammonia production

A recent OECD report on the decarbonisation of the Dutch industry contains a case study on green hydrogen's annual expected cash flows in ammonia production (Anderson et al., 2021[14]). Table 3.1 gives an overview of the case study characteristics and shows that the capital investments for a 100 MW electrolyser are about EUR 50-75 million and the operational costs currently represent EUR 1.5 million per year.

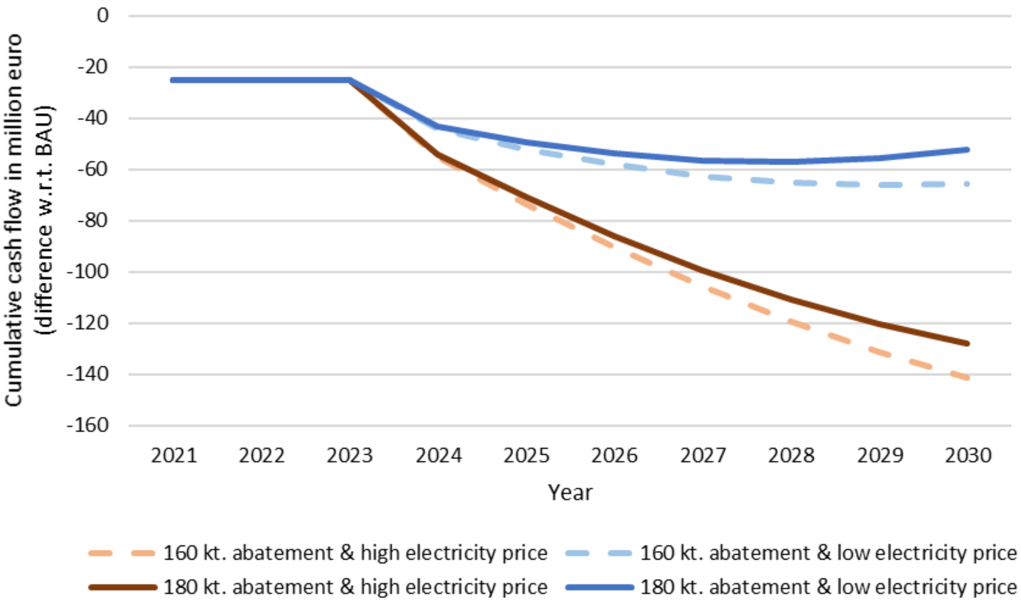
Table 3.1. Characteristics of a typical green hydrogen project for ammonia production

Case Study Characteristics	Quantity
Total annual production ammonia at Yara	1820 kt
Ammonia production of 100 MW electrolyser	100 kt
Emission abatement 100 MW electrolyser	160 - 180 kt CO_2
CAPEX 100 MW electrolyser	50 - 75 EUR mln
OPEX 100 MW electrolyser	1.5 EUR mln/a
Development study	25-30 EUR mln
Lifetime 100 MW electrolyser	80.000 h (~ 10 year)
Electricity consumption 100 MW electrolyser	0.8 TWh/y
Natural gas savings 100 MW electrolyser	0.52 TWh/y
SMR OPEX savings	3 EUR mln/y

Source: OECD (2021[15]).

Figure 3.1 shows the green hydrogen electrolyser cumulative cash flows for different scenarios presented in the case study. The scenarios differ in the level of abatement (160 kt or 180 kt) and in expected electricity prices. None of the four scenarios leads to positive returns for investors, regardless of the level of abatement or the energy prices considered. Compared to the business-as-usual (BAU) scenario in which ammonia is produced out of natural gas, cumulative losses after ten years are between EUR 52 and 141 million. The figure shows that the cumulative loss is about twice as large if electricity prices are high compared to the low electricity price scenario. Higher levels of abatement lead to slightly lower losses (thanks to savings from the existing carbon tax in the Netherlands), but do not make a large difference.

Figure 3.1. Green hydrogen electrolyser cumulated cash flows for different scenarios



Note: The development cost is incurred in 2021 and the CAPEX in 2024.
Source: OECD (2021[15]).

In the most favourable scenario (low electricity prices and 180kt abatement), the annual cash flows of the project become competitive in terms of annual OPEX with the BAU after eight years, but the additional benefits are not enough to make up for the additional OPEX costs in the first 8 years, not even considering the initial investment costs. In the case of a high-energy price scenario, the annual cash flows remain negative until the end of the lifecycle. Without public subsidies, the green hydrogen project is thus not economically viable.

In addition, despite generous support programmes for the decarbonisation of the industry and a newly introduced carbon levy, current policies in the Netherlands are insufficient to make the hydrogen project financially attractive, even in the rather favourable case in which all eligible subsidies would be awarded (Anderson et al., 2021[14]). At the end of the period, the CO_2 tax savings will make the electrolyser competitive with the business as usual (BAU) technology, but this is not enough to recoup the investment within this ten-year period.

Low electricity prices, abundant supply of renewable electricity and increased energy efficiency of electrolysers are drivers for the future business case, but green hydrogen projects are currently unlikely to be developed, even in the Netherlands where support is already relatively generous.

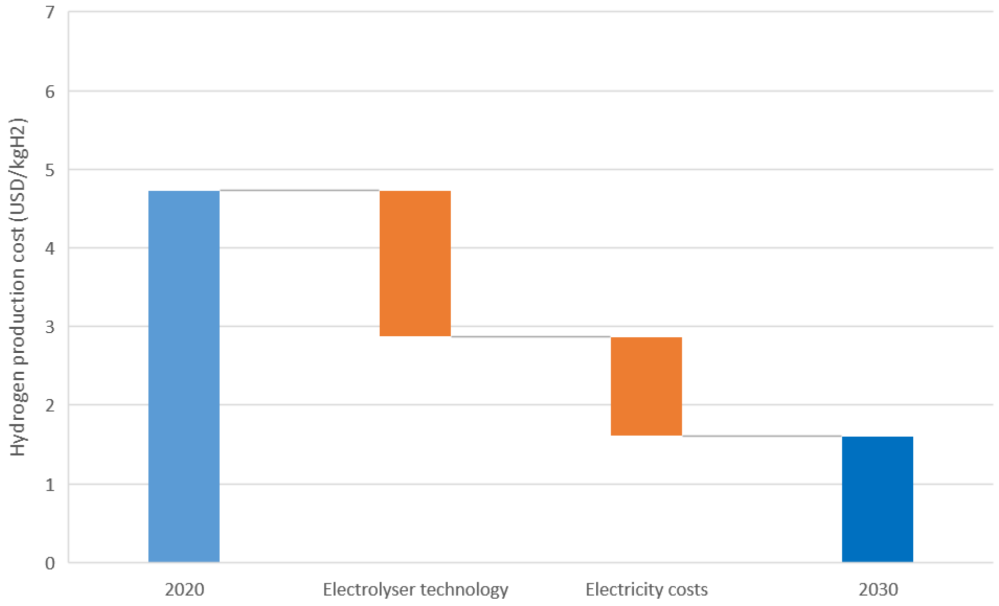
3.2. How to bring down the costs of green hydrogen production?

The cost of green hydrogen production through electrolysis has already fallen by 60 percent over the past decade as electricity prices have dropped and electrolysis CAPEX has fallen (Hydrogen council, 2020[9]), resulting in a green hydrogen cost of USD 4-6 per kg.

Figure 3.2 shows that green hydrogen production costs can be further reduced by up to 70% at the 2030 horizon through a combination of cheaper electricity and reductions in electrolysers costs, including both investment costs and operational costs through increased efficiency and increased operating hours of electrolysers (IRENA, 2020[4]; Hydrogen Council and McKinsey & Company, 2021[3]; Hydrogen council, 2020[9]). Such a reduction would put the cost of green hydrogen production at USD 1.6 per kg in the most favourable regions (USD 2.3/kg in the average region), making it competitive with fossil fuel-based hydrogen. About 40 percent of these cost reductions would be realised through lower electricity costs, with the other 60 percent coming from cost reductions of electrolysers. The competitiveness of hydrogen-based solutions will also depend on the cost of fossil fuels, which will be affected by global demand and supply factors, but also by public policies, including carbon prices.

This dramatic decrease in hydrogen production costs should not be taken as granted, but considered as uncertain (BEIS, 2021[23]) and, in addition to technological uncertainties, would only result from investments and public policies. For instance, Glenk, Meier and Reichelstein (2021[24]) estimate that the learning rate for green hydrogen is 10%, which means that the production cost decreases by 10% when the global production volume doubles. This learning rate would be consistent with a 60% cost decrease over the next decade (Hydrogen council, 2020[9]). Glenk, Meier and Reichelstein (2021[24]) find higher learning rates for technologies such as solar PVs, onshore wind turbines and lithium-ion batteries.

Figure 3.2. Expected future cost reductions for green hydrogen



Note: This figure is based on the (unweighted) average of (1) the average region scenario in McKinsey and Company (2021[3]); (2) the optimal region scenario in McKinsey and Company (2021[3]); (3) the scenario on cost reductions in IRENA (2020[4]). The IRENA (2020[4]) scenario does not necessarily refers to 2030, but to the future which may go beyond 2030, leading to our average estimated cost for 2030 being closer to the optimal scenario in the McKinsey report. Cost reductions related to the electrolyser technology includes up to 80% cost reduction for the electrolyser itself, improvements in electrolyser efficiency, an increase in the number of load hours, a longer lifetime of electrolysers, a lower weighted average cost of capital (WACC) and lower operational and maintenance costs more generally. The estimated cost reduction for the electrolyser technology in the McKinsey report includes a learning rate on CAPEX and the impact of larger electrolyser size (from 2 MW to 80 MW). The IRENA's (2020[4]) scenario '2020' captures best and average conditions. 'Average' signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value – LHV), an electricity price of USD 53/MWh, 3 200 full load hours per year (onshore wind), and a weighted average cost of capital (WACC) of 10% (relatively high risk). 'Best' signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, 4 200 full load hours per year (onshore wind), and a WACC of 6% (similar to renewable electricity today).
Source: McKinsey and Company (2021[3]) and IRENA's (2020[4])

3.2.1. Reducing the cost of electrolysers

Around 60% of the cost decrease are related to electrolysers, whose operating price could go down by up to 80%, through improvements in efficiency, an increase in the number of load hours, a longer lifetime, a lower weighted average cost of capital (WACC) and lower operational and maintenance costs more generally. A significant part of this decline will result from R&D, economies of scale and learning-by-doing. This subsection describes the technical levers through which these gains are expected to occur, while Section 6. underlines policies to trigger these developments.

Many of these electrolyser cost reductions could be brought about by **research and development activities**, notably on stacks[3]. To reduce the cost of stacks, research is needed to improve available technologies and make progress on emerging technologies. IRENA (2020[4]) highlights several areas to reduce stack costs by improving their design for a greater efficiency, a higher durability or an increased density. Technical challenges depend on the specific technology, which now are at different Technology Readiness levels (TRL): Polymer Electrolyte Membrane (PEM) and Alkaline electrolysers are at TRL 9 (actual system proven in operational environment), whereas Anion Exchange Membranes (AEM) are still at TRL 4 (technology validated in lab) (IEA, 2021[13]). In addition, IRENA (2020[4]) underlines the importance to prevent critical materials from becoming a barrier to scaling up, e.g. by transitioning to platinum- and cobalt-free designs in case of alkaline and platinum- and iridium-free designs in the case of PEM electrolysers.

Plant-level economies of scale are another avenue to reduce the investment costs (IRENA, 2020[4]). Increased module size from 1 MW to 20 MW can reduce costs by more than a third. Increasing the facility size saves on the balance of plant (BoP), which is the part of the electrolyser consisting of power supply, water supply, purification, compression, electricity and hydrogen buffers and hydrogen processing. Other cost reductions from scaling up are cheaper procurement of materials, efficiency and flexibility in operations and optimisation of different industrial applications.

Finally, further cost reductions are expected through **learning-by-doing and scaling up at the global level**. The cost of green hydrogen highly depends on its installed capacity, and large cost reductions (about 40%) are expected with a 5 TW installed capacity by 2050 compared to a 1 TW installed capacity scenario (IRENA, 2020[4]). The largest economies of scale will be reached when new added capacity reach 1 GW per year, meaning that cost reductions are expected to be largest during the early phase of demonstration which is starting now. Most economies of scale in the short-term are expected for the stack component of the electrolyser, in particular in the porous transport layer, the bipolar plates, the assembly and end plates, the catalyst coated membrane, the frame and the balance of stack, with cost penalties of over 100% for low production volumes (IRENA, 2020[4]; Mayyas et al., 2019[25]).

The Hydrogen council, representing companies active in the field of hydrogen with over USD 6.6 trillion in total market capitalisation, states that an investment of 65 GW of electrolysis is needed to make green hydrogen competitive with grey hydrogen. This scaling-up is expected to lead to a rapid industrialisation of the electrolysis value chain, and would make green hydrogen competitive in a number of end-use applications in 2030 (Hydrogen Council and McKinsey & Company, 2021[3]). In the manufacturing sector, using green hydrogen for ammonia is expected to become already competitive with grey ammonia by 2030 for a carbon price of USD 50 per tonne of CO_2. Green hydrogen used as a reductant for the production of steel from scrap metal in an electric arc furnace can become competitive by 2030 with a carbon price of USD 45 per tonne of CO_2. However, this scaling-up requires to overcome a funding gap of around USD 50 billion (Hydrogen Council and McKinsey & Company, 2021[3]).

3.2.2. Green hydrogen deployment rests on large amounts of low-cost renewable electricity

40% of the decrease in production costs comes from cheaper renewable electricity, assuming that the cost of renewable electricity goes down from 53 to 20 USD/MWh, amidst booming demand.

Vast amounts of renewable electricity are required to produce the large quantities of green hydrogen needed to reach net-zero by 2050. The Net-Zero scenario from the IEA predicts the need of 322 million tonnes of green hydrogen in 2050, requiring a global electrolyser capacity of 3 585 GW, which corresponds to about 20% of the world's electricity supply in 2050 (IEA, 2021[2]). This is more than the total global renewable energy generation capacity available today, which was only 2 799 GW at the end of 2020 (IRENA, 2021[26]). 200 million tonnes of blue hydrogen are required in the net-zero scenario of the IEA, meaning that even more renewable electricity supply would be needed if this blue hydrogen was to be replaced by green hydrogen.

Load hours are another important factor, which needs to be optimised. A combination of wind and solar PV can provide the desired load hours of more than 3 000 hours per year. In particular, offshore wind can be used at places with a lower solar power potential.

Beyond the availability of large quantities of renewable electricity, its cost will be of paramount importance to make green hydrogen competitive, as the price of renewable electricity significantly affects the production costs of green hydrogen. For example, Hydrogen Council and McKinsey & Company (2021[3]) shows that the cost of green hydrogen production is expected to become about 40% lower in regions with cheap renewable electricity compared to an average region (respectively USD 1.4/kg and USD 2.3/kg). This difference can determine whether or not green hydrogen is competitive with grey hydrogen produced from natural gas.

As a consequence, it may **be more cost-effective to produce hydrogen where renewable electricity costs are low and then transport it** to places where it is consumed through a hydrogen pipeline network (Hydrogen Council and McKinsey & Company, 2021[3]).

A key challenge to transport hydrogen is its low energy density, which makes transport and storage very costly today. Transportation and storage costs are higher for hydrogen than for fossil fuels, and can be up to three times larger than production costs (IEA, 2019[1]). These costs are the consequence of energy requirements for the compression, liquefaction or conversion of hydrogen and of the physical properties of hydrogen (leakage due to the small molecule size and metal embrittlement) (Griffiths et al., 2021[11]).

Hydrogen can be transported at a lower cost via dedicated pipelines (similar to natural gas). Today, approximately 5,000 km of hydrogen pipelines exist (compared to the 3 million km of natural gas pipelines) (IEA, 2019[1]). Existing high pressure natural gas transmission lines could be used (if they are no longer needed for natural gas) with slight upgrades, but their suitability need to be assessed on a case-by-case basis. Also, hydrogen can be blended with natural gas and can then be used by conventional end users of natural gas to generate power and heat. A certain amount of hydrogen can be blended into existing natural gas pipelines (around 2% to 10% in Europe), which is currently the cheapest option for transport over distances of less than 1,500 km (IEA, 2019[1]), but this technology is not mature yet, with a TRL of 6 according to IEA (2021[13]).

Compared to renewable electricity, hydrogen pipelines can transmit ten times the energy at one-eighth the cost, making it more cost-effective to transport hydrogen directly. For instance, the cost of transporting hydrogen through a pipeline from North Africa to central Germany is projected to cost about USD 0.5 per kg of hydrogen (Hydrogen Council and McKinsey & Company, 2021[3]). This is less than the production cost difference between an optimal and an average region (around USD 0.9 per kg of hydrogen in 2030) (Hydrogen Council and McKinsey & Company, 2021[3])).

For long distance transport (more than 1,500 km), the most cost effective option could be to store the hydrogen in other larger molecules – either ammonia or liquid organic hydrogen carrier (LOHC) (IEA, 2019[1]). However, such molecules cannot be consumed as final products so the hydrogen will need to be liberated as a final step before consumption. There are experiments with marine tankers, which are either in early adoption or large prototype, respectively (IEA, 2020[18]). The other option is to transport ammonia through pipelines, which could be cheaper than pipelines for pure hydrogen.

Another option is the liquefaction of hydrogen. Liquefying is possible, but the process is expensive and consumes about 25% of the hydrogen as compared to gas, which only consumes 10% (IEA, 2019[1]). This option is considered for the local distribution of hydrogen (tube or cryogenic trailer trucks) or for long distance transport (liquefied hydrogen tankers) (Griffiths et al., 2021[11]).

Hydrogen storage is also challenging. Whereas some technologies are already mature (storage in stationary tanks or salt caverns), others are still under development (metal hydrides and storage in depleted oil and gas fields or in aquifers) (IEA, 2021[13]). While the existing technologies mainly focus on short-term storage, storage in depleted oil and gas fields or aquifers could bring new perspective for seasonal storage (Griffiths et al., 2021[11]), which would be needed for hydrogen to play a role in smoothing renewable electricity production cycles.

4. Global hydrogen innovation

As shown in section 3, **innovation is needed to reduce the costs of green hydrogen**. This section uses patent and trademark data to provide insights into the global hydrogen innovation landscape.

The use of patent data as a measure of innovative activity is widespread, particularly in the field of climate change mitigation technologies for which the European Patent Office has developed a dedicated classification scheme (referred to as the Y02 tagging scheme) to identify relevant inventions in global patent databases such as PATSTAT. Although patents do not provide a measure of all innovation, they give a wealth of information on both the nature of the invention and the applicant – including the location of innovation activity – allowing for cross-country comparisons. More importantly, patent data can be disaggregated into highly specific technological areas, including hydrogen-related inventions.

The data used for this section comes from the PATSTAT database, maintained by the European Patent Office. PATSTAT is unique in that it covers more than eighty patent offices worldwide and contains over a hundred million patent documents. It is updated biannually. Patent applications related to hydrogen technologies were identified using Co-operative Patent Classification (CPC) codes (Box 1). PATSTAT includes the country of residence of the inventors of those technologies for which patent protection is sought (independent of the country in which the applications are actually filed). This information is used to measure a country's innovation performance.

A well-known limitation of patent data is that the value of individual patents is heterogeneous, making cross-country comparisons of innovative activity based on simple patent counts problematic. In this analysis, international patent filings through the Patent Co-operation Treaty (PCT) are used as the main measure of innovation. It has been shown that only patents of a certain value are transferred internationally. Thus, the quality of PCT patents is assumed to be above a threshold that makes cross-country comparisons more robust. In addition, other measures of patent quality, such as patent citations, are only available with a considerable lag. PCT patenting activity can be observed until 2019.

Another advantage of using PCT patent applications is that each PCT patent application represents a single international patent family (a set of individual patent applications to various jurisdictions). Once filed through the PCT, a patent application is typically transferred to multiple jurisdictions, leading to multiple individual patents in each patent office of destination. Therefore, PCT applications avoid double-counting patent applications filed across jurisdictions and each of them represents a single invention.

While patent data focus are informative about the production of new innovation, they do not indicate whether the technology protected by the patent is actually being used by the owner. For this reason, data on trademark filings is used to complement patent data by focusing on the commercialisation phase of innovations.

A trademark is "any sign that individualises the goods of a given enterprise and distinguishes them from the goods of its competitors" (WIPO, 2004). Trademarks therefore fulfil two fundamental functions: they indicate the origin of the market offerings by linking them to the firm responsible for bringing them to market, and they flag to consumers that those offerings are different from competing offerings in the same marketplace. Importantly, trademarks include a "use in market" requirement. This requirement implies that trademark filers cannot simply claim potential use but have to prove actual use, and non-use typically results in cancellation (Graham et al., 2013). Therefore, while a successful patent application means that a firm has developed a new product or a new production method, a trademark registration indicates that a firm has introduced a new product or service on the market. For this reason, trademarks have also been used as an indicator of innovation in the services sector.

Data on trademark applications used in this report relate to trademarks registered at the European Union Intellectual Property Office (EUIPO), the Japan Patent Office (JPO) and the United States Patent and Trademark Office (USPTO). Trademarks are filed in accordance with the International Classification of Goods and Services, also known as the Nice Classification[4]. However, the Nice Classification is not as detailed as patent classification schemes. To identify goods and services related to hydrogen production and distribution, trademark descriptions were searched for the presence of hydrogen-related keywords (see Box 1).

Box 1. Identifying hydrogen patents and trademarks

Patents related to hydrogen technologies were identified using the following CPC classification codes available in PATSTAT:

Y02E60/32: Hydrogen storage

Y02E60/34 : Hydrogen distribution

Y02E60/36: Hydrogen production from non-carbon containing sources, e.g. by water electrolysis

Y02E60/50 : Fuel cells

Y02P 90/40 : Fuel cell technologies in production processes

Y02P 90/45: Hydrogen technologies in production processes

Trademarks related to hydrogen were identified by searching for the following keywords in the trademark's description:

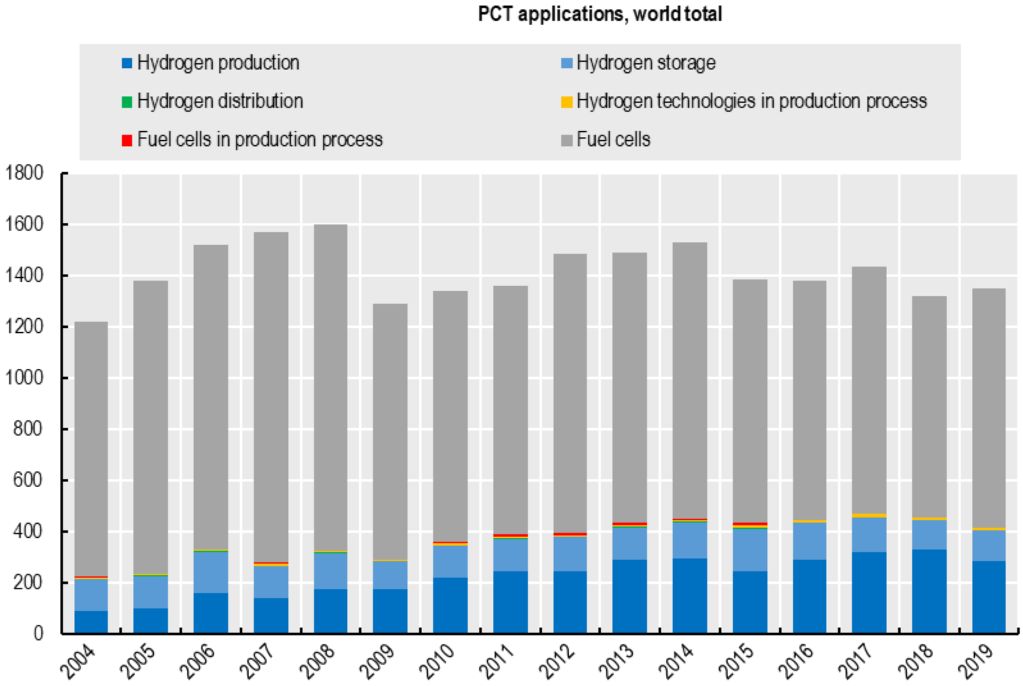
fuel cell, fuel cell technology production, green hydrogen, hydrogen battery, hydrogen distribution, hydrogen fuel, hydrogen gas, hydrogen generation, hydrogen generator, hydrogen powered, hydrogen production water splitting, hydrogen purifier, hydrogen storage, hydrogen technology production, hydrogen technology transportation, hydrogen technology transportation fuel, photocatalytic water splitting, solar hydrogen, water splitting.

Figure 4.1 shows the annual number of patents filed in hydrogen technologies between 2004 and 2019 through the PCT. **While hydrogen ambitions have increased for several years, this has not yet translated into an increase in the number of hydrogen patents filed globally.** In fact, the number of yearly hydrogen patents (including fuel cells) has been lower every year since 2009 than it was at the peak of 2008.

However, the pace of innovation is heterogeneous across technologies. In particular, patents related to hydrogen production have risen sharply from just 88 patents in 2004 to 328 in 2018 (283 in 2019), while the number of patents for fuel cells has decreased (1292 patents in 2007, 932 in 2019). A plausible reason for this decline is that a consensus is emerging that battery-powered electric vehicles will outperform hydrogen cars for light passenger vehicles, at least in the short to medium run, reducing the attractiveness of fuel cell innovation.

Innovations in hydrogen production technologies may lower hydrogen production costs, which are important for increasing the competitiveness of green hydrogen as a feedstock and for energy storage. The lack of growth in patenting activity on hydrogen technologies which appears from Figure 4.1 (and the slowly-growing pace in hydrogen production and storage technologies) suggests that the pace of innovation activity is not aligned with new hydrogen ambitions to achieve net-zero. It will be interesting to observe whether the increased investments and commitments in green hydrogen of the past couple of years will lead to an increase in hydrogen innovations in the near future.

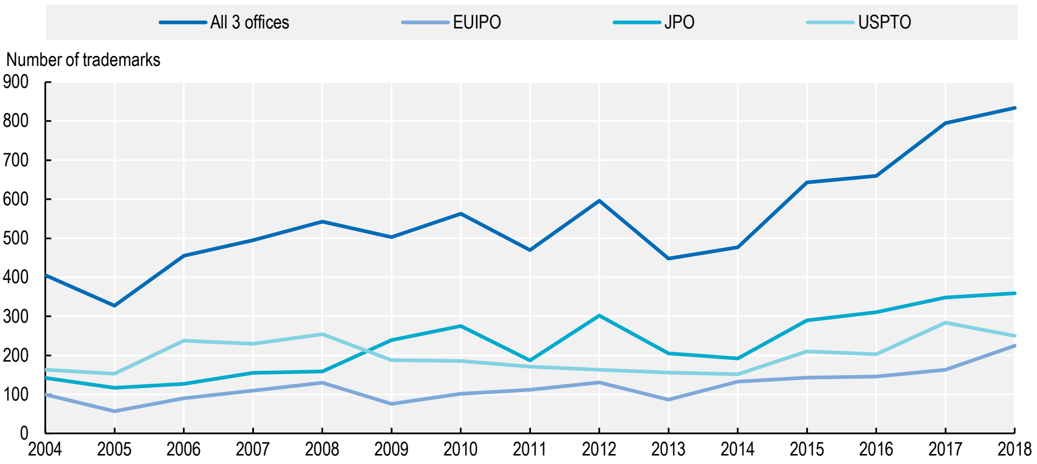
Figure 4.1. Number of annual patent filings in different hydrogen technologies, 2004-19



Note: PCT applications are international patent applications made through the Patent Cooperation Treaty and are considered 'high-value' inventions because of the higher costs associated with filing the same patent across several jurisdictions. Annual patent counts are based on the filing date.
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2021.

Figure 4.2 shows the annual number of hydrogen-related trademarks filed between 2004 and 2018 at the world's main intellectual property offices (the trademark data does not allow us to easily distinguish between different types of hydrogen-related goods and services). Over the fifteen years of the sample period, a doubling of the annual number of hydrogen trademarks has been observed, with a marked acceleration since 2014 (477 trademarks filed in 2014 against 834 in 2018). This suggests that owners of hydrogen technologies are putting increasing emphasis on the commercialisation of hydrogen. However, the hydrogen-related trademarks only represent 2.7% of all climate-related trademarks for the 2014-2018 period (Aristodemou et al., forthcoming). In comparison, 5.9% of all climate-related patents are related to hydrogen technologies. This is in line with the relatively low degree of maturity of hydrogen technologies, where companies' efforts are still mostly dedicated to R&D than to commercialisation.

Figure 4.2. Number of trademarks related to hydrogen, 2004-18



Note: See Box 1 for details on how hydrogen-related trademarks are identified.
Source: Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, October 2021.

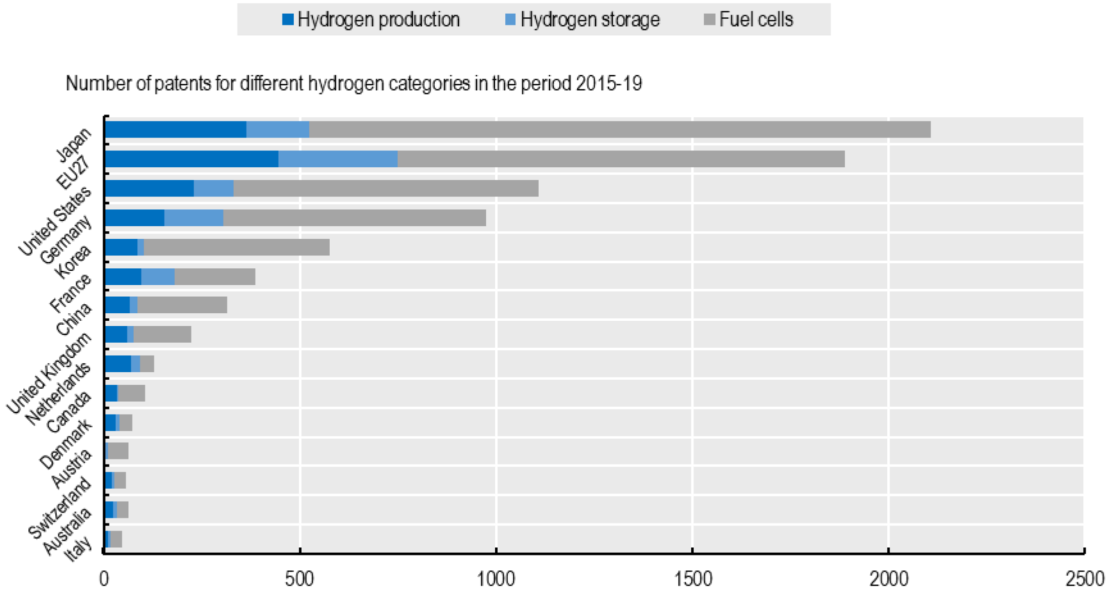
Figure 4.3 shows the ranking of countries with regard to hydrogen-related patents over the period 2015-19 for the three main hydrogen categories - hydrogen production, hydrogen storage and fuel cells. Japan is leading with more than 2 000 hydrogen-related patents, with a large majority of Japanese patents related to fuel cells, but Japan is also the country with the highest absolute number of patents for hydrogen production.

The United States is the second country in the ranking, but has only about half of the number of patents as Japan, with slightly more than 1 000 patents over the period 2015-19. The ratio between the different hydrogen categories is comparable to Japan, with fuel cells leading, then hydrogen production and finally hydrogen storage.

In the EU27, however, we find a stronger focus on hydrogen production and hydrogen storage compared to fuel cells. In particular, Germany stands out for its large number of patents for hydrogen storage, which is about the same as in Japan and greater than in the United States. In total, the EU27 has slightly less patents than Japan, reaching almost 2 000 over the period 2015-19.

Like Japan, Korea is specialised in fuel cells, while France, the United Kingdom and the Netherlands are relatively more specialised in hydrogen production technologies. With 300 hydrogen patents filed over 2015-19, Figure 4.3 suggests that the People's Republic of China (hereafter "China") is not (yet) a significant player in the area of hydrogen-related innovation. While Chinese inventors represent 15% of global PCT patents across all technologies, they are responsible for less than 4% of global hydrogen patents.

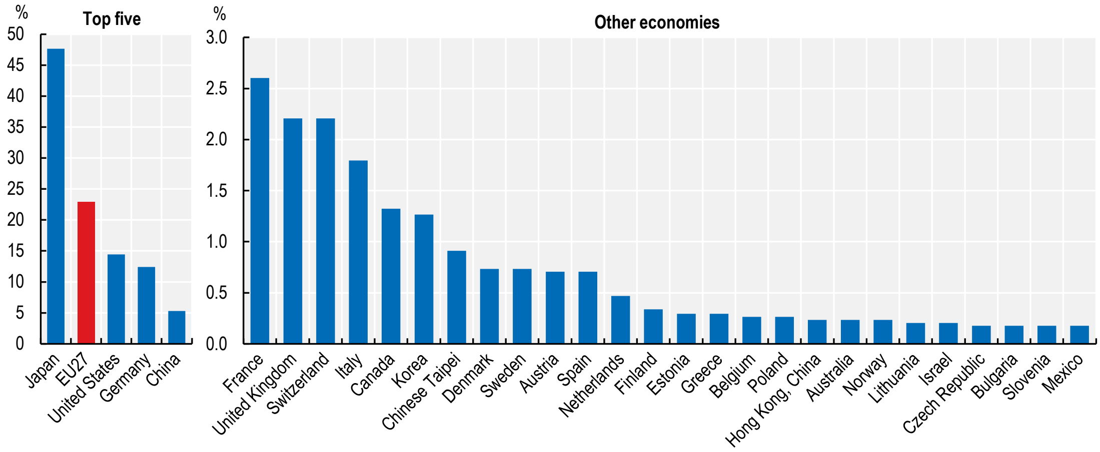
Figure 4.3. Top hydrogen innovation countries



Note: Data refer to patent applications filed under the Patent Cooperation Treaty (PCT) in green hydrogen technologies. Patent counts are based on the filing date and the inventor's country, using fractional counts. Only countries featuring more than 50 hydrogen technology patents over the period 2014-19 are included.
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2021.

Figure 4.4 shows the distribution of hydrogen-related trademarks by applicant country. The same set of countries can be observed for trademark as for patent owners, but the leadership of Japan is clearer on trademarks, with nearly half of all hydrogen trademarks being filed by Japanese companies. EU27 countries come a distant second, while China's ranking is higher (4th on trademarks, 6th on patents). Other differences appear, such as Switzerland, which is not among the top inventing countries, but fares well on trademarks.

Figure 4.4. Main owners of hydrogen trademark by country, 2014-2018



Note: Trademark counts are based on the filing date and the country of origin of the owner.
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, October 2021.

Absolute numbers of patents in hydrogen-related technologies can signal either the overall innovation performance and size of a country or its focus on hydrogen technologies. To disentangle these two explanations, Figure 4.5 shows the Relative Technology Advantage (RTA) in green hydrogen innovation. This index is obtained by dividing each country's share of hydrogen patents with the global share of hydrogen patents. The share of hydrogen patents is obtained as the number of PCT hydrogen patents divided by the total number of PCT patents filed by the same country or region. The blue bars denote the RTA index for the years 2015-19 and the white diamonds show the RTA's for 2004-08.

Denmark, Germany and Austria appear as the countries with the highest specialisation in hydrogen for the period 2015-19. Interestingly, none of these three countries were specialised in hydrogen innovation in the period 2004-08, with an RTA of less than one. A similar specialisation occurred for two other European countries, France and the United Kingdom. This suggests that European countries have recently specialised in hydrogen innovation. This coincides with the increased European hydrogen ambitions, but this correlation does not imply that public policies in Europe induced this specialisation. An alternative interpretation could be that the emergence of European technological leaders increased political attention to hydrogen on the continent.

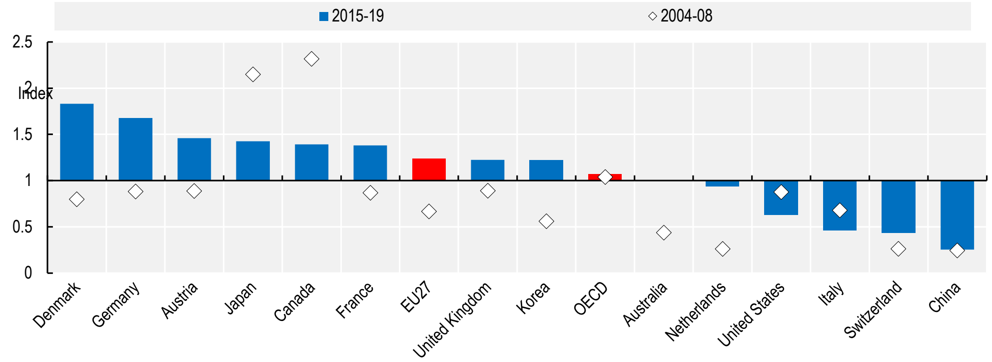
Japan's specialisation in hydrogen innovation is comparable to that of the leading countries in Europe. For Japan, however, we observed a much higher RTA of 2.2 in the earlier period 2004-08. This decline in Japan's specialisation over time is related to the decline in fuel cells patents shown in Figure 4.1, as Japan is most specialised in fuel cells.[5]

Canada also saw a decline in its specialisation toward hydrogen compared to 2004-08, but continues to be relatively specialised in this technology (Figure 4.3). Korea, on the other hand, was not specialised in hydrogen in 2004-08 (RTA of 0.6), but now has the largest absolute number of hydrogen patents after Japan, the United States and Germany, and has an RTA of 1.2. Two smaller economies are catching up on hydrogen innovation: Australia and the Netherlands.

For the United States, the share of hydrogen patents out of total patents is below average, with an RTA of 0.6 in 2015-19. However, in absolute terms, the United States still has the second largest number of hydrogen patents after Japan (Figure 4.3). Hence, the United States is not specialised in hydrogen, but as the country with the second largest number of hydrogen patents in the world, it remains an important player for hydrogen-related innovation.

The decline in specialisation for the United States could be due to a decline in public RD&D spending on hydrogen and fuel cells. In general, there also seems to be some correlation between countries' specialisation and the degree of ambition of domestic hydrogen policies. These issues are discussed in section 5. .

Figure 4.5. Relative technology advantage in hydrogen technologies, 2004-08 and 2015-19



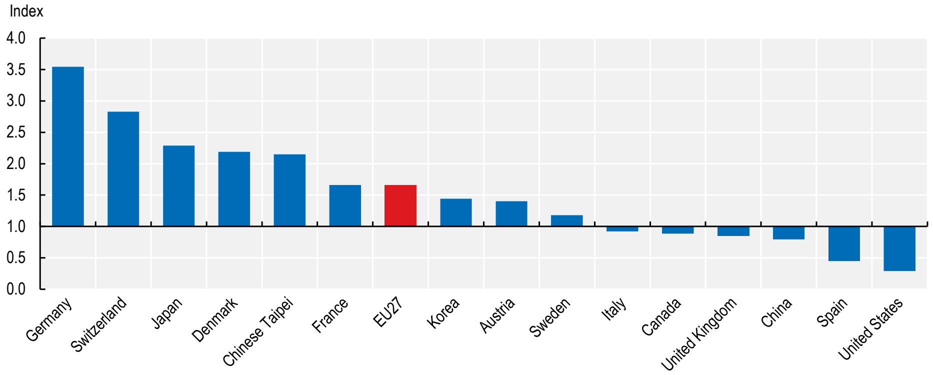
Note: Data refer to PCT patents in hydrogen technologies. Patent counts are based on the filing date and the inventor's location, using fractional counts. Only economies featuring more than 50 hydrogen technology patent families over the period 2014-19 are included.
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, June 2021.

Figure 4.6 presents a trademark specialisation index in hydrogen-related trademarks. This indicator is similar to the revealed technological advantage indicator for patents and is obtained by dividing each country's share of hydrogen trademarks with the global share of hydrogen trademarks. It indicates whether companies located in a particular country file a greater (index >1) or smaller (index <1) proportion of hydrogen-related trademarks than the world average.

Germany, Switzerland, Japan, Denmark and Chinese Taipei appear as the economies with the highest specialisation in hydrogen trademarks for the period 2014-18. Germany leads the ranking, with a proportion of hydrogen-related trademarks owned by German companies over three times greater than the world average.

Overall, there is a clear correlation between patent specialisation as shown in Figure 4.5 and trademark specialisation, but there is heterogeneity across countries. For example, companies based in Switzerland do not exhibit a strong innovation specialisation in hydrogen technologies but they strive in commercialisation of hydrogen, with a much higher than average rate of trademark filing. Symmetrically, companies based in Canada enjoy a much better position on innovation than on the commercialisation front.

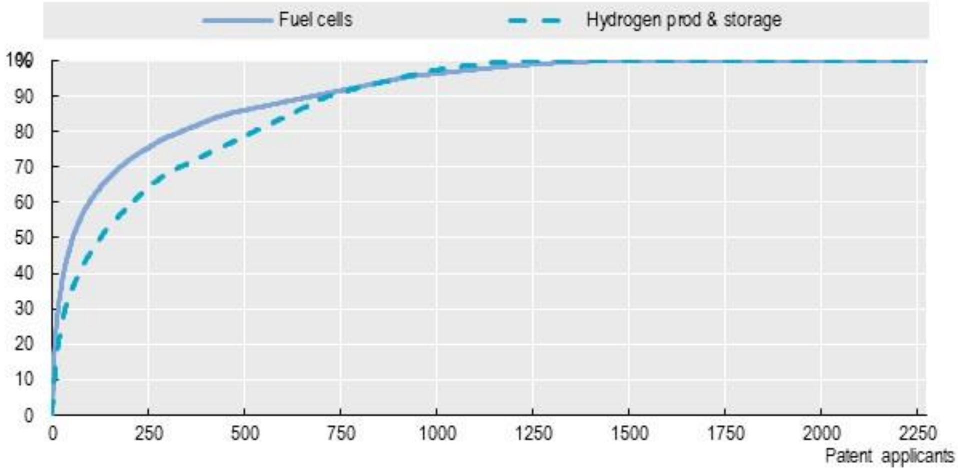
Figure 4.6. Trademarks specialisation toward hydrogen, 2014-18



Note: Only economies featuring more than 20 hydrogen trademarks over the period 2014-18 are included.
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, October 2021.

Figure 4.7 shows the cumulative share of patents owned by all hydrogen patent applicants for the period 2015-19. In total, over 2 250 applicants filed hydrogen-related patents over this period. Innovation in fuel cells is significantly more concentrated than innovation in hydrogen production and storage technologies, in line with the results presented below in Figure 4.9 showing that the share of patents coming from new firms is higher in the latter category. In fuel cells, 53 companies in the world are responsible for 50% of all patents filed, and 242 firms own 75% of all patents. In hydrogen production and storage, 88 firms own 50% of patents and 419 firms own 75% of them. Overall, innovation in hydrogen-related technologies appears more concentrated than innovation in "average" technology: a recent report shows that the world's top 2 000 R&D investors together owned 63% of global patents across all technological fields, whereas this share is 72% for hydrogen-related patents (OECD-JRC 2021).

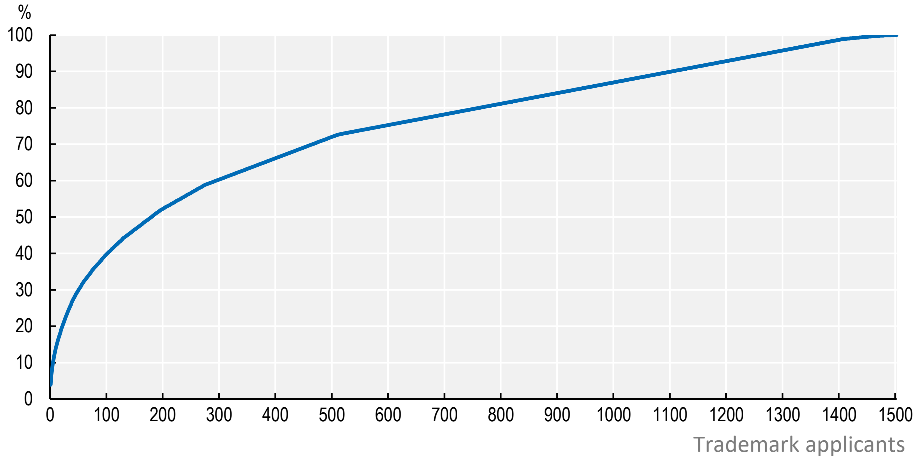
Figure 4.7. Concentration of patenting activity in hydrogen, 2015-2019



Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, October 2021.

Similarly to Figure 4.7, Figure 4.8 shows the concentration of hydrogen-related trademarks among applicants for the period 2014-18. Trademarking appears less concentrated than patenting, with half of the trademarks being filed by 179 firms. However, trademark concentration is much greater in hydrogen than on average, consistent with hydrogen being a relatively new and small sector: for example, the world's top 2 000 R&D investors jointly owned only 6% of all trademarks filed at EU IPO, JPO and USPTO but 28% of hydrogen-related trademarks (OECD-JRC 2021).

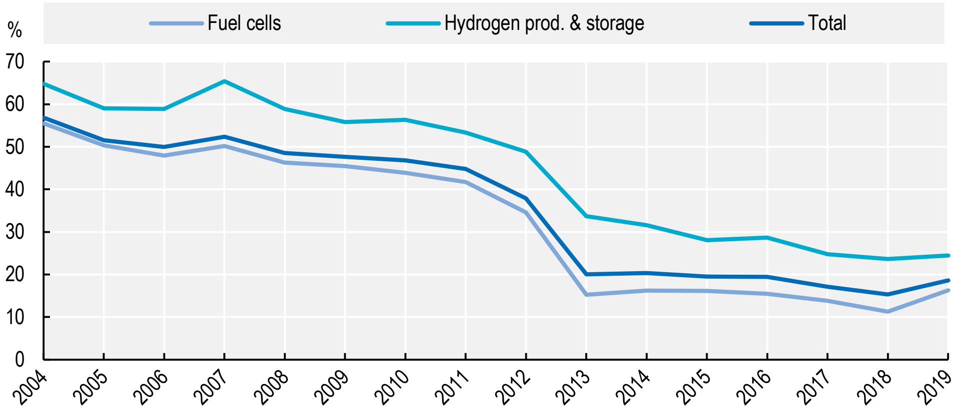
Figure 4.8. Concentration of hydrogen-related trademarks (2014-2018)



Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, October 2021.

Figure 4.9 shows the share of hydrogen patents filed by young firms between 2004 and 2019, distinguishing between fuel cells and hydrogen production and storage technologies (which together represent 99% of all hydrogen patents, as shown in Figure 4.1). Young firms are defined as companies with a date of incorporation no more than five years before the patent was filed. The share of patents produced by young firms was extremely high at the beginning of the period, as is the case for novel technological fields. However, this proportion has decreased markedly over time, from 57% across all hydrogen patents in 2004 to 19% in 2019. About one third of this decrease results from the switchover of young firms into the "old firm" category, while the rest comes from an increase in the patenting activity of 'old firms'. The share of young firms is greater in hydrogen production and distribution compared to fuel cells, possibly reflecting the relatively lower maturity of these technologies and differences in the structure of the two industries.

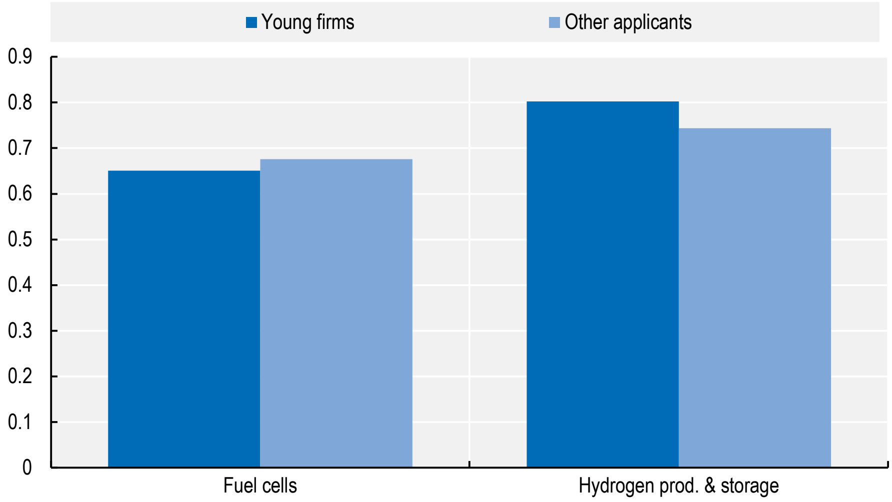
Figure 4.9. Share of young firms in hydrogen patents, 2004-19



Note: Young firms are identified as companies with a date of incorporation no more than five years before the patent was filed. When missing, the date of incorporation of the applicant was replaced with the earliest date of patent filing in the portfolio of a given applicant.
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, October 2021.

Figure 4.10 compares the average "originality" of hydrogen patents filed by young firms and by other applicants in the economy. The index of patent originality refers to the breadth of the technology fields on which a patent relies, with more original patents combining knowledge from a more diverse set of existing technological fields. Figure 4.10 shows that patents in hydrogen production and storage filed by young firms are more original than patents filed by other applicants (older firms) in the economy. The difference is highly statistically significant ($p<0.001$). This suggests that young firms, on average, produce more radically novel innovations than established firms, who might focus more on incremental innovation. There is evidence that young firms tend to be major drivers of radical innovation (Andrews, Criscuolo and Menon, 2014[27]; Calvino, Criscuolo and Menon, 2016[28]). Hence, while large firms are key in terms of ensuring high rates of hydrogen innovation, other applicants – in particular young and small firms – will be important to engage in potentially breakthrough inventions for the hydrogen revolution. This is however not true in fuel cells-related innovation, where the originality of patents produced by young and older firms is similar.

Figure 4.10. Average originality index of hydrogen patents, 2010-15



Note: Young firms are identified as companies with a date of incorporation no more than five years before the patent was filed. When missing, the date of incorporation of the applicant was replaced with the earliest date of patent filing in the portfolio of a given applicant.
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, October 2021.

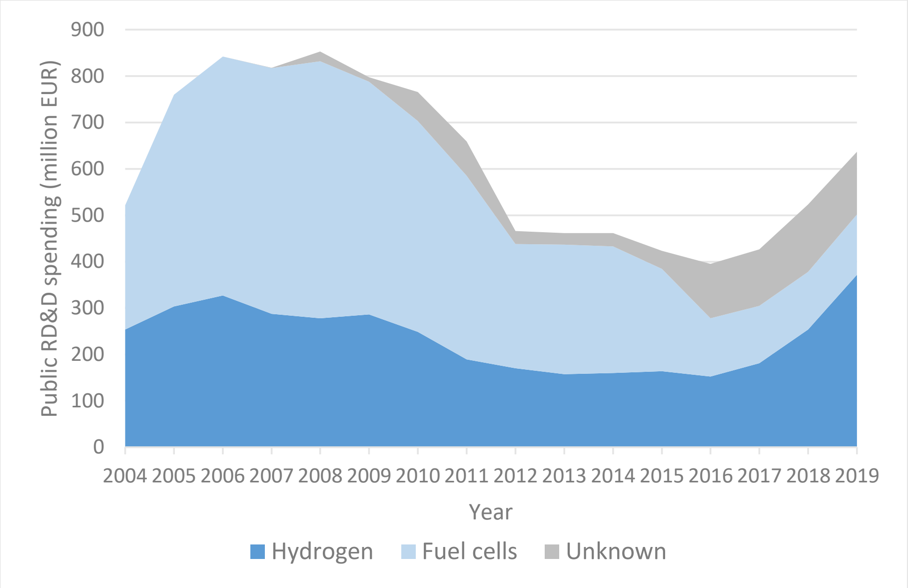
5. Comparison of hydrogen policy developments across main hydrogen economies

5.1. Public RD&D spending on hydrogen

Since large-scale producing of green hydrogen is not yet commercially viable, a top priority should be to increase the necessary research, development and demonstration (RD&D) expenditures. In particular, as shown in Section 3, innovation activity can substantially reduce the costs of electrolysis, potentially saving billions of euros in the deployment phase of green hydrogen that lies ahead.

Part of the necessary increase in R&D expenditures may be covered by public sources. Figure 5.1 shows the total public RD&D spending in OECD countries on hydrogen and fuel cells over the period 2004-2019. Following a peak in 2006-08 when total spending reached EUR 852 million, public spending on hydrogen and fuel cells R&D has decreased markedly until 2016 (EUR 395 million). Most of this decrease is driven by spending on fuel cells research. Public R&D spending has increased significantly since 2016, driven by hydrogen research, which has grown from EUR 152 million in 2016 to EUR 371 million in 2019. Public RD&D spending toward hydrogen and fuel cells represents 3.3% of total energy-related RD&D spending across OECD countries (down from 5.8% in 2008). In comparison, 6% of the cumulative emissions reductions over the period 2021-2050 in the IEA's Net-Zero Emissions scenario come from hydrogen deployment (IEA Global Hydrogen Review 2021). This suggests some misalignment between public R&D support and the potential contribution of hydrogen to the achievement of climate neutrality objectives, particularly in light of the lower maturity of hydrogen compared with other technologies such as renewable energy or CCS.

Figure 5.1. Public RD&D spending in OECD countries on hydrogen and fuel cells, 2004-2019



Note: the "unknown" category is mostly composed of public expenditures in the US, for which no breakdown is available since 2016 (EUR 106 million in 2019). In 2015, 70% of US public funding went to fuel cells and 30% to hydrogen.
Source: IEA Energy Technology RD&D Budget Database, 2021.

Table 5.1 shows the amounts of public spending on hydrogen RD&D for the main hydrogen economies in 2008 (the historical peak), 2016 (the lowest year on record) and 2019 (the latest available year). Important differences in the amount of spending exist between countries and periods. In 2019, public RD&D spending ranged from EUR 10 million euros in Italy and Australia to EUR 255 million in Japan. This corresponds to between 6 EUR per million EUR of GDP in Italy and the US to 61 EUR per million EUR of GDP in Japan. In proportion of GDP, Japan largely outperforms every other country. Korea and the Netherlands come in as distant 2nd and 3rd, with around 20 EUR per million units of GDP. Using this metric, the US comes last among all the main hydrogen economies.

Between 2008 and 2019, Australia, Germany, Japan, the Netherlands and the United Kingdom increased public RD&D spending on hydrogen, while Canada, Italy, Korea, and the United States cut public spending on RD&D by more than half. Most notably, in 2008 the United States represented 40% of total OECD hydrogen RD&D (340 million euros), but this reduced to only 17% in 2019 (EUR 107 million).

With the exception of Australia who started from a very low basis in 2008, all countries decreased public RD&D spending between 2008 and 2016, but nearly all of them increased public RD&D spending since then (except Canada and Korea). Australia, Germany, Japan, the Netherlands and the UK significantly ramped up funding, with 2-digit average annual growth rates between 2016 and 2019. Most of this overall increase (+17% per year on average across OECD countries) is driven by Japan, which increased public RD&D spending on hydrogen from 116 million to 255 million (+EUR 139 million), which is greater than the increase observed in all other OECD countries combined (+ EUR 104 million). However, in other countries such as Canada, France, Italy, Korea and the US, we do not yet observe a significant mobilisation of public resources for RD&D on green hydrogen. Therefore, a top priority in these countries could be to gradually increase current public investments in R&D.

Table 5.1. Public RD&D spending on hydrogen and fuel cells by country

Country	2008	2016	2019	Average annual growth 2008-16	Average annual growth 2016-19	2019 public RD&D per million EUR of GDP
Australia	0.25	2.55	10.85	+34%	+62%	10.0
Canada	54.99	14.84	12.28	-15%	-6%	9.2
France	64.98	31.02	38.74	-9%	+8%	18.3
Germany	29.07	16.49	45.98	-7%	+41%	14.8
Italy	28.50	9.92	10.45*	-12%	+2%	6.8
Japan	183.11	116.47	254.91	-5%	+30%	61.8
Korea	67.87	31.85	28.97	-9%	-3%	21.8
Netherlands	9.83	1.00	14.68	-25%	+145%	19.7
United Kingdom	15.93	17.06	32.21	+1%	+24%	14.6
United States	339.73	95.30	106.64	-15%	+4%	6.3
Total IEA	**852.88**	**395.16**	**637.19**	**-9%**	**+17%**	**15.0**

Note: Data in million EUR (2020 prices and exchange rates). *Data for Italy is not available for 2019 and is therefore replaced by data for 2018.
Source: IEA Energy Technology RD&D Budget Database, 2021

5.2. Planned hydrogen capacity deployment

Besides RD&D activity, new large-scale projects are important to achieve cost-reductions through learning-by-doing and economies of scale. The International Energy Agency's Hydrogen Policy Database[6], created for the Japanese Presidency of G20 in 2020 and updated in October 2021, describes the main green and blue hydrogen projects. Based on this database, Table 5.2 presents the planned low-carbon (green and blue) hydrogen production capacity by country and Table 5.3 shows the capacity of the largest hydrogen projects in the world.

France stands out of Table 5.2 as the country with the largest planned capacity, mainly driven by a shared project with Spain. Australia is the third, with the objective of becoming the hydrogen hub for South East Asia, making use of relatively cheap renewable energy (solar PV) in Western Australia. The United Kingdom ranks second, the key difference being that the UK's planned capacity will rely almost exclusively on one large-scale blue hydrogen project (natural gas combined with CCS) whereas France's and Australia's projects relies on green hydrogen (see Table 5.3).

An interesting observation is that some of the countries with the largest low-carbon hydrogen projects in the pipeline – in particular Australia, the United Kingdom and the Netherlands – are not among the countries that spend the most on public RD&D in hydrogen production. Column 3 of Table 5.2 shows the public RD&D expenditures in hydrogen-related innovation (hydrogen production, distribution, storage, infrastructure and end-uses), thus excluding fuel cells (the second component of public RD&D as reported in Table 5.1 and in Figure 5.1). The contrast between columns 2 and 3 is particularly striking regarding Japan, which spends by far the most on public RD&D (in absolute terms as well as in proportion to GDP) but currently plans very little deployment. Thus, while Japan seems to focus on RD&D, other countries seems to focus more on deployment.

Table 5.2. Planned hydrogen capacity in main economies (until 2040)

Country	Estimated normalised capacity [nm³ H2/hour]	Public RD&D expenditures in hydrogen in million EUR (per million EUR of GDP)
France	7 699 914*	27.5 (12.9)
United Kingdom	6 212 549*	20.8 (9.4)
Australia	5 901 882	7.3 (6.7)
Netherlands	3 979 794*	14.7 (19.7)
Germany	3 024 605	26.6 (8.5)
Canada	1 863 908*	6.8 (5.0)
China	1 783 343	n.a.
United States	905 246	32.0** (1.9)
Italy	218 887	4.4*** (2.8)
Japan	3 429	201.5 (48.5)

Note: Restricted to hydrogen projects with a date online before 2040.
* For the Netherlands, the Pernis CCUS project is not taken into account as it will replace the up and running CCU project. The United Kingdom is leading in blue hydrogen by the H21 North of England and the Hynet projects, but is among the lowest ranked countries in terms of green hydrogen. Canada and the Netherlands also have large blue hydrogen projects. For France, the figure include half of the HyDeal Ambition project, which is shared with Spain and is currently the most ambitious project (see Table 5.2).
** No breakdown is available for US since 2016. The total (hydrogen + fuel cells) value for 2019 is used (EUR 106.6 million) multiplied by 30%, which corresponds to the share of US public funding that went to hydrogen in 2015.
*** 2018 value
Source: Normalised capacity: own calculations based on IEA (2021[13]). Public R&D expenditures: IEA Energy Technology RD&D Budget Database, 2021

Table 5.3. Largest planned hydrogen projects in the world (until 2040)

Project name	Country	Announced start date	Estimated normalised capacity [nm³ H2/hour]	Type of hydrogen
HyDeal Ambition	ESP/FRA	2030	14 888 889	Green
H21 North of England	GBR	2035	3 890 730	Blue
Asian Renewable Energy Hub	AUS	2028	3 111 111	Green
Oman green H2 project, phase 2	OMN	2038	2 074 000	Green
Baicheng, Jilin wind-solar project	CHN	2035	1 282 643	Green
Shell heavy residue gasification CCU - Pernis refinery	NLD	2005 (2024 for carbon storage)	1 282 643	Blue
AquaVentus (phase 4)	DEU	2035	1 111 111	Green
AquaVentus (phase 3)	DEU	2030	1 044 444	Green
Hynet Northwest, phase 2	GBR	2030	1 038 941	Blue
Oman green H2 project, phase 1	OMN	2028	1 037 111	Green
Murchison	AUS	2028	961 538	Green
Port of Pecem - Base One	BRA	2025	769 586	Green
Air Products Net-Zero Hydrogen Energy Complex	CAN	2024	667 135	Blue
Stanwell-Iwatani Galdstone project	AUS	2030	666 667	Green
NortH2, phase 2	NLD	2030	666 667	Green

Note: Restricted to hydrogen projects with a date online before 2040.
Source: IEA (2021[13]).

5.3. Countries' hydrogen strategies

This section provides a detailed analysis of the hydrogen strategies in the main hydrogen-producing countries (Australia, Canada, China, France, Germany, Italy, Japan, Korea, the Netherlands, the United Kingdom, the United States and the European Union)[7]. Countries with a National Hydrogen Strategy include Australia, Canada, France, Germany, Japan, the Netherlands and the United Kingdom. Korea adopted a Hydrogen Economy Roadmap and the United States has a Hydrogen Program Plan, both similar to National Hydrogen Strategies in other countries. In addition, the European Union has also adopted such a strategy, and Italy published some "Guidelines for a National Hydrogen Strategy" in anticipation of a full-fledged Strategy that is expected to be published later. China, the largest CO_2 emitter in the world, does not yet have a National Hydrogen Strategy, nor is it officially working on one.

For completeness, the strategy documents are complemented with other national hydrogen policy documents. The analysis is organised along (i) targets, (ii) policy instruments, (iii) infrastructure priorities, (iv) regulatory standards and (v) international cooperation policies.

5.3.1. Main messages

Details of the strategies are presented below, but in a nutshell, the following messages come out of the analysis:

- The adopted deployment targets for 2030 are ambitious compared to the present situation, but very far from the necessary deployment at the 2050 horizon. Some longer-term objectives (until 2050) could provide more certainty to investors.
- The policy instruments and support schemes in place to reach these intermediate objectives rely primarily on deployment subsidies, which appear very large compared to public RD&D funding presented in Section 5.1. A re-balancing of support toward R&D, prototypes and demonstration seems necessary.
- Hydrogen infrastructure commitments are still at a very early stage in almost all major economies. This could be a major bottleneck going forward.
- Hydrogen-related regulatory standards (on purity, origin, blending with natural gas, safety, etc.) are being discussed across countries, but few have been finalised. The importance of international cooperation on standards is widely recognised, but different platforms of discussion exist at various level (bilateral, multilateral, international, EU level…).

5.3.2. Targets

Table 5.4 shows the different hydrogen targets in place in the main hydrogen economies. Most targets are defined in the National Hydrogen Strategies, but some are taken from other policy documents when National Hydrogen Strategies do not yet exist, or do not specify a target. Most countries define targets in terms of GW production capacity by 2030, but other countries, such as the United States and Japan, defining targets in terms of future hydrogen costs. This complicates the comparison of the targets across countries.

In general, most countries have targets of 2-15 GW green hydrogen production capacity in 2030. This is significantly more than the virtually non-existent current global production capacity of 218 MW in 2021 (IEA, 2020[29]), and probably more than the 54 GW of projects under development (both green and blue) identified by the IEA (2021[13]). At the same time, however, these targets are only a small first step to reach the milestone of 3 000 GW capacity by 2050 in the IEA net zero scenario (IEA, 2021[2]).

Table 5.4. Hydrogen targets in main hydrogen economies

Countries	Hydrogen targets
Australia	**Hydrogen strategy** Production cost target of $2/kg by 2030.
Canada	**Hydrogen strategy:** • 45 Mt emissions reduction in 2030 and 190 Mt CO_2 emissions reduction in 2050
China	No hydrogen strategy yet, most hydrogen used today is produced using coal.
France	**Hydrogen strategy**: 2030: • 6.5 GW of carbon-free hydrogen electrolysers • 20-40% of total hydrogen and industrial hydrogen consumption sourced from low-carbon and renewable hydrogen
Germany	**Hydrogen strategy:** **2030:** 5 GW of renewable hydrogen electrolysers **2040:** 10 GW of renewable hydrogen electrolysers
Italy	Guidelines for a National Hydrogen Strategy **2030**: 5 GW of electrolysis capacity
Japan	**Basic Hydrogen Strategy** **2030:** Procure 300 000 tonnes of hydrogen/year and reduce the cost of hydrogen to USD 3 per kg by 2030 **2050**: Reduce the cost of hydrogen to USD 2 per kg
Korea	**Korea Hydrogen Economy Roadmap 2040:** **2040:** 15 GW of fuel cell for power generation, 1 200 hydrogen refilling stations and 41 000 hydrogen buses
United Kingdom	**2030:** 5GW of low-carbon hydrogen production capacity (both green and blue hydrogen). 1GW by 2025.
United States	No (green) hydrogen strategy, but **hydrogen program plan** Only broad targets, without mentioning a date: • USD 2/kg for hydrogen production • USD 1/kg hydrogen for industrial and stationary power generation applications • Electrolyser capital cost of USD 300/kW, 80 000 hour durability and 65% system efficiency
Netherlands	**Hydrogen strategy:** **2025**: 500 MW of renewable hydrogen electrolysers **2030**: 2-4 GW of renewable hydrogen electrolysers
European Union	**Hydrogen strategy:** **2024**: • At least 6 GW of renewable hydrogen electrolysers • Production of 1 million tonnes of clean hydrogen **2030**: • 40 GW renewable hydrogen electrolysers in the EU • Production of 10 million tonnes of renewable hydrogen in the EU • Imports of hydrogen relying on 40 GW of electrolysers in Europe’s neighbourhood

Source: National Hydrogen Strategies and other (policy) documents.

5.3.3. Instruments

Table 5.5 gives an overview of the most important hydrogen policy instruments in place across countries. Overall, the main message that comes out of Table 5.5 is that the policy instruments and support schemes in place to reach the targets described above rely primarily on deployment subsidies, which appear very large compared to public RD&D funding presented in Section 5.1. Given the low maturity of hydrogen, re-balancing support toward R&D, prototypes and demonstration seems reasonable.

France, Germany and Australia seem to be among the countries with the most extensive support to green hydrogen, with annual budgets of respectively EUR 850 million, more than EUR 300 million and AUD 1.3 billion (approx. EUR 810 million) in public subsidies for green hydrogen deployment. In the UK, the new Net Zero Hydrogen Fund (NZHF) will provide up to GBP 240 million of government co-investment to support new low carbon hydrogen production between 2022 and 2025.

Italy and the Netherlands have also started to mobilise public resources for the transition to green hydrogen. In particular, Germany started to discuss support to overcome the barrier of large operational expenditures (OPEX) through Carbon Contracts for Difference (CfD) schemes. This is a way to guarantee revenues for reduced carbon emissions, helping to make the business case for green hydrogen.

In line with their targets, Japan and Korea focus more on fuel cells and hydrogen cars. Japan has made a USD 640 million budget available to support hydrogen while South Korea has planned to expand the supply of electric and hydrogen vehicles (with a target of 200 000 hydrogen-powered vehicles by 2025 and 450 hydrogen fuelling stations).

Moreover, China and the United States – the two largest CO_2 emitters in the world – do not currently have any specific support instruments for the diffusion of hydrogen, although the green hydrogen sector in these major economies benefit from more general support to low-carbon innovation – in the form of R&D tax credits, carbon markets or the US' 45Q tax credit (targeted at CCS). These countries must now increase their support to green hydrogen in order to trigger the necessary investments that will make green hydrogen competitive.

Table 5.5. Hydrogen Instruments in main hydrogen economies

Countries	Hydrogen Instruments
Australia	• Several funds for clean hydrogen: Renewable Hydrogen Deployment Funding Round (AUD 70 million) to fund two or more large scale electrolyser projects, Advancing Hydrogen Fund (AUD 300 million), Tasmanian Renewable Hydrogen Industry Development Funding Program (AUD 50 million), Queensland Hydrogen Industry Development Fund (AUD 15 million), Western Australia Renewable Hydrogen Fund (AUD 10 million). • Several strategies and plans to promote clean hydrogen: National Hydrogen Strategy, South Australia Hydrogen Action Plan, Queensland Hydrogen Industry Strategy, Western Australian Renewable Hydrogen Strategy, Tasmanian Renewable Hydrogen Action Plan, Victorian Hydrogen Investment Program • The National Hydrogen Strategy identifies 57 joint actions. Actions are themed around national coordination, developing production capacity, supported by local demand; responsive regulation; international engagement; innovation and research and development (R&D); skills and workforce; and community confidence. • Between 2015-19, the government invested AUD 146 million in hydrogen projects, of which AUD 68 million on R&D, AUD 5 million on feasibility, AUD 5 million on demonstration and AUD 69 million on pilots. • AUD 464 million are invested in the Clean Hydrogen Industrial Hubs program to develop 7 hydrogen hubs across Australia. • In total, nearly AUD 8 billion in support until 2030 is available for hydrogen and underpinning renewables across all Australian governments, including AUD 1.4 billion from the Australian government, AUD 3.8 bn from New South Wales government, AUD 2 bn from Queensland government and AUD 570 million from Western Australia government.
Canada	• CAD 1.5 billion for Low-carbon and Zero-emissions Fuels Fund (not limited to hydrogen) • 2019 Hydrogen Pathways formulating ten actions
China	• National fuel cell subsidy scheme and several initiatives at the local (province or city) level.
France	• For the 2020-2023 period, EUR 3.4 billion is available to be divided among industrial decarbonisation (54%), hydrogen transport development (27%) and research and development (19%), including: ○ EUR 1.5 Bn of funding through the IPCEI (see below this European initiative) ; ○ Call for project « Briques technologiques et démonstrateurs » (demonstrators and building blocks) (EUR 350 million) ○ A call for project « Hydrogen Territorial Hub » (EUR 275 million)
Germany	• A new pilot programme entitled **Carbon Contracts for Difference,** which mostly targets the steel and chemical industries with their process-related emissions (EUR 500 million until 2023). • EUR 1.5 Bn over 2021-2026 through the IPCEI (see below this European initiative), focused on industrial applications of hydrogen. • A demand quota for climate-friendly base substances, e.g., green steel, is being considered. • H2 Global;l Hydrogen Technology Initiative. • Funding Guideline International Hydrogen Projects (EUR 450 million). • Energy Efficient Building and Renovation - Fuel Cell Grant (EUR 50-60 million per year). • H2 + Hybrid-electric Flying (LuFo-Program) (EUR 200 million).
Italy	• Three-year electrical research plan.
Japan	• Strategy for Developing Hydrogen and Fuel-Cell Technologies • Subsidy for R&D, demonstration (national government initiative) • JPY 95.5 billion government budgetary support for hydrogen in 2021
Korea	• Renewable Portfolio Standard (RPS) policy to support fuel cell power generation.
United Kingdom	• GBP 240 million Net Zero Hydrogen Fund (launched early 2022) for co-investment in early hydrogen production projects. • GBP 60 million Low Carbon Hydrogen Supply 2 Competition to develop novel hydrogen supply solutions (part of the GBP 1bn Net Zero Innovation Portfolio innovation support programme). GBP 68 million for the Longer Duration Energy Storage Demonstration competition, where storing hydrogen produced from excess electricity is included. • Ultra low emission trucks scheme: GBP 20 million programme to let vans go electric and to let lorries run on hydrogen.
United States	• Focus on conducting coordinated RD&D activities to enable the adoption of hydrogen technologies across multiple applications and sectors • US 45Q tax credit for CCUS, which is important for blue hydrogen, providing a credit of USD 35 or more for each tonne of carbon dioxide captured and stored.
Netherlands	• Electrolysis scale up scheme (EUR 250 million), max 40% of CAPEX, 100% funding gap. • Groenvermogen hydrogen pilot tender (EUR 30 million), max 40% CAPEX or EUR 15 million. • Subsidies open to hydrogen, but also to other green technologies: SDE++, DEI+, HER+, VEKI
Europe	• **European Clean Hydrogen Alliance (Important Project of Common European Interest – IPCEI):** Within the IPCEI framework, state aid is permitted if selected projects meet the following conditions: i) contribute to strategic EU objectives; ii) involve several EU countries; iii) include private financing by the beneficiaries, iv) generate positive spill-over effects across the EU; and v) show high research and innovation ambitions.

Source: National Hydrogen Strategies and other (policy) documents.

5.3.4. Hydrogen infrastructure priorities

While hydrogen can be produced on-site by final users, economies of scale can make it more cost-effective to produce hydrogen at a large scale and then distribute it to various users, including industrial plants, cars and trucks. This is the case both for blue hydrogen – which requires the local availability of large-scale storage capacity for carbon – and for green hydrogen, which can benefit from the existence of cheap renewable energy resources. Centralised production in turn requires the existence of a hydrogen storage and transportation network infrastructure, including pipelines and hydrogen filling stations for trucks and cars. Public commitment to infrastructure investment – at both national international level – can therefore strongly accelerate the development and deployment of hydrogen. Hydrogen infrastructure need not be built from scratch, many countries considering the gas grid to transport hydrogen.

Table 5.6 shows the hydrogen infrastructure priorities in the main hydrogen economies. While most countries are starting to discuss at least some infrastructural bottlenecks and opportunities in their National Hydrogen Strategies and other policy documents, **hydrogen infrastructure commitments are still at a very early stage in almost all major economies**. Across countries, it seems that priority is given to hydrogen production support instruments over infrastructure building.

At this stage, however, **some countries have started a comprehensive assessment of the necessary future hydrogen infrastructure**. The European Union has requested the Trans-European Network for Energy to review the compatibility of the internal gas market legislation with pure hydrogen and cross-border operation rules. The European Union is also planning a network of fuelling stations in the Ten-Year Network Development Plans. Australia, Germany and the Netherlands are also working on assessments of their national hydrogen infrastructure. In addition, the United Kingdom, Germany and the Netherlands are trying to better connect the electricity and gas infrastructure to facilitate hydrogen production. The Netherlands even set a target to realise a “hydrogen Backbone” in Europe, using a mix of new and existing natural gas pipelines.

Japan and Korea are focusing again more on hydrogen fuel cell infrastructure. Japan is investing USD 27 million in R&D projects on the construction of low-cost hydrogen infrastructure utilising ultra-high pressure, and another USD 27 million in a hydrogen infrastructure development project. Korea subsidises pilot cities for hydrogen distribution infrastructure.

Table 5.6. Hydrogen infrastructure priorities in main hydrogen economies

Countries	Hydrogen infrastructure priorities
Australia	• National Hydrogen Infrastructure Assessments: The Australian Government will lead a National Hydrogen Infrastructure Assessment that will guide government and private sector investment as the industry grows. • The Australian gas regulatory framework is being amended to bring hydrogen, bio-methane and other renewable gas blends within its scope including a review on the economics of blending and the eventual use of 100% hydrogen in Australian gas network
Canada	**Gas grid** • Pilot projects to determine the technical feasibility of blending hydrogen into existing natural gas systems • Enbridge Gas and Cummins, supported by Sustainable Development Technology Canada, announced a AUD 5.2 million project, which will blend renewable hydrogen gas into the existing Enbridge Gas natural gas network.
China	**Gas Grid:** Blending hydrogen with natural gas (less than 10% hydrogen by volume) has been proposed as a viable option to boost renewable development.
France	**Gas grid** • At this stage, the only projects injecting hydrogen into the natural gas network are experimental (for instance, project GRHYD or project Jupiter 1000). • Pilot project by Engie in Northern France blending hydrogen with natural gas up to 20% of its volume. • Participation in the European Hydorgen Backbone (see below).
Germany	**Gas grid:** Studying the use of existing structures (dedicated hydrogen infrastructure as well as parts of the natural gas infrastructure that can be adjusted and back-fitted to make it H_2-ready) – Measure 20 of the National Hydrogen Strategy. **Electricity grid** • Efforts to better link up the electricity, heat, and gas infrastructure will continue. The aim is to shape the planning, financing, and the regulatory framework in a way that makes it possible to coordinate these different parts of the infrastructure. • New business and cooperation models for operators of electrolysers and for the grid and gas network operators (principle of regulatory unbundling)
Italy	**Gas grid:** Minimum target of 2% of distributed natural gas being replaced by hydrogen
Japan	• JPY 11 billion public investments in Infrastructure development project using hydrogen (refuelling stations) • JPY 3.2 billion public investments in R & D projects for the construction of low-cost hydrogen supply infrastructure utilising ultrahigh pressure hydrogen technology
Korea	• Subsidy to pilot cities for hydrogen distribution infrastructure.
United Kingdom	**Gas grid:** A pilot in which hydrogen is blended with natural gas up to 20% of total volume (by HyDeploy), which is the highest share in Europe together with a similar project in France. Project Union to explore the development of a UK hydrogen network which would join industrial clusters around the country, potentially spanning 2 000 km, repurposing 25% of the current gas transmission pipelines. **CCS**: GBP 1bn for the Carbon Capture and Storage (CCS) Infrastructure Fund
United States	• Target of USD 2/kg for delivery and dispensing for transportation applications
Netherlands	**Gas grid:** Government will review whether and under what conditions part of the gas grid can be used for the distribution of hydrogen (with the aim of developing of North-Western Europe hydrogen market). Gradually increase blending obligation from 2% to 10-20%. **Electricity grid** • Gasunie and TenneT (public firms) develop and coordinate hydrogen and electricity grid • Government will coordinate the precise locations of electrolysers (Main Energy Infrastructure Programme) The Netherlands sets a target to realise its portion of the European “Hydrogen Backbone”.
European Union	**Gas Grid:** Up to 2030: Review of Trans-European Networks for Energy to review the internal gas market legislation to ensure compatibility with pure hydrogen and cross-border operation rules. Elements of the existing gas infrastructure will be repurposed for the cross-border transport of hydrogen. Creation a European hydrogen backbone by 2040 from Spain to Sweden. The goal is to create an initial 6,800 km pipeline network by 2030, connecting hydrogen valleys. The infrastructure would then further expand by 2035 and stretch into all directions by 2040 with a length almost 23,000 km.This infrastructure should consist of repurposed natural gas pipelines with only a few new pipelines created. **General**: Ten-Year Network Development Plans (TYNDPs) (2021) taking into account also the planning of a network of fuelling stations.

Source: National Hydrogen Strategies and other (policy) documents.

5.3.5. Regulatory standards and international cooperation

There are many ways to produce and use hydrogen. On the supply side, differences exist not only between grey, blue and green hydrogen, but also between production technologies (Alkaline, PEM, etc.), as explained in Section 3. . Hydrogen can be produced on-site, but also in a centralised manner before being stored and transported via tanks or pipes, in a pure form or blended with natural gas. This wide variation in the modes of producing, storing and transporting hydrogen suggest that regulatory standards can facilitate the creation of a dynamic hydrogen market.

The necessary regulations are often technical and must deal with issues such as how and where pressurised or liquefied hydrogen can be used, who can work with it, where can hydrogen vehicles go, conversion between energy carriers, tax regimes, whether carbon can be stored using CCS, and how much hydrogen can be blended in natural gas pipelines.

Regulatory standards can help to reduce uncertainty and facilitate coordination. Standards are needed on the purity of hydrogen for passenger vehicles, on the gas composition for cross-border sales, on safety measures (such as materials used for hydrogen tanks), and on how to measure lifecycle environment impacts from hydrogen production (IEA, 2019[1]). As it is impossible to assess from hydrogen itself how it has been produced, accounting standards for the origin of hydrogen are needed to create a market for blue or green hydrogen.

Standardisation faces a trade-off: advancing fast on a national basis or slower at the international level. For example, China has already adopted 93 standards for hydrogen infrastructure and applications. Even EU-countries do not yet rely on EU-standards. For example, Italy has adopted a national specific regulation on hydrogen fuelling stations.

Regulatory standards can build on the work already undertaken by standard-setting bodies. At the international level, the International Organization for Standardization (ISO) already published 17 ISO standards related to hydrogen and there are 16 further ISO hydrogen standards still under development. In addition to the ISO, the **International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)** is an international inter-governmental partnership with the objective to accelerate progress in hydrogen and fuel cell technologies. The IPHE Hydrogen production analysis taskforce was created to propose an internationally agreed methodology and analytical framework to determine the GHG emissions related to a unit of produced hydrogen. This work could form a new ISO standard to determine the emissions associated with the production of hydrogen.

Table 5.7 shows some of the main hydrogen standards adopted or discussed in the main hydrogen economies.

Most countries recognise that standards are important and should ideally be set at the international level, and **international cooperation related to hydrogen is thus mostly about harmonising codes and standards** (see Table 5.8 for more detail on international cooperation). For example, Australia and the United Kingdom both stress the importance of establishing a clear regulatory framework to facilitate the hydrogen transition through a process of reviewing and reforming the underlying legal frameworks, which should lead to a supportive investment climate. Canada stresses the importance of updating, harmonising and developing standards, both at the national and international level, to facilitate the adoption of hydrogen technologies and infrastructure. The United States is working together with other countries in the US Center for Hydrogen Safety and with Canada in the Canada/US Regulatory Cooperation council to develop a common methodology to harmonise codes and standards.

The European Union, Germany and the Netherlands are currently working on ‘contracts of origin’ standards, which are considered crucial for a well-functioning hydrogen market. These **contracts of origin are needed to distinguish between grey, blue and green hydrogen, and are therefore crucial for the emergence of a separate market for blue and green hydrogen**. The European Union is working on low-carbon thresholds and standards for production facilities, as well as on a comprehensive terminology and EU-wide criteria for the certification of low-carbon and green hydrogen. Germany urges for international harmonisation for hydrogen mobility applications and fuel-cell based systems, such as refuelling standards and hydrogen quality.

Standards addressing safety concerns are also important to reduce uncertainties for investors. Japan has introduced a number of strict safety regulations for the production and storage of hydrogen, such as in the Regulation on Safety of General High Pressure Gas. In addition, the Japanese High Pressure Gas Safety Act provides technical standards on how hydrogen should be transported.

Another form of standards that can support the demand for hydrogen are South Korea’s Hydrogen Portfolio Standards (HPS), which require state-utilities to meet a certain quota of hydrogen when purchasing fuel. **Similarly, most of the National Hydrogen Strategies refer to the possibility of blending hydrogen with natural gas in the gas grid**. This includes an announced minimum target of 2 percent in Italy, an obligation to gradually increase blending from 2 percent to 10 percent in the Netherlands and pilots for up to 20 percent of hydrogen blending in the United Kingdom and France. China has also proposed blending hydrogen with natural gas (up to 10 percent) as an option to boost renewable hydrogen development (Table 5.6).

Table 5.7. Hydrogen standards in main hydrogen economies

Countries	Hydrogen standards
Australia	• Ongoing review of the legal and regulatory framework.
Canada	• Recommendation in National Hydrogen Strategy: updating, harmonising, and developing standards domestically and internationally to enable deployment and to facilitate adoption of new technology and infrastructure.
China	• Set standards for subsidising Fuel Cell Electric Vehicles (FCEVs). • China now has 93 national standards for hydrogen infrastructure and applications.
France	-
Germany	• Need for reliable sustainability standards and for a sophisticated quality infrastructure, proof (of origin) for electricity from renewable energy and for green hydrogen and its downstream products. • Advocacy for an international harmonisation of standards for mobility applications for hydrogen and fuel-cell-based systems (e.g. refuelling standards, hydrogen quality, official calibration, hydrogen-powered car type approval, licencing for ships etc.).
Italy	• Italy has adopted a national specific regulation on hydrogen fuelling stations.
Japan	• Different strict safety regulations apply to the production and storage of hydrogen, e.g. the Regulation on Safety of General High Pressure Gas. • High Pressure Gas Safety Act provides technical standards how hydrogen must be transported.
Korea	• Hydrogen Portfolio Standards (HPS) to require state-utilities to meet a certain quota when purchasing fuel.
United Kingdom	• Ongoing work for a UK low carbon emissions standard aimed for 2022.
United States	-
Netherlands	• Guarantees of Origin system is required, Vertogas (Certifies green gas) will be designated to develop this system. • Hydrogen Safety Innovation Programme – implemented as PPPs – to adequately address any issues.
European Union	• Establish common low-carbon threshold/standard for hydrogen production installations (full lifecycle GHG). • Comprehensive terminology and European-wide criteria for the certification of renewable and low-carbon hydrogen. • Establish Guarantees of Origin between low-carbon and green hydrogen.

Source: National Hydrogen Strategies and other (policy) documents.

Table 5.8. International cooperation on hydrogen in main hydrogen economies

Countries	International cooperation on hydrogen
Australia	• Through international engagement, Australia will work with other countries to develop a scheme to track and certify the origins of internationally traded clean hydrogen and will work constructively to shape international markets and open new frontiers for trade.for instance, the Australian Government is a member of the U.S. Center for Hydrogen Safety. This gives all Australian governments access to some of the world's foremost expertise in hydrogen safety. Other partners include Germany, Japan, Korea, Singapore and the United Kingdom.
Canada	• Canada works with other countries to harmonise codes and standards, among others in the Canada/US Regulatory Cooperation Council, to develop common methodology
China	• The National Alliance of Hydrogen and Fuel Cell (NAHFC) cooperated with the Hydrogen Council for the research report "Path to Hydrogen Competitiveness – A Cost Perspective"
France	• France signed a manifesto for the development of a hydrogen value chain with 22 other countries. France is supporting this project with a financial allocation of €1.5bn. This project will consider the research and development of electrolysers, a Giga-factory of electrolysers, the industrialisation of components of hydrogen fuel cells, etc. • Participation in the EU IPCEI.
Germany	• Participation in the EU IPCEI. • The establishment of a European hydrogen company to promote and develop joint international production capacities and infrastructure is being explored and will be progressed if there is sufficient European backing. • Strengthening the existing international activities, particularly in the context of the energy partnerships and of multilateral cooperation, such as that of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA). • Pilot projects in partner countries, not least as part of German development cooperation involving German firms, are to show whether and how green hydrogen and its downstream products can be produced and marketed there on a sustainable and competitive basis. • Funding of grants for international projects on green hydrogen, in particular with Canada.
Italy	• Receiving EUR 2bn to be allocated to develop the hydrogen supply chain within the framework of the Next Generation EU initiative to alleviate the economic impact of the Covid-19 pandemic on the national economy. • Participation in the EU IPCEI.
Japan	• The Hydrogen Ministerial Meeting has been held since 2018 to discuss issues and policies for the realisation of an international hydrogen society and to promote international cooperation. • Collaborating with many countries in participation and cooperation in international frameworks (International Partnership for Hydrogen and fuel cells in the Economy – IPHE, Clean Energy Ministerial (CEM) Hydrogen Initiative, coordinated by the IEA) and bilateral dialogue.
Korea	• Cooperate and participate in the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)
United Kingdom	• Co-leadership of Mission Innovation Clean Hydrogen • Participation in Clean Energy Ministerial (CEM), International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), and Hydrogen Energy Ministerial
United States	• International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) is an international inter-governmental partnership with the objective to accelerate progress in hydrogen and fuel cell technologies, generate common codes and standards, and information sharing on infrastructure development.
Netherlands	• Direct contact with European Commission at every conceivable level • Pentalateral Forum (Benelux, Germany, France, Austria and Switzerland) – develop standards, market incentives, regulations • Consultations with North Sea countries, North Sea Wind Power Hub Project • Feasibility study – on Dutch/Germany offshore wind energy and the benefits for scaling up green hydrogen, which would then be made available through Dutch gas pipelines (HY3 project) • IPCEI – Netherlands will be focusing on green hydrogen
European Union	• IPCEI – Clean Hydrogen Alliance • Strengthen EU leadership in international fora for technical standards, regulations and definitions on hydrogen. • Develop the hydrogen mission within the next mandate of Mission Innovation (MI2). • Promote cooperation with Southern and Eastern Neighbourhood partners and Energy Community countries, notably Ukraine on renewable electricity and hydrogen. • Set out a cooperation process on renewable hydrogen with the African Union in the framework of the Africa-Europe Green Energy Initiative. • Develop a benchmark for euro-denominated transactions by 2021.

Source: National Hydrogen Strategies and other (policy) documents

6. Hydrogen policies: what can governments do now?

Private investment in hydrogen suffers from significant technological risks as this solution might me supplanted by alternative technologies such as electric vehicles, biofuels, heat pumps and electrification of high-temperature heat (IEA, 2019[1]).

Governments willing to invest in hydrogen technologies, know-how and infrastructure face the same risk.

However, without clear policy commitments and actions, it is unlikely that hydrogen will thrive, leaving governments with fewer options for reaching net zero and potentially missing an important lever of competitiveness for their firms.

Given the technological uncertainty inherent to the transition to a net-zero economy, countries should support a portfolio of technologies, hydrogen having the potential to be one of these technologies.

This paper therefore argues that countries willing to support hydrogen now should follow these five recommendations:

1. Ensure greater support R&D in green hydrogen and demonstration projects
2. Ensure a sufficient supply of renewable energy where possible, and encourage the creation of an international hydrogen market
3. Use carbon pricing and carbon price trajectories to provide investors with the right incentives
4. Reduce uncertainties for investors through regulatory action and standardisation
5. Consider blue hydrogen as an interim solution to facilitate the transition to green hydrogen.

6.1. Support to R&D and demonstration should be a key component of industrial policies for green hydrogen

The cost of green hydrogen is falling rapidly thanks to lower renewable electricity prices, but green hydrogen is still 2-3 times more expensive than blue hydrogen (produced from fossil fuels with carbon capture and storage). Section 3. shows that innovation coming from R&D activities, economies of scale and learning-by-doing can be expected to reduce costs by around 40%, through more cost-effective electrolysis and the use of cheaper materials in electrolysers.

R&D and demonstration have the potential to bring down the cost of electrolysers and make large-scale green hydrogen production more competitive. However, the lack of growth in patenting activity on hydrogen technologies (Figure 4.1) suggests that the pace of innovation activity is not aligned with new hydrogen ambitions compatible with net-zero GHG emissions. Similarly, public RD&D spending on hydrogen is lower than it was in the years 2006-2008 and represents 3.3% of total energy-related RD&D spending across IEA countries (down from 5.8% in 2008). Despite this, the policy instruments and support schemes in place to reach hydrogen targets presented in Section 5 rely primarily on deployment subsidies, which appear very large compared to public RD&D funding. Hence, **R&D subsidies should be increased or re-targeted** to speed up the development of hydrogen innovations that are urgently needed.

Specific R&D support instruments are required. Horizontal R&D support has indisputable advantages, including its low administrative cost and technological neutrality, but by construction, they benefit mostly technologies that are closest to the market. Support to an emerging technology such as hydrogen might justify a stronger focus on targeted instruments for R&D, complementing horizontal instruments. As technological uncertainty remains significant, support should not focus on particular production processes to avoid lock-in and to give all green hydrogen technologies that are still at low TRL (e.g. AEM, SOEC, turquoise hydrogen, biomass gasification, thermochemical water splitting) a fair chance.

Demonstration projects of large-scale green hydrogen are also needed to further reduce costs. Not all cost reductions can be realised through Research and Development, particularly for technologies that are already at a high TRL (e.g. Alkaline, PEM). Section 3. showed that investments in demonstration are crucial because most of the cost reductions are expected to take place in the scaling-up phase, through economies of scale, economies of scope and learning-by-doing effects. These cost reductions crucially depend on investments (IRENA, 2020[4]). Demonstration is needed for, among other technologies, large-scale electrolysers and scaling-up of liquefaction and regasification facilities.

Financial instruments (including public loans or guarantees, government venture capital) could be an efficient way to support demonstration projects. If returns to scale and learning-by-doing accrue largely to the firm running the demonstration, the main obstacle to overcome will be the riskiness and the financing needs of the project. Consequently, using public financial instruments to partly de-risk the project could allow crowding in private money, while maximising the efficiency of public spending.

Nevertheless, if subsidies are required to make demonstration projects available, support should be at least partly conditional on knowledge sharing, for example by funding consortia rather than individual firms, to facilitate innovation diffusion and cost reductions in the sector.

Ensuring that knowledge can flow across firms and that newcomers can benefit from earlier R&D and demonstration projects (partly) funded out of public money is all the more important as the hydrogen sector is particularly concentrated, as patent and trademark data have shown in section 4. As projects become bigger and require larger financial resources, concentration could further increase in the near future, leading to higher prices for hydrogen in the long run. Ensuring sound competition and low barriers to entry – through regulations and standards that do not favour incumbents, and well-designed subsidy instruments open to younger players – is therefore an essential element of green hydrogen industrial policies.

In order to avoid duplicating costs at demonstration phase, it is important that countries share knowledge and experiences and co-invest to ensure enough resources flow to the urgently needed green hydrogen demonstration projects. With a huge market emerging, there may be competitive tensions from the perspective of individual countries or firms, resulting in too little knowledge sharing. To avoid this situation, incentives should be put in place to share knowledge, while still maintaining the strong incentives for firms to invest. This requires a great deal of **cooperation and coordination between countries** to accelerate the transition.

6.2. Ensure a sufficient supply of renewable energy where possible and encourage the creation of an international hydrogen market

Since renewable electricity is the main input for the production of green hydrogen, an enormous supply of low-cost green electricity (3 000 GW in 2050) is needed for large-scale green hydrogen production to become possible and cost-effective. Making green hydrogen competitive will thus require a significant decrease in the cost of renewable electricity. This is all the more challenging as demand for renewable electricity will also increase for other uses (replacing fossil fuel based power generation, transportation, electricity for low-temperature heating in the industry…).

In principle, green hydrogen should be considered as green only when the whole electricity production comes from renewable sources. Assuming that a strictly positive share of electricity production is made from non-renewable sources, then turning off the electrolyser and reducing electricity demand practically allows reducing non-renewable electricity production in the relevant market. In other words, the 'green' nature of hydrogen should be determined based on the marginal source of electricity in the system (France Stratégie, 2021[17]). But this argument is lessened if electrolysers produce hydrogen only when renewable electricity supply is higher than demand (e.g. windy nights). Nevertheless, with a lower number of load hours, it becomes harder to make the large investments in electrolysers profitable, even if renewable electricity is potentially cheaper during these periods (France Stratégie, 2021[17]).

Ensuring sufficient green electricity supply is particularly challenging for countries with low renewable energy sources (sun, wind). These countries have to consider importing renewable electricity or green hydrogen from abroad. As hydrogen can be stored and transported relatively effectively and efficiently over long distances compared to electricity, it is more cost-effective to produce green hydrogen at places with low electricity prices and export it, compared to importing the green electricity to produce green hydrogen locally (see section 2.).

Therefore, an international market for hydrogen must be created. Australia is one of the first countries willing to export green hydrogen on a large-scale on the international market, as it has the ambition to become the green hydrogen hub for South-East Asia. This ambitious goal explains why Australia currently hosts some of the world's largest investments in green hydrogen. Chile[8], Morocco[9] and Oman (see Table 5.3), also relying on the abundance of solar renewable energy, have similar ambitions in their respective regions.

In this respect, **having effective international standards is a pre-requisite to build a trustworthy and resilient hydrogen market**. This will not only help reduce investors' uncertainty (see Section 6.4), but will also facilitate coordination along the supply chains. This is all the more important that hydrogen could give rise to a new global value chain where technology development, hydrogen production, storage (of hydrogen and potentially of the carbon captured for blue hydrogen) and consumption occur in different locations (Griffiths et al., 2021[11]).

6.3. Support carbon pricing and clear carbon price trajectories

Adequate carbon pricing (i.e. fully pricing the negative environmental externality associated with carbon emissions) would contribute to a cost-efficient decarbonisation, could provide revenue to fund support to new green technologies (including hydrogen) and would make green hydrogen more competitive. It will not only improve the competitiveness of green (and blue) hydrogen vis-à-vis brown and grey hydrogen, but also its economic relevance compared to fossil energy carriers (e.g. natural gas for high temperature processes in the industry).

Hydrogen in its current form is responsible for a significant amount of CO_2 emissions, as nearly all hydrogen currently produced uses coal (brown hydrogen) or natural gas (grey hydrogen). As mentioned above, green hydrogen production is still about two to three times more expensive than hydrogen produced based on fossil fuels. This lower cost of fossil-fuel based hydrogen, however, does not price in the environmental harm that is created by emitting CO_2, meaning that from a social welfare perspective, too much brown and grey hydrogen is produced and used. Using carbon pricing mechanisms – such as emission trading schemes, carbon levies or energy taxes on coal and natural gas – can increase efficiency by forcing companies to take these environmental costs into account.

Section 6.1 makes it clear that, **at the moment, deployment subsidies should not be the priority of governments**. From a cost-effectiveness perspective, it makes sense to prioritise support to large-scale demonstration first, to foster learning and cost reductions, before focussing on large-scale deployment. It remains too early to determine whether deployment subsidies will be necessary, on top of carbon pricing, to cover the price difference with fossil fuel-based alternatives in the medium run, but a combination of strong RD&D support and clear carbon pricing trajectories could well be sufficient.

Nevertheless, governments should act now to ensure that investors in hydrogen technologies do not bear the carbon price risk. For instance, Carbon Contracts-for-Difference (CCfD), experimented in Germany, decrease uncertainty thanks to forward-contracts on the price of abated greenhouse gases. The Dutch carbon levy, a top-up on the EU ETS with an explicit carbon price trajectory, is another example of how policy instruments can reduce carbon price uncertainty for investors.

6.4. Reduce uncertainties for investors through infrastructure build-up, standardisation and certification

Reducing risk and uncertainty for investors in hydrogen is one of the main priorities, beyond the carbon price risk. Even if hydrogen is already used as a feedstock, its use as an energy carrier or as a way to store energy is expected to become relevant only in ten to twenty years from now. The policy and technological uncertainties associated with this long horizon weigh on the investments that are needed today.

This requires strong government signals regarding the potential role of green hydrogen in the net-zero emission economy. National Hydrogen Strategies provide a good way to set common expectations at the national level, reduce uncertainty and trigger private investments.

As infrastructure is in some regions a pre-requisite for the adoption of hydrogen, governments should start planning the hydrogen infrastructure now, by evaluating the infrastructure needs for the transport of hydrogen, identifying the appropriate economic model for this infrastructure and coordinating the public and private sectors. While hydrogen can be produced on-site, economies of scale make it more profitable to produce hydrogen in large installations and then distribute it to the different users. Public-private partnerships can help to increase investments in infrastructure, but they also come with coordination failures that need to be overcome by clearly defining responsibilities. Investments in infrastructure are not only needed at a national level, but also at an international level to allow for hydrogen imports.

Regulatory standards are another cost-effective way to reduce uncertainty and to support green hydrogen. International standards are particularly important for guarantees of origin (e.g. blue or green hydrogen), hydrogen purity, the design of liquefaction/conversion and regasification/reconversion facilities, equipment specifications and blending hydrogen into the gas grid.

By coordinating stakeholders on technical norms, standardisation allows the compatibility between actors and is expected to generate positive externalities. But it can also have social costs, by reducing variety and competition or leading to the adoption of suboptimal technologies (Rabier, 2017[30]; Blind, Jungmittag and Mangelsdorf, 2012[31]). The International Organization for Standardization (ISO) already published 17 ISO standards related to hydrogen and there are 16 ISO hydrogen standards still under development.

A low-carbon hydrogen certification and trading system similar to the one currently in place for the renewable energy market could be introduced. On the electricity market, Renewable Energy Certificates (REC) – sometimes referred to as green certificates – are tradable assets which prove that electricity has been generated by a renewable energy source. Similar certificates for hydrogen are needed to move towards regional or global green hydrogen markets, which are needed to ensure a cost-effective transition to green hydrogen. Such a market would allow green hydrogen to be primarily produced where costs are lowest, in countries rich in renewable energy. The existence of certificates of origin to trace back if hydrogen is green or blue is a crucial condition for this market to be created.

Other required regulatory frameworks include standards on pressurised and liquefied hydrogen, conversion between energy carriers, rules on carbon storage options for blue hydrogen, and hydrogen blending into natural gas pipelines (see Section 5.3).

6.5. Consider blue hydrogen as an interim solution to facilitate the transition to green hydrogen

Blue hydrogen production (from natural gas with CCS) is low-carbon but not zero-carbon: with the development of advanced gas reforming technologies, it could reach CO_2 capture rates of 90%, but not 100 (Committee on Climate Change, 2018[19]). However, blue hydrogen could be an interesting option to reduce emissions in the short run and to facilitate the transition to green hydrogen in the longer-run (IRENA, 2020[10]). For this reason, some countries – in particular the United Kingdom – are pursuing a twin track approach of developing both blue and green hydrogen production routes.

On the one hand, blue hydrogen may help the transition from fossil fuels to green hydrogen:

- by decarbonising earlier the production of hydrogen, in particular hydrogen used as feedstock, for which there is no alternative in the short run. Grey and brown hydrogen, which are responsible for significant emissions of CO_2, have to be made low-carbon as quickly as possible. Around three-quarters of hydrogen is currently produced from natural gas, and adding CCS facilities to these existing installations may be relatively easy compared to transitioning to green hydrogen.
- by facilitating the emergence of a growing hydrogen market and triggering investments in the necessary hydrogen infrastructure, thereby making the economy ready for green hydrogen;
- by decarbonising earlier some industrial sectors, as well as transportation. For instance, heavy industrial processes like steel production require high temperature heating, for which blue hydrogen could be a solution until the necessary green hydrogen and renewable energy capacity become available (IRENA, 2020[10]).

On the other hand, blue hydrogen suffers from important drawbacks:

- It is not carbon neutral as carbon capture rates are expected to reach a maximum of 85-95% (IEA, 2019[1]), and will require negative emissions in a net-zero setting. Some studies argue that the additional energy needed to power the carbon capture installation (a priori natural gas) can limit the advantage of blue over grey hydrogen, especially when taking into account the additional fugitive methane emissions associated with the mining, transport, storage, and use of the natural gas needed to produce the hydrogen and power carbon capture (Howarth and Jacobson, 2021[20]).

- Blue hydrogen may absorb part of the subsidies needed for green hydrogen, and may thereby slow down the required private investments to make green hydrogen competitive. More generally, absent an effective and adequate carbon price or in the presence of inefficient fossil fuel subsidies, blue hydrogen can develop at the expense of green hydrogen. In short, there is a risk of lock-in in a second-best scenario.
- Finally, CCS requires affordable and secure storage options, and a certain level of social acceptance.

The extent to which blue hydrogen can be used as an intermediate step depends mostly on country characteristics. For example, in countries relying on shale gas, fugitive methane emissions make the case for blue hydrogen weaker. Since green hydrogen costs strongly depend on renewable electricity costs, it is more attractive for countries with relatively competitive renewable electricity prices to transition to green hydrogen directly. Meanwhile, it may be more meaningful for countries with more expensive electricity prices to invest in blue hydrogen as an intermediate step, at least if cost-effective CO_2 storage options are available (e.g. in the North Sea).

The case for using blue hydrogen also differs across industries. For instance, the use of blue hydrogen for high-temperature heating in the steel industry may trigger the innovations and infrastructure that will contribute to the uptake of green hydrogen. In the chemical industry, hydrogen is already used as input in the production process, meaning that learning curves related to hydrogen use could be flatter in this industry. On the other hand, given that hydrogen as an input is crucial for the chemical industry, investing in blue hydrogen can accelerate carbon abatement. All in all, countries should compare the country- and industry-specific case for blue hydrogen with its alternative.

Endnotes

[1] Often this involves steam methane reforming of natural gas. Asia still produces a large proportion of hydrogen from coal (e.g., ammonia and methanol producers).

[2] Other technologies exist, such as turquoise hydrogen (methane pyrolysis powered by renewable electricity, producing hydrogen and carbon black, the latter having potential uses in the industry), which remains at the R&D stage (Technology Readiness Level – TRL 3 to 6) (IEA, 2021[13]; France Stratégie, 2021[17]).

[3] Electrolysers are made of stacks, which in turn consist of several cells. A cell contains the two electrodes and the water that is split into hydrogen and oxygen. A stack is a group of cells, which share the same power and water supply, the same environment (pressure, temperature…) and contribute to same output flow of hydrogen. Finally, the electrolyser consists of a collection of stacks sharing the same management system for inputs (electricity and water) and outputs (balance of plant – BoP) (Wirkert et al., 2020[38]; Glenk, Meier and Reichelstein, 2021[24]; IRENA, 2020[4]).

[4] See https://www.wipo.int/classifications/nice/en

[5] Japanese companies develop fuel cells both for the transportation sector and other applications. Nissan Motor is the first Japanese patent applicant in fuel cells for the 2015-2019 period, but Sumitomo and Kyocera are respectively second and third. These two companies produce fuel cells for various applications in the energy sector, the built environment or infrastructure.

[6] https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database

[7] Hydrogen strategies have also been published in other OECD countries (e.g. Chile, Poland, Slovakia) or are under discussion (e.g. Costa Rica, Turkey).

[8] https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf

[9] https://www.mem.gov.ma/Lists/Lst_rapports/Attachments/28/Stategie%20nationale%20de%20l%20Hydrogene%20vert.pdf

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Annex A. Most important hydrogen policy documents in different countries

Table 6.1. Most important sources used in international comparison section

Countries	
Australia	National Hydrogen Strategy: https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf STIP compass: https://stip.oecd.org/stip.html Australian Hydrogen Council: https://h2council.com.au/policy-regulation/government-policies STIP Compass
Canada	National Hydrogen Strategy: https://www.nrcan.gc.ca/climate-change/the-hydrogen-strategy/23080 Article on OSLER, Federal government announces Canada's hydrogen strategy: https://www.osler.com/en/resources/regulations/2020/federal-government-announces-canada-s-hydrogen-strategy
China	Energy Iceberg article on China's Green Hydrogen Effort in 2020: Gearing Up for Commercialization: https://energyiceberg.com/china-renewable-green-hydrogen/ Review of Hydrogen Standards for China: https://www.researchgate.net/publication/336259184_Review_of_Hydrogen_Standards_for_China/fulltext/5d973df6299bf1c363f7a2f9/Review-of-Hydrogen-Standards-for-China.pdf
France	WFW: https://www.wfw.com/articles/the-french-hydrogen-strategy/ https://www.bdi.fr/wp-content/uploads/2020/03/PressKitProvisionalDraft-National-strategy-for-the-development-of-decarbonised-and-National strategy for the development of decarbonised and renewable hydrogen in France: renewable-hydrogen-in-France.pdf The French Green Hydrogen Plan 2020-2030 (presentation): https://www.tresor.economie.gouv.fr/Articles/4a1ac560-a021-4358-a466-f5430928a1db/files/7d2fd0e2-8a3d-4ce8-bbb3-94cbd5b9c3d1 Hydrogen Public Funding Compass (France): https://ec.europa.eu/docsroom/documents/45891
Germany	National Hydrogen Strategy: https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6 WFW: https://www.wfw.com/articles/the-german-hydrogen-strategy/#:~:text=The%20German%20government%20foresees%20a,to%20110%20TWh%20by%202030.&text=This%20corresponds%20to%20a%20green,by%202040%20at%20the%20latest. Hydrogen Public Funding Compass (Germany): https://ec.europa.eu/docsroom/documents/45866
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