IRENA
International Renewable Energy Agency

GREEN HYDROGEN

A GUIDE TO **POLICY MAKING**

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ABOUT IRENA

The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation, a centre of excellence, a repository of policy, technology, resource and financial knowledge, and a driver of action on the ground to advance the transformation of the global energy system. An intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

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INTRODUCTION

The world is facing the major challenge of climate change. In 2015 the global community committed to taking action to keep global temperature rise this century well below 2°C above pre-industrial levels. A growing number of countries are pledging to reach net-zero carbon dioxide (CO_2) emissions by mid-century with the goal of limiting temperature rise to 1.5°C. Achieving the deep or full decarbonisation of economies will require concerted and wide-ranging action across all economic sectors.

We have barely begun such emission reductions. It has been estimated that 8.8% less CO_2 was emitted in the first six months of 2020 than in the same period in 2019, following the COVID-19 pandemic and the consequent lockdowns (Liu *et al.*, 2020). But for continued long-term reduction, the need for structural and transformational changes in our global energy production, consumption and underlying socio-economic systems cannot be understated.

Dramatic emission reductions are both technologically feasible and economically affordable. IRENA's Global Renewables Outlook report offers a perspective for reaching net-zero emissions in the 2050-2060 timeframe. The Deeper Decarbonisation Perspective suggests possibilities for accelerated action to bring down CO_2 emissions while bringing an economic payback of between USD 1.5 and USD 5 for every USD 1 spent on the energy transition (IRENA, 2020a).

The energy transformation requires a major shift in electricity generation from fossil fuels to renewable sources like solar and wind, greater energy efficiency and the widespread electrification of energy uses from cars to heating and cooling in buildings. Still, not all sectors or industries can easily make the switch from fossil fuels to electricity. Hard-to-electrify (and therefore hard-to-abate) sectors include steel, cement, chemicals, long-haul road transport, maritime shipping and aviation (IRENA, 2020b).

Green hydrogen an provide a link between growing and sustainable renewable electricity generation and the hard-to-electrify sectors (IRENA, 2018). Hydrogen in general is a suitable energy carrier for applications remote from electricity grids or that require a high energy density, and it can serve as a feedstock for chemical reactions to produce a range of synthetic fuels and feedstocks.

Additional benefits of green hydrogen include: the potential for additional system flexibility and storage, which support further deployment of variable renewable energy (VRE); contribution to energy security; reduced air pollution; and other socio-economic benefits such as economic growth and job creation, and industrial competitiveness.

Nevertheless, green hydrogen will have to overcome several barriers to fulfil its full potential. Chief among those barriers is cost.

Overcoming the barriers and transitioning green hydrogen from a niche player to a widespread energy carrier will require dedicated policy in each of the stages of technology readiness, market penetration and market growth. **An integrated policy approach is needed to overcome the initial resistance and reach a minimum threshold for market penetration, resting on four central pillars: building national hydrogen strategies, identifying policy priorities, establishing a governance system and enabling policies, and creating a system for guarantee of origin for green hydrogen.**

ABOUT THIS GUIDE

This publication is the first of a series of briefs that aim to guide policy makers in the design and implementation of policy to support green hydrogen as one of the feasible methods of decarbonising the energy sector.

This guide is composed of three chapters. The first focuses on the status and drivers of green hydrogen and the barriers it faces. The second chapter explores the pillars of national policy making to support hydrogen, and the third presents the main policy recommendations in different segments of the green hydrogen value chain.

The forthcoming brief is due to be published and will address the supply side, covering electrolysis and infrastructure. The following briefs will first explore specific policies for different uses of green hydrogen in the hard-to-abate sectors, including industrial applications and long-haul transport (aviation, maritime shipping). Selected policy recommendations for these uses are presented here in the third chapter. Future briefs will explore niche applications for hydrogen, such as power generation and heating, and land transport.

Each of the policy briefs will present relevant case studies to highlight previous experiences and provide potential starting points for governments, exploring policies to support greater use of green hydrogen. They will also offer policy recommendations, which can be adapted and tailored for specific countries depending on their context and priorities beyond the energy system, such as economic development objectives.

Some of the necessary policy tools already exist in energy sector and only need to be expanded in scope. However, in other cases dedicated attention might be needed.

IRENA'S WORK ON **GREEN HYDROGEN** AND HARD TO ABATE SECTORS.

This report is part of IRENA's ongoing programme of work to provide its members countries and the wider community with expert analytical insights into the potential options, enabling conditions and policies that could deliver the deep decarbonisation of economies.

IRENA's annual Global Renewable Outlook provides detailed global and regional roadmaps for emission reductions alongside assessment of the socioeconomic implications. The 2020 edition includes Deep Decarbonisation Perspectives detailing options for achieving net-zero or zero emissions.

The 2021 edition will include further detailed analysis of a pathway consistent with a 1.5-degree goal.

Building on its technical and socio-economic assessment IRENA is analysing specific facets of that pathway including the policy and financial frameworks needed. One particular focus is on the potential of green hydrogen.

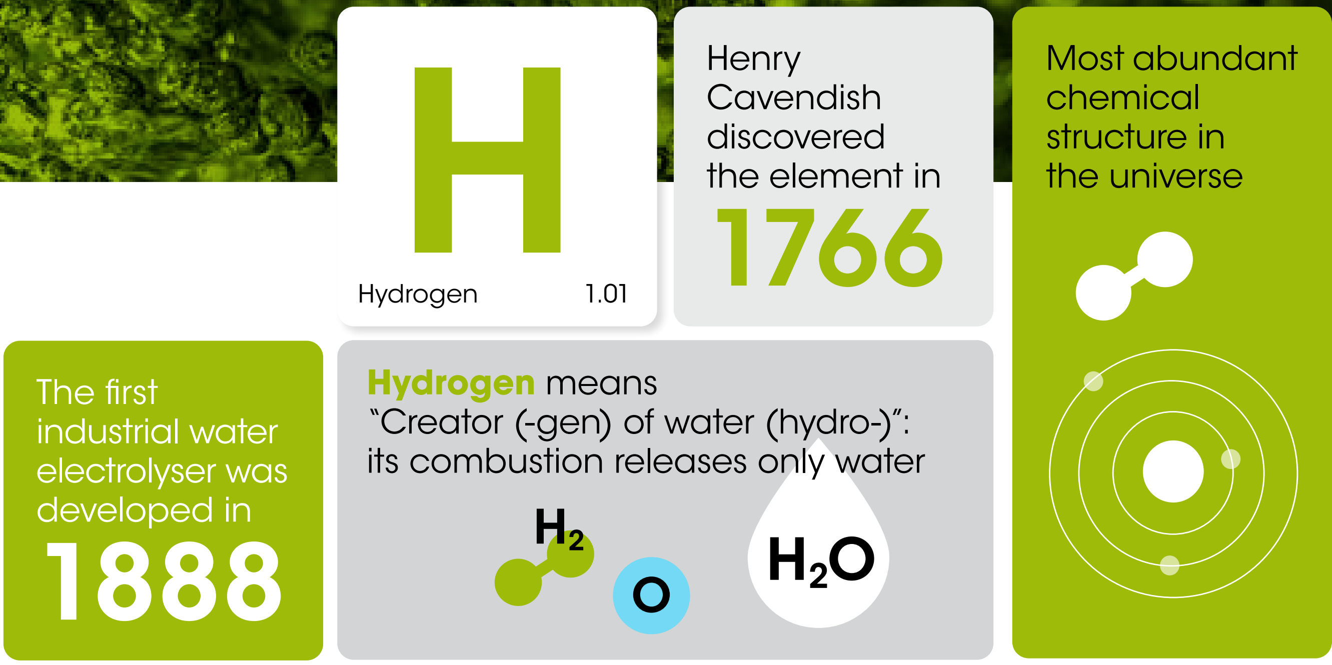
Recent and upcoming publications include:

- "Hydrogen: A renewable energy perspective" (2019);
- "Reaching zero with renewables" (2020) and its supporting briefs on industry and transport;
- "Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5°C climate goal" (forthcoming);
- "Renewable energy policies in a time of transition: Heating and cooling" (forthcoming)
- and the subsequent briefs to this report.

These reports complement IRENA's work on renewables-based electrification, biofuels and synthetic fuels and all the options for specific hard-to-abate sectors

This analytical work is supported by IRENA's initiatives to convene experts and stakeholders, including IRENA Innovation Weeks, IRENA Policy Days and Policy Talks, and the IRENA Collaborative Platform on Green Hydrogen. These bring together a broad range of member countries and other stakeholders to exchange knowledge and experience.

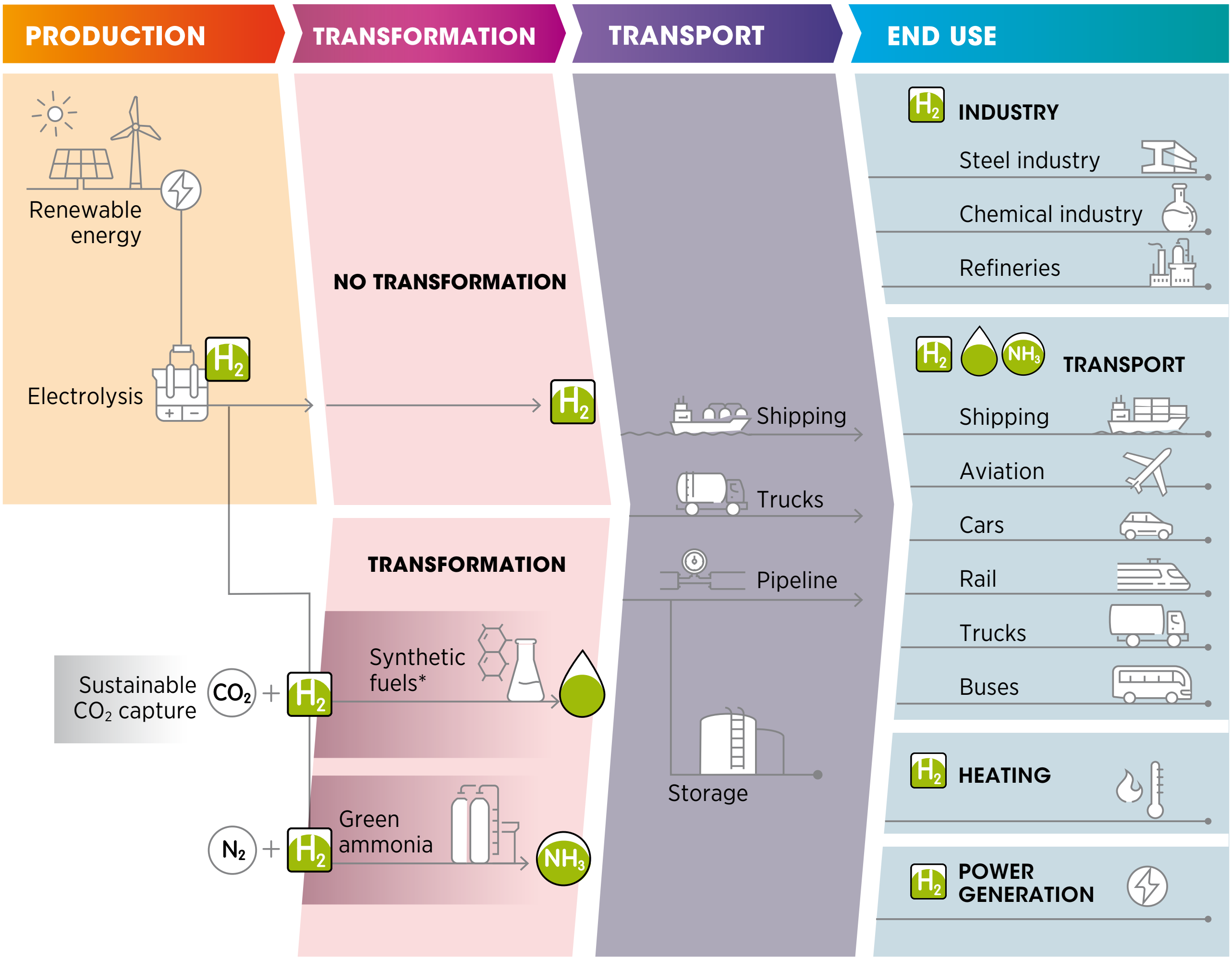
1 GREEN HYDROGEN: STATUS, DRIVERS AND BARRIERS



Green hydrogen is an energy carrier that can be used in many different applications (Figure 1.1). However, its actual use is still very limited. Each year around 120 million tonnes of hydrogen are produced globally, of which two-thirds are pure hydrogen and one-third is in a mixture with other gases (IRENA, 2019a). Hydrogen output is mostly used for crude oil refining and for ammonia and methanol synthesis, which together represent almost 75% of the combined pure and mixed hydrogen demand.

Today's hydrogen production is mostly based on natural gas and coal, which together account for 95% of production. Electrolysis produces around 5% of global hydrogen, as a by-product from chlorine production. Currently, there is no significant hydrogen production from renewable sources: green hydrogen has been limited to demonstration projects (IRENA, 2019a).

FIGURE 1.1 Green hydrogen production, conversion and end uses across the energy system



Source: IRENA.

* *The term synthetic fuels refers here to a range of hydrogen-based fuels produced through chemical processes with a carbon source (CO and CO_2 captured from emission streams, biogenic sources or directly from the air). They include methanol, jet fuels, methane and other hydrocarbons. The main advantage of these fuels is that they can be used to replace their fossil fuel-based counterparts and in many cases be used as direct replacements – that is, as drop-in fuels. Synthetic fuels produce carbon emissions when combusted, but if their production process consumes the same amount of CO_2, in principle it allows them to have net-zero carbon emissions.*

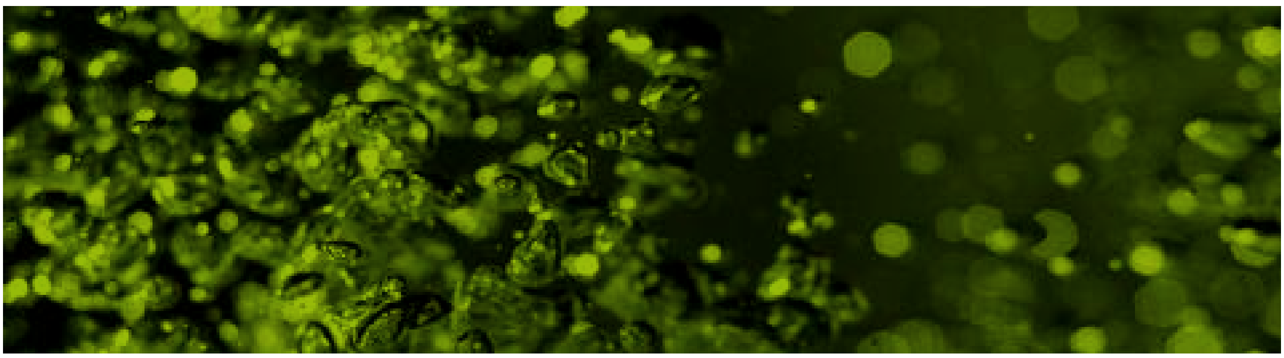
1.1. DIFFERENT **SHADES** OF HYDROGEN

Hydrogen can be produced with multiple processes and energy sources; a colour code nomenclature is becoming commonly used to facilitate discussion (Figure 1.2). But policy makers should design policy using an objective measure of impact based on life-cycle greenhouse gas (GHG) emissions, especially since there might be cases that do not fully fall under one colour (*e.g.* mixed hydrogen sources, electrolysis with grid electricity) (see Section 2.3).

FIGURE 1.2 Selected shades of hydrogen

Color	GREY HYDROGEN	BLUE HYDROGEN	TURQUOISE HYDROGEN*	GREEN HYDROGEN
Process	SMR or gasification	SMR or gasification with carbon capture (85-95%)	Pyrolysis	Electrolysis
Source	Methane or coal	Methane or coal	Methane	Renewable electricity

Note: SMR = steam methane reforming.
** Turquoise hydrogen is an emerging decarbonisation option.*



GREY HYDROGEN

GREY HYDROGEN[1] is produced with fossil fuels (i.e. hydrogen produced from methane using steam methane reforming (SMR) or coal gasification). The use of grey hydrogen entails substantial CO_2 emissions, which makes these hydrogen technologies unsuitable for a route toward net-zero emissions.

BLUE HYDROGEN

During early stages of the energy transition, the use of **BLUE HYDROGEN** (i.e. grey hydrogen with carbon capture and storage [CCS]) could facilitate the growth of a hydrogen market. Around three-quarters of hydrogen is currently produced from natural gas. Retrofitting with CCS would allow the continued use of existing assets while still achieving lower GHG emissions. This is an option is to produce hydrogen with lower GHG emissions while reducing pressure on the renewable energy capacity installation rate to produce green hydrogen. Notably, industrial processes like steel production may require a continuous flow of hydrogen; blue hydrogen could be an initial solution while green hydrogen ramps up production and storage capacity to meet the continuous flow requirement.

However, blue hydrogen has limitations that have so far restricted its deployment: it uses finite resources, is exposed to fossil fuel price fluctuations, and does not support the goals of energy security. Moreover, blue hydrogen faces social acceptance issues, as it is associated with additional costs for CO_2 transport and storage and requires monitoring of stored CO_2. In addition, CCS capture efficiencies are expected to reach 85-95% at best,[2] which means that 5-15% of the CO_2 will still be emitted. And these high capture rates have yet to be achieved.

In sum, the carbon emissions from hydrogen generation could be reduced by CCS but not eliminated. Moreover, these processes use methane, which brings leakages upstream, and methane is a much more potent GHG per molecule than CO_2. This means that while blue hydrogen could reduce CO_2 emissions, it does not meet the requirements of a net-zero future. For these reasons, blue hydrogen should be seen only as a short-term transition to facilitate the uptake of green hydrogen on the path to net-zero emissions.

TURQUOISE HYDROGEN

TURQUOISE HYDROGEN combines the use of natural gas as feedstock with no CO_2 production. Through the process of pyrolysis, the carbon in the methane becomes solid carbon black. A market for carbon black already exists, which provides an additional revenue stream. Carbon black can be more easily stored than gaseous CO_2. At the moment, turquoise hydrogen is still at the pilot stage. (Philibert, 2020; Monolith, 2020).

GREEN HYDROGEN

Among the different shades of hydrogen, **GREEN HYDROGEN** – meaning hydrogen produced from renewable energy – is the most suitable one for a fully sustainable energy transition. The most established technology options for producing green hydrogen is water electrolysis fuelled by renewable electricity. This technology is the focus of this report. Other renewables-based solutions to produce hydrogen exist.[3] However, except for SMR with biogases, these are not mature technologies at commercial scale yet (IRENA, 2018). Green hydrogen production through electrolysis is consistent with the net-zero route, allows the exploitation of synergies from sector coupling, thus decreasing technology costs and providing flexibility to the power system. Low VRE costs and technological improvement are decreasing the cost of production of green hydrogen. For these reasons, green hydrogen from water electrolysis has been gaining increased interest.

1 Sometimes referred to as black or brown hydrogen.

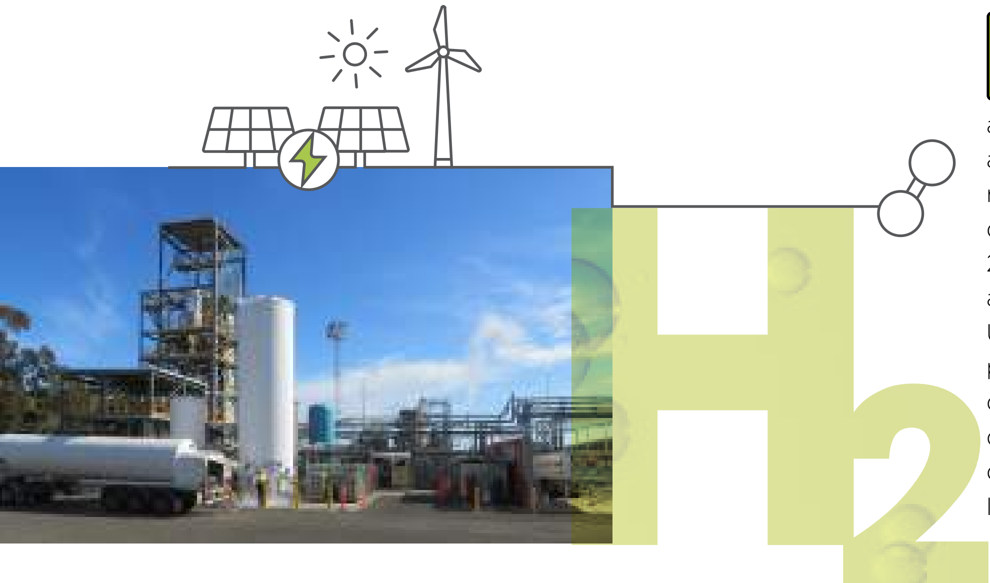
2 An alternative route to SMR could be a process called autothermal reforming, for which it is estimated that a possible capture rate up to 94.5% of the CO_2 emitted is possible (H-Vision, 2019).

3 For example, biomass gasification and pyrolysis, thermochemical water splitting, photocatalysis, supercritical water gasification of biomass, combined dark fermentation and anaerobic digestion.

1.2. DRIVERS OF THE NEW WAVE OF GREEN HYDROGEN

There have been several waves of interest in hydrogen in the past. These were mostly driven by oil price shocks, concerns about peak oil demand or air pollution, and research on alternative fuels. Hydrogen can contribute to energy security by providing another energy carrier with different supply chains, producers and markets; this can diversify the energy mix and improve the resilience of the system. Hydrogen can also reduce air pollution when used in fuel cells, with no emissions other than water. It can promote economic growth and job creation given the large investment needed to develop it as an energy carrier from an industrial feedstock.

As a result, more and more energy scenarios are giving green hydrogen a prominent role, albeit with significantly different volumes of penetration (see Box 1.1). The new wave of interest is focused on delivering low-carbon solutions and additional benefits that only green hydrogen can provide. The drivers for green hydrogen include:



1. Low variable renewable energy (VRE) electricity costs. The major cost driver for green hydrogen is the cost of electricity. The price of electricity procured from solar PV and onshore wind plants has decreased substantially in the last decade. In 2018, solar energy was contracted at a global average price of 56 USD/MWh, compared with 250 in 2018. Onshore wind prices also fell during that period, from 75 USD/MWh in 2010 to 48 in 2018 (IRENA, 2019b). New record-low prices were marked in 2019 and 2020 around the world: solar PV was contracted at USD 13.12/MWh in Portugal (Morais, 2020) and USD 13.5/MWh in the United Arab Emirates (Abu Dhabi) (Shumkov, 2020); onshore wind was contracted at USD 21.3/MWh in Saudi Arabia (Masdar, 2019) while in Brazil, prices ranged between USD 20.5 and 21.5/MWh (BNEF, 2019). With the continuously decreasing costs of solar photovoltaic and wind electricity, the production of green hydrogen is increasingly economically attractive.

2. Technologies ready to scale up. Many of the components in the hydrogen value chain have already been deployed on a small scale and are ready for commercialisation, now requiring investment to scale up. The capital cost of electrolysis has fallen by 60% since 2010 (Hydrogen Council, 2020), resulting in a decrease of hydrogen cost from a range of USD 10-15/kg to as low as USD 4-6/kg in that period. Many strategies exist to bring down costs further and support a wider adoption of hydrogen (IRENA, forthcoming). The cost of fuel cells[4] for vehicles has decreased by at least 70% since 2006 (US DOE, 2017).

4 Fuel cells use the same principles as an electrolyser, but in the opposite direction, for converting hydrogen and oxygen into water in a process that produces electricity. Fuel cells can be used for stationary applications (*e.g.* centralised power generation) or distributed applications (*e.g.* fuel cell electric vehicles). Fuel cells can also convert other reactants, such as hydrocarbons, ethers or alcohols.

While some technologies have not been demonstrated at scale yet (such as ammonia-fuelled ships) (IRENA, 2020b), scaling up green hydrogen could make those pathways more attractive as production costs decrease.

3. **Benefits for the power system.** As the share of VRE rapidly increases in various markets around the world, the power system will need more flexibility. The electrolysers used to produce green hydrogen can be designed as flexible resources that can quickly ramp up or down to compensate for fluctuations in VRE production, by reacting to electricity prices (Eichman, Harrison and Peters, 2014). Green hydrogen can be stored for long periods, and can be used in periods when VRE is not available for power generation with stationary fuel cells or hydrogen-ready gas turbines. Flexible resources can reduce VRE curtailment, stabilise wholesale market prices and reduce the hours with zero or below zero electricity prices (or negative price), which increases the investment recovery for renewable generators and facilitates their expansion. Finally, hydrogen is suitable for long-term, seasonal energy storage, complementing pumped-storage hydropower plants. Green hydrogen thus supports the integration of higher shares of VRE into the grid, increasing system efficiency and cost-effectiveness.

4. **Government objectives for net-zero energy systems.** By mid-2020, seven countries had already adopted net-zero GHG emission targets in legislation, and 15 others had proposed similar legislation or policy documents. In total, more than 120 countries have announced net-zero emissions goals (WEF, 2020). Among them is the People's Republic of China (hereafter "China"), the largest GHG emitter, which recently pledged to cut its net carbon emissions to zero within 40 years. While these net-zero commitments have still to be transformed into practical actions, they will require cutting emissions in the "hard-to-abate" sectors where green hydrogen can play an important role.

5. **Broader use of hydrogen.** Previous waves of interest in hydrogen were focused mainly on expanding its use in fuel cell electric vehicles (FCEVs). In contrast, the new interest covers many possible green hydrogen uses across the entire economy, including the additional conversion of hydrogen to other energy carriers and products, such as ammonia, methanol and synthetic liquids. These uses can increase the future demand for hydrogen and can take advantage of possible synergies to decrease costs in the green hydrogen value chain. Green hydrogen can, in fact, improve industrial competitiveness, not only for the countries that establish technology leadership in its deployment, but also by providing an opportunity for existing industries to have a role in a low-carbon future. Countries with large renewable resources could derive major economic benefits by becoming net exporters of green hydrogen in a global green hydrogen economy.

6. **Interest of multiple stakeholders.** As a result of all the above points, interest in hydrogen is now widespread in both public and private institutions. These include energy utilities, steel makers, chemical companies, port authorities, car and aircraft manufacturers, shipowners and airlines, multiple jurisdictions and countries aiming to use their renewable resources for export or to use hydrogen to improve their own energy security. These many players have also created partnerships and ongoing initiatives to foster collaboration and co ordination of efforts.[6]

However, green hydrogen still faces barriers.

5 System flexibility is here defined as the ability of the power system to match generation and demand at any timescale.

6 The Hydrogen Council is an example of a private initiative. Launched in 2017, it has 92 member companies (by October 2020). The Hydrogen Initiative under the Clean Energy Ministerial is an example of a public initiative, where nine countries and the European Union are collaborating to advance hydrogen. The Fuel Cell and Hydrogen Joint Undertaking is an example of private-public partnership in the European Union.

Box 1.1 Roles for green hydrogen in different energy transition scenarios

The role given to green hydrogen in existing regional and global energy transition scenarios differs greatly due to a number of factors.

First, not all scenarios aim for the same GHG reduction target. The more ambitious the GHG reduction target, the greater is the amount of green hydrogen expected in the system. For low levels of decarbonisation, renewable power and electrification might be enough. But with deeper decarbonisation targets, green hydrogen would play a larger role in the future energy mix.

Second, not all scenarios rely on the same set of enabling policies. The removal of fossil fuel subsidies, for example, would increase the space for carbon-free solutions.

Third, the technology options available vary between scenarios. Scenarios that give greater weight to the social, political and sustainability challenges of nuclear, carbon capture, use and storage, and bioenergy anticipate limited contributions from those technologies to the energy transition, and thus require greater green hydrogen use.

Fourth, the more end uses for green hydrogen included in a scenario, the higher the hydrogen use will be. Scenarios that cover all hydrogen applications and downstream conversion to other energy carriers and products provide more flexibility in ways to achieve decarbonisation. More hydrogen pathways also help create larger economies of scale and faster deployment, leading to a virtuous circle of increasing both demand and supply.

Finally, cost assumptions, typically input data including capital and operating costs (Quarton et al., 2019) differ between scenarios. Those with the highest ambitions for hydrogen deployment are those with the most optimistic assumptions for cost reduction.

For all these reasons, the role of green hydrogen varies widely between scenarios. However, as more and more scenarios are being developed to reach zero or net-zero emissions, green hydrogen is more prominently present in scenarios and public discourse.

1.3. **BARRIERS** TO THE UPTAKE OF GREEN HYDROGEN

Green hydrogen faces barriers that prevent its full contribution to the energy transformation. Barriers include those that apply to all shades of hydrogen, such as the lack of dedicated infrastructure (*e.g.* transport and storage infrastructure), and those mainly related to the production stage of electrolysis, faced only by green hydrogen (*e.g.* energy losses, lack of value recognition, challenges ensuring sustainability and high production costs).

1. **HIGH PRODUCTION COSTS** Green hydrogen produced using electricity from an average VRE plant in 2019 would be two to three times more expensive than grey hydrogen (see Box 1.2). In addition, adopting green hydrogen technologies for end uses can be expensive. Vehicles with fuel cells and hydrogen tanks cost at least 1.5 to 2 times more than their fossil fuel counterparts (NREL, 2020). Similarly, synthetic fuels for aviation are today, even at the best sites in the world, up to eight times more expensive than fossil jet fuel (IRENA, 2019a). Box 1.2 provides examples of the production and transport costs of green hydrogen.

2. **LACK OF DEDICATED INFRASTRUCTURE.** Hydrogen has to date been produced close to where it is used, with limited dedicated transport infrastructure. There are only about 5 000 kilometres (km) of hydrogen transmission pipelines around the world (Hydrogen Analysis Resource Center, 2016), compared with more than 3 million km for natural gas. There are 470 hydrogen refuelling stations around the world (AFC TCP, 2020), compared with more than 200 000 gasoline and diesel refuelling stations in the United States and the European Union. Natural gas infrastructure could be repurposed for hydrogen (IRENA, IEA and REN21, forthcoming), but not all regions of the world have existing infrastructure. Conversely, synthetic fuels made from green hydrogen may be able to use existing infrastructure, though it might need to be expanded.

3. **ENERGY LOSSES.** Green hydrogen incurs significant energy losses at each stage of the value chain. About 30-35% of the energy used to produce hydrogen through electrolysis is lost (IRENA, forthcoming). In addition, the conversion of hydrogen to other carriers (such as ammonia) can result in 13-25% energy loss, and transporting hydrogen requires additional energy inputs, which are typically equivalent to 10-12% of the energy of the hydrogen itself (BNEF, 2020; Staffell *et al.*, 2018; Ikäheimo *et al.*, 2017). Using hydrogen in fuel cells can lead to an additional 40–50% energy loss. The total energy loss will depend on the final use of hydrogen. The higher the energy losses, the more renewable electricity capacity is needed to produce green hydrogen.

   The key issue, however, is not the total capacity needed, since global renewable potential is in orders of magnitude higher than the hydrogen demand, and green hydrogen developers are likely to first select areas with abundant renewable energy resources. The key issue is whether the annual pace of development of the solar and wind potential will be fast enough to meet the needs for both the electrification of end-uses and the development of a global supply chain in green hydrogen, and the cost that this additional capacity will entail.

4. **LACK OF VALUE RECOGNITION.** There is no green hydrogen market, no green steel, no green shipping fuel and basically no valuation of the lower GHG emissions that green hydrogen can deliver. Hydrogen is not even counted in official energy statistics of total final energy consumption, and there are no internationally recognised ways of differentiating green from grey hydrogen. At the same time, the lack of targets or incentives to promote the use of green products inhibits many of the possible downstream uses for green hydrogen. This limits the demand for green hydrogen.

5. **NEED TO ENSURE SUSTAINABILITY.** Electricity can be supplied from a renewable energy plant directly connected to the electrolyser, from the grid, or from a mix of the two. Using only electricity from a renewable energy plant ensures that the hydrogen is "green" in any given moment. Grid-connected electrolysers can produce for more hours, reducing the cost of hydrogen. However, grid electricity may include electricity produced from fossil fuel plants, so any CO_2 emissions associated with that electricity will have to be considered when evaluating the sustainability of hydrogen. As a result, for producers of hydrogen from electrolysis, the amount of fossil fuel-generated electricity can become a barrier, in particular if the relative carbon emissions are measured based on national emission factors. Box 1.3 discusses how to ensure that grid-connected electrolysers deliver hydrogen with minimum emissions.

Box 1.2 Key cost components for green hydrogen

Green hydrogen competes both with fossil fuels and with other shades of hydrogen. It is important, therefore, to understand the factors that determine the cost of green hydrogen.

The production cost of green hydrogen depends on the investment cost of the electrolysers, their capacity factor,[7] which is a measure of how much the electrolyser is actually used, and the cost of electricity produced from renewable energy.

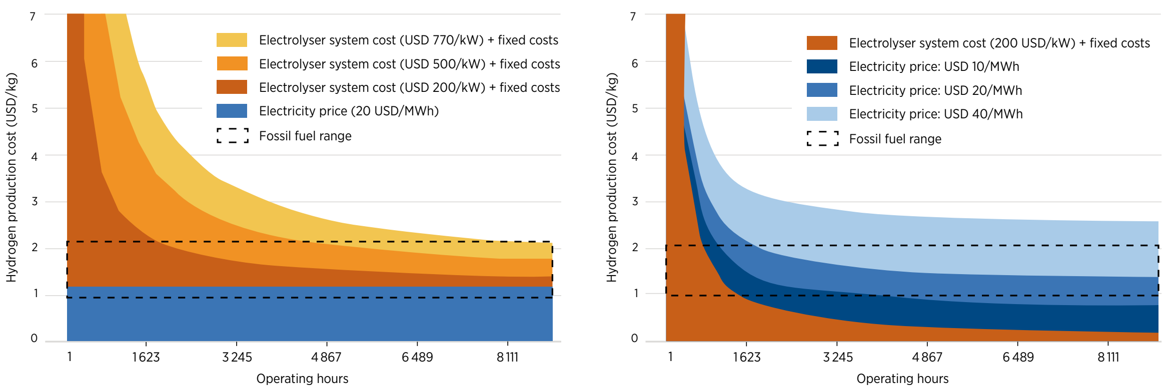
By 2020, the investment cost for an alkaline electrolyser is about USD 750-800 per kilowatt (kW). If the capacity factor of the green hydrogen facility is low, such as below 10% (fewer than 876 full load hours per year), those investment costs are distributed among few units of hydrogen, translating into hydrogen costs of USD 5-6/kg or higher, even when the electrolyser is operating with zero-priced electricity. In comparison, the cost of grey hydrogen is about USD 1-2/kg of hydrogen (considering a price range of natural gas of around USD 1.9 – 5.5 per gigajoule [GJ]). If load factors are higher, however, investment costs make a smaller contribution to the per-kg green hydrogen cost. Therefore, as the facility load factor increases, the electrolyser investment cost contribution to the final hydrogen production cost per kg drops and the electricity price becomes a more relevant cost component.

At a given price of electricity, the electricity component in hydrogen's final cost depends on the efficiency of the process. For example, with an electrolyser efficiency of 0.65 and electricity price of USD 20 per megawatt hour (MWh), the electricity component of the total cost would go up to USD 30/MWh of hydrogen, equivalent to USD 1/kg.[8]

Given today's relatively high electrolyser costs, low-cost electricity is needed (in the order of USD 20/MWh) to produce green hydrogen at prices comparable with grey hydrogen (see Figure 1.3). The objective of green hydrogen producers is now to reduce these costs, using different strategies (IRENA, forthcoming). Once electrolysers costs have fallen, it will be possible to use higher-cost renewable electricity to produce cost-competitive green hydrogen.

Transporting hydrogen generates additional costs. Transport costs are a function of the volume transported, the distance and the energy carrier. At low volumes, the cost of transporting compressed hydrogen 1 000 km in a truck is around USD 3.5/kg. For large volumes, shipping green ammonia is the lowest-cost option and adds only USD 0.15/kg of hydrogen (without considering conversion costs, i.e. cracking). Similar low costs can be achieved using large pipelines (around 2 000 tonnes per day) over short distances (BNEF, 2020). Hydrogen transport by pipeline can be one-tenth of the cost of transporting the same energy as electricity (Vermeulen, 2017).

FIGURE 1.3 Hydrogen production cost depending on electrolyser system cost, electricity price and operating hours



Notes: Efficiency = 65% (lower heating value). Fixed operational cost = 3% of the capital costs. Lifetime = 20 years. Interest rate = 8.0%. Fossil fuel range: grey hydrogen, considering fuel costs of USD 1.9–5.5/GJ for coal and natural gas.

Source: IRENA, forthcoming.

7 The capacity factor can span between 0 and 100% and represents the average full load hours of use of the electrolyser as a percentage of the total number of hours in a year (8 760). For example, a capacity factor of 50% indicates an average use of 4 380 hours.

8 1 kg of hydrogen contains around 33.33 kilowatt hours (kWh).

Box 1.3 Hydrogen emissions from grid-powered electrolysis

For hydrogen from electrolysis to have lower overall emissions than grey hydrogen, CO_2 emissions per unit of electricity need to be lower than 190 grams of CO_2 per kilowatt hour (gCO_2/kWh) (Reiter and Lindorfer, 2015). Only a few countries (mostly benefiting from hydropower) have average CO_2 emissions per kWh below that threshold and thus can ensure the sustainability of electrolytic hydrogen. Most other countries are currently above that threshold.

However, electrolysers can be designed to be flexible demand-side resources and can be ramped down or turned off when the national power mix is above a certain threshold of CO_2 emissions, if tracked, and then turned back on when renewable production is higher, and in particular when VRE production would otherwise be curtailed. In general, low electricity prices are a proxy for high renewable energy production (IRENA, 2020c), so electricity prices may be naturally the signal for electrolyser activities. Moreover, when electricity prices are too high to produce competitive hydrogen, the electrolyser would shut down anyway. The significant (for some countries) and increasing renewable energy share of electricity production will also decrease the carbon footprint of electrolytic hydrogen production.

A hybrid model can also be used, where off-grid VRE generation is the main source of electricity, but grid electricity can top up production to decrease the impact of initial investment costs while causing only a small increase in the carbon footprint of the electrolysis plant.

Power purchase agreements with grid-connected VRE plants may also ensure the sustainability of electricity consumption and at the same time make green hydrogen an additional driver for the decarbonisation of the power grid.

1.4. POLICIES TO SUPPORT GREEN HYDROGEN

Historically, every part of the energy system has enjoyed some form of policy support. This has been and is still true for fossil fuels (which are supported with both direct and indirect subsidies) and for renewable energy sources, across all sectors – power, heating and cooling, and transport (IRENA, IEA and REN21, 2018). The hydrogen sector has also received some attention from policy makers with dedicated policies. But more dedicated policy support is needed at each stage of technology readiness, market penetration and market growth.

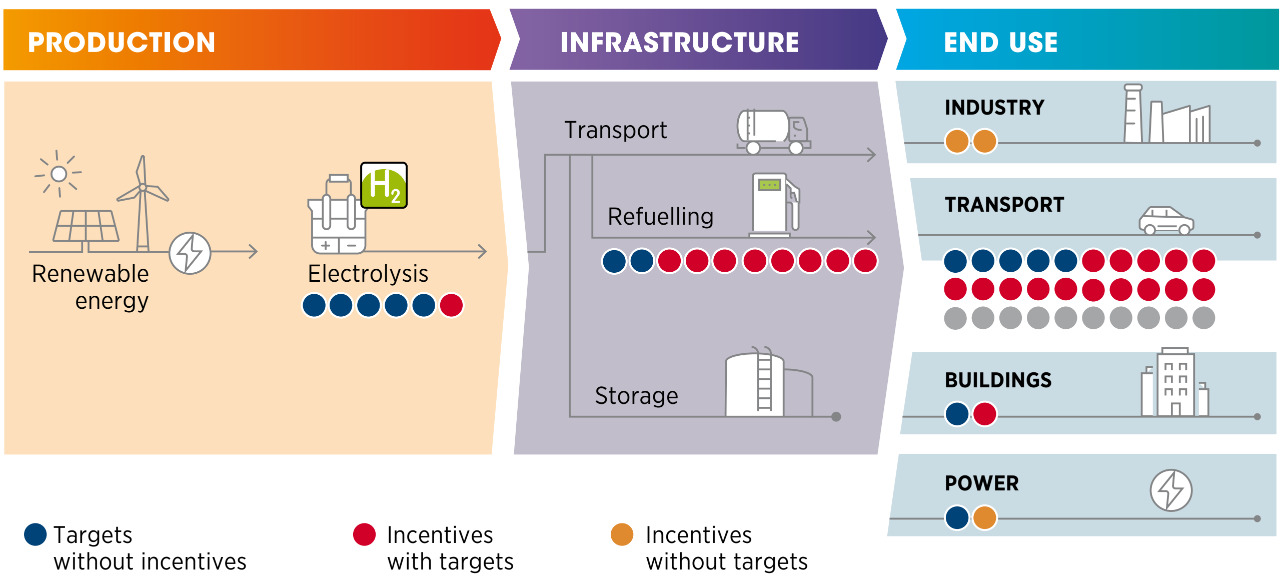
Status of policy support for green hydrogen

By 2019, hydrogen was being promoted in at least 15 countries and the European Union with supporting policies (other than standardisation processes or national strategies).[9] These policies directly or indirectly promoted hydrogen use across various end uses. However, due to previous focus on land transport uses for hydrogen, about two-thirds of the policies targeted the transport sector (Figure 1.4).

Most countries include FCEVs with battery electric vehicles in their zero-emission vehicle policies. This gives FCEVs the opportunity to benefit from incentives given to zero-emission vehicles in general, without the need for policies that specifically promote hydrogen use.

The past two years, however, represented a game-changing moment for green hydrogen policies, with interest rising around the world. Many countries (including Austria, Australia, Canada, Chile, France, Germany, Italy, Morocco, the Netherlands, Norway, Portugal and Spain, along with the European Union) announced, drafted or published national hydrogen strategies and post-COVID-19 recovery packages that included support measures for clean hydrogen.

FIGURE 1.4 Number of hydrogen policies at a global level by segment of the value chain



Source: IRENA analysis based on IEA (2019)

9 Belgium, Canada, China, France, Germany, Iceland, Italy, Japan, the Netherlands, Norway, New Zealand, Republic of Korea, Spain, United Kingdom and United States.

The change is not just quantitative (with pledges in the order of the billions of USD), but also qualitative: the emphasis of these new strategies has shifted to industry and product differentiation and future competitiveness, away from the previous focus on hydrogen use in transport.

Indeed, hydrogen can cater for a wide range of uses, as shown in Figure 1.1. It is important to prioritise the sectors where its use can add the most value to avoid diluting efforts or putting hydrogen in competition with more immediate decarbonisation solutions, such as battery electric vehicles. When green hydrogen has achieved higher shares of final energy consumption, policy priorities should expand and evolve (see Section 2.2).

The stages of green hydrogen policy support

As the penetration of green hydrogen technologies increases and costs come down, policies will have to evolve accordingly. The briefs following this report use the concept of **policy stages** to reflect the evolution of policy needs with the increased deployment of green hydrogen. Here are the three basic stages and the overall milestones for each:

STAGE 1

First stage: Technology readiness. At this stage, green hydrogen is a niche technology with little use except in demonstration projects; it is mostly produced on-site with limited infrastructure development. The largest barrier to greater use is cost. The main role of policy makers is to encourage and accelerate further deployment of electrolysers. This can be done in part through long-term signals, such as a commitment to net-zero emissions, which offer certainty to the private sector and improve the business case for green hydrogen.

As important, however, are shorter-term policies that help to close the investment and operational cost gaps. These include research and development (R&D) funding, risk mitigation policies and co-funding of large prototypes and demonstration projects to decrease the cost of capital. In addition, end uses still at the demonstration stage may need dedicated mission-driven innovation programmes with clear timelines and collaboration with the private sector to accelerate their commercialisation. Supportive governance systems and guidelines should also be put in place at this stage, ensuring that the growth of green hydrogen is sustainable.

STAGE 2

Second stage: Market penetration. At this stage, some applications are operational and able to prove what green hydrogen can do and at what cost. Scaling up these technologies and developing experience through learning-by-doing reduces costs and helps close the profitability gap. This stage also begins to see benefits from synergies between applications, increasing hydrogen demand and realising economies of scale for production and infrastructure. These synergies can take place in industrial clusters, hydrogen valleys (*e.g.* cities) or hubs (*e.g.* ports).

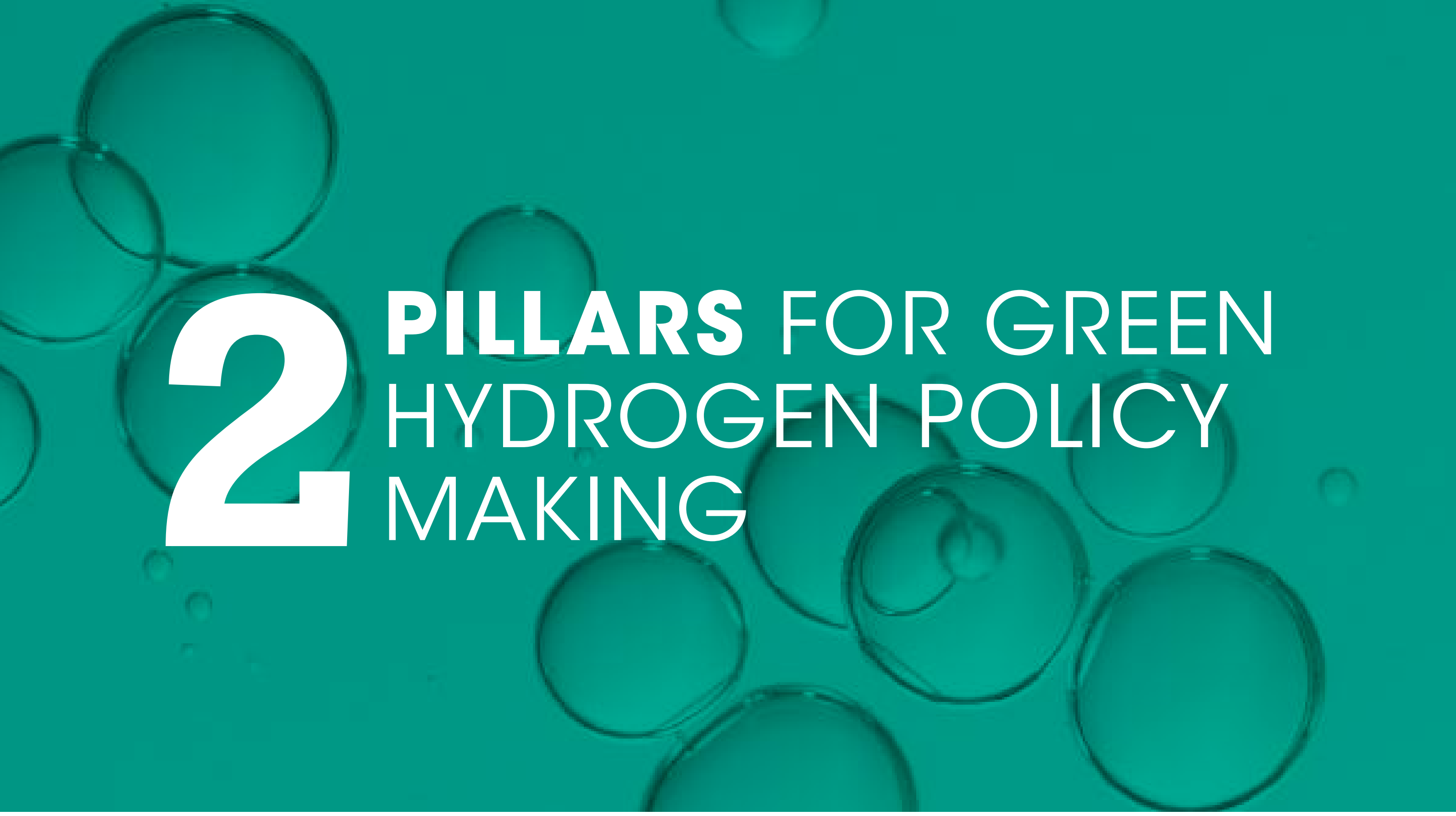
Industrial users can drive the development of dedicated "green hydrogen corridors" that connect regions generating low-cost renewable energy with demand centres. Most of this infrastructure is not developed from scratch, but is repurposed from existing natural gas networks and power grids. The first international trading routes for hydrogen (or its derived products) are established at this stage, and the existence of multiple producers and users leads to the creation of a real global market for hydrogen. As the use of green hydrogen grows, it becomes necessary to ensure that sufficient renewable electricity generating capacity is available, so that green hydrogen production does not displace more efficient direct electrification.

STAGE 3

Third stage: Market growth. At this stage, green hydrogen becomes a well-known and widely used energy carrier and is close to reaching its full potential. It has become competitive both on the supply side and in its end uses. Direct incentives are no longer needed for most applications and private capital has replaced public support in driving hydrogen growth. There is full flexibility in converting hydrogen to other energy carriers, making it possible to use the most convenient alternative depending on the specific conditions in each region. The power system has been decarbonised and only green hydrogen is being deployed. Most natural gas infrastructure has been repurposed to transport pure hydrogen.

Currently, green hydrogen is at the first stage for most sectors. Some regions may be more advanced in specific sectors or uses, while still being immature in others. For instance, California is ahead in FCEV deployment, but has no large-scale electrolysis industry, while Germany has focused on converting natural gas infrastructure to hydrogen. These cases illustrate how progress will be mixed in individual countries and that each country should not necessarily focus at the onset on all end uses of green hydrogen.

The stage approach described here provides the background for the policy pillars discussed in the second chapter.



2 PILLARS FOR GREEN HYDROGEN POLICY MAKING

Transitioning green hydrogen from a niche player to a widespread energy carrier will require an integrated policy approach to overcome initial resistance and reach a minimum threshold for market penetration. That policy approach should have four central pillars: national hydrogen strategies, policy priority setting, guarantees of origin, and enabling policies.

In addition to the four pillars presented in this chapter, successful hydrogen policy making should include the same elements that have been necessary to assist the deployment of renewable energy solutions in the power sector. These inlude, for example, long-term commitments. Long-term signals are essential for private and institutional investors to take the risk of investing in a novel technology, and this is particularly true for green hydrogen. The large levels of investment that are required mean that, in general, public capital alone is not enough to move hydrogen from niche to mainstream.

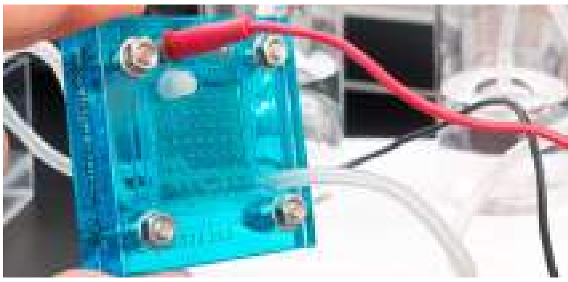
Long-term commitment from government is necessary to make available the private capital required for the transition to green hydrogen.

International collaboration on energy has been beneficial for countries in many ways, as demonstrated in the R&D and aligning of national agendas to accelerate the energy transition. Collaboration on the deployment of hydrogen-related solutions (e.g. upgrade of the gas grid in a cluster of countries) allows the sharing of risks, lessons learned and best practices, which translates into lower costs. Collaboration on safety and standards enables countries to speak a common language and execute projects that cross borders, as well as enabling replication.

The following sections explore in greater detail the four policy pillars needed to support a green hydrogen transition.

P1 P2 P3 P4

H_2



2.1. POLICY PILLAR 1: **NATIONAL STRATEGIES**

P1

National Strategies

Recently announced hydrogen strategies result from a long process and mark the beginning of a new wave of policies. The strategy process usually starts with the establishment of **R&D programmes** to understand the fundamental principles of the technology, to develop the knowledge base that will inform future stages, and to explore multiple technologies and possibilities given that, at this early stage, the end applications are far from clear.

The next step is usually a **vision** document that clarifies the "why": "why hydrogen", "why this jurisdiction", and "why now". The vision document represents a beacon that guides research, industry efforts and early demonstration programmes. Such vision documents are often co-created by governments and private actors attracted by the growth prospects of breakthrough applications.

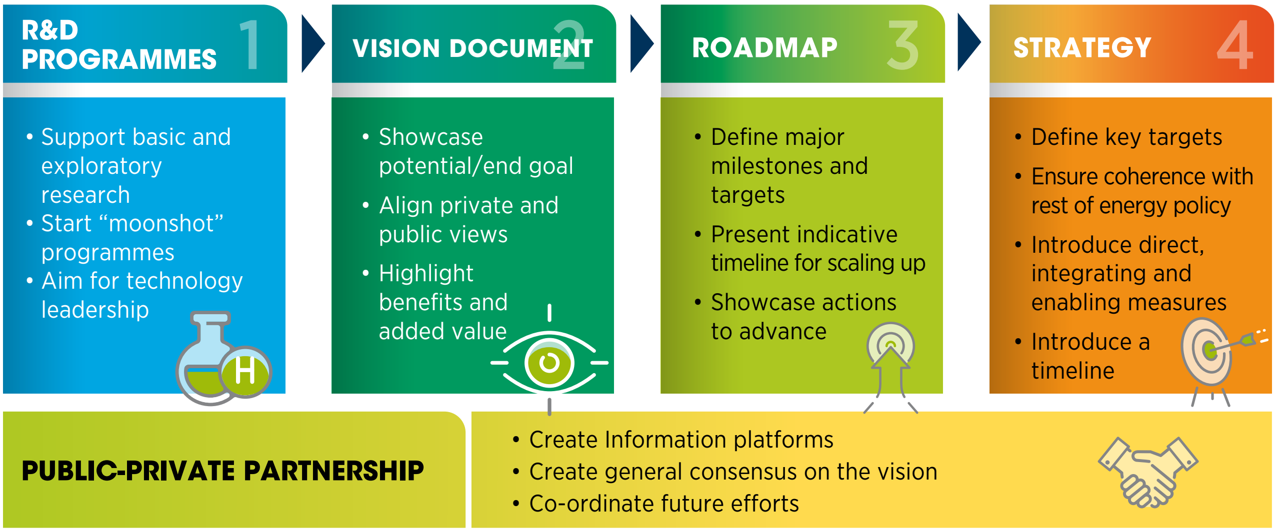
Next is a **roadmap** that goes one step further. It defines an integrated plan with the activities needed to better assess the potential for hydrogen. It identifies the short-term actions needed to advance deployment, and defines the research areas with the highest priority and the applications where demonstration projects are most needed.

Finally, the **strategy** itself defines the targets, addresses concrete policies and evaluates their coherence with existing energy policy.

The strategy covers not only specific direct policies (such as feed-in premiums for green hydrogen), but also includes integrating and enabling policies that are needed to ensure deployment across the system, such as those that support the development of a skilled workforce. The strategy is informed by extensive scenario modelling, often with input from academia and industry. It sets the level of ambition that will guide the work in subsequent stages.

Throughout the process of preparing the strategy (Figure 2.1), **public-private partnerships** are often formed. They serve as a platform to exchange information to advance technological progress, create consensus, align views, develop incentives and co-ordinate activities. Public-private partnerships can reduce the risks during early deployment, facilitating the transition from demonstration to commercialisation. They allow companies to build experience while providing the benefits of first-mover advantage in case of success. The objective should be to reach a point where no further public support is needed. This model has already been successful in mobility and in the European Union (through the Fuel Cells and Hydrogen Joint Undertaking) to demonstrate hydrogen technologies for multiple pathways.

FIGURE 2.1. Steps leading to the formulation of a national strategy



P1
National Strategies

A follow-up to the strategy is a set of analyses to assess the impact of the introduction or change of specific policies. The analyses assess the economic, social and environmental consequences of the implementation of the proposed measures in the strategy. They evaluate alternative timelines and scopes, as well as interactions with other technologies. After these analyses, the actual regulations and laws are introduced, followed by regular revisions to adjust them according to progress and latest trends.

This process from R&D to strategy is far from linear or quick. Moreover, countries can skip the public-facing steps described here and issue a national hydrogen strategy while keeping the investigation activities confidential.

Public support for R&D programmes on hydrogen was triggered by the oil crisis in the 1970s, with leading efforts from the **United States** and **Europe**. At about the same time, platforms for international collaboration were established, such as the International Journal of Hydrogen Energy (1976). Support from federal governments started in **Canada** in the early 1980s and in Japan in 1992 (Behling, Williams and Managi, 2015). The **United States** was one of the leading countries, establishing a public-private partnership in 1999 (California) and issuing a vision document and a roadmap in 2002 (US DOE, 2002).

R&D programmes are still very active and necessary today, with one of the largest recently being adopted in **China**. China is exploring solutions to use hydrogen in cities: the previous subsidies for FCEVs are being replaced by pilot demonstrations in selected cities for an initial phase of four years. A focus will be on research into and application of critical components, and support from central government will be in the form of financial awards to these cities rather than purchase subsidies for consumers.

Other countries have developed their vision or roadmap documents, with final strategies expected in the next years. For example, **New Zealand** published its vision document in 2019, which outlined the potential uses of hydrogen and explored in a non-quantitative manner some of the issues around its use. The anticipated next stage is a roadmap to identify the steps towards making the use of hydrogen possible in the wider economy.

The pace of action is accelerating. In the last two years, given the new wave of interest in hydrogen, many countries have progressed through the steps in Figure 2.1 and have issued their own national strategies (Figure 2.2). **France** first published a hydrogen strategy in 2018, which was updated in June 2020. The **European Union** established a High-Level Working Group on hydrogen in 2002 (with 19 stakeholders from the research community, industry, public authorities and end users), issuing its vision document one year later (European Commission, 2003). It established the Fuel Cell Technology Platform in 2004, which paved the way for the inception of the Fuel Cells and Hydrogen Joint Undertaking (FCH JU, 2017).

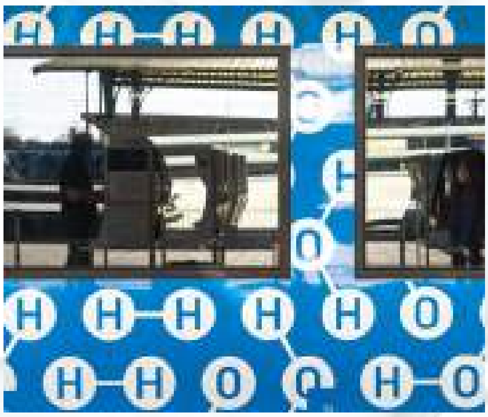
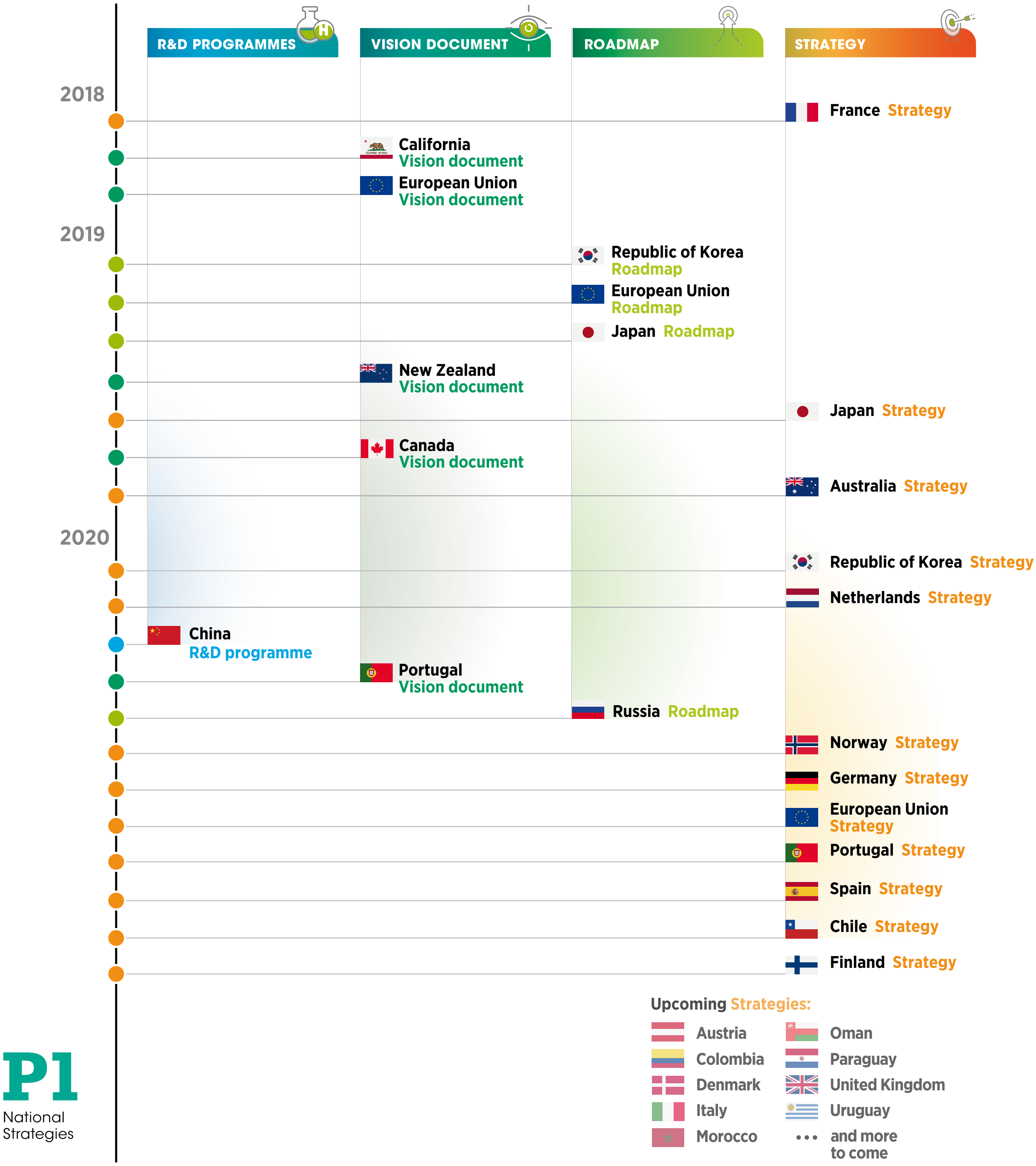


FIGURE 2.2. Government hydrogen-related initiatives announced between June 2018 and November 2020



Notes: Hydrogen policies are evolving rapidly. Information on this figure has been kept as detailed and complete as possible at the time of writing, however more countries may have announced, drafted and published vision, roadmap and strategy documents.

With the arrival of the new wave of interest, the European Union finally released its overall green hydrogen strategy (Box 2.1), with some policies scheduled for introduction in 2021.

Many countries are expected to publish their hydrogen strategies in the coming years. Progress is expected in Latin America, following the launch of Chile's national strategy, in the Arabian Peninsula and in the member states of the European Union, following the EU strategy. Austria and Italy, for example, already included hydrogen as part of their national energy and climate plans (NECPs); the aim for European countries is to achieve a co-ordinated roll-out and to ensure that the strategies fit within their overall NECPs and the European Union strategy.

Activities are also taking place at the subnational level. Roadmaps and strategies have been released by California (United States), provinces in the North of the Netherlands, and by South Australia, Western Australia, Victoria, Queensland and Tasmania, together with the Australian national strategy (COAG, 2019).

Developing the optimal zero or net-zero CO_2 emissions strategy – including the most effective green hydrogen strategy – is a challenging task. There are competing decarbonisation solutions for most applications and end uses, and the relative costs and benefits of each solution will be constantly changing according to the pace of innovation and development of each specific technology. Governments, therefore, have difficult choices to make on which technologies will be the best fit for the future of their countries, while avoiding numerous possible pitfalls, such as locking in slower or less efficient pathways to reducing emissions. For this reason, establishing policy priorities is an important component of green hydrogen policy making.

P1

National Strategies

Box 2.1 The EU hydrogen strategy

The EU strategy aims for an integrated view of the hydrogen value chain, and establishes a supporting governance system and policy framework to promote hydrogen deployment (Figure 2.3).

The ambition of EU policymakers is to make the European industry a global leader, both in green hydrogen equipment and zero-carbon heavy industry. For this reason, the strategy identifies green hydrogen as the only shade of hydrogen compatible with a net-zero emission system.

The strategy aims to create at least 6 GW of electrolyser capacity by 2024, enough to produce up to 1 Mt/yr of green hydrogen. That would increase to 40 GW in EU countries by 2030, with an additional 40 GW of electrolyser capacity in southern and eastern neighbours (e.g. Ukraine or Morocco), from which the European Union could import green hydrogen.

The strategy sets a number of actions, including not only regulatory changes indicated by impact assessments, but also supporting investments designed to kick-start deployment.

The strategy adopts a staged approach, similar to the one followed in this report:

2020

STAGE 1 (2020-2024): Scale-up electrolyser capacity to 6 GW and produce up to 1 Mt/yr of renewable hydrogen. The focus is on decarbonising applications that already use hydrogen and facilitating the uptake of green hydrogen in new end-use applications. The hydrogen supply would be mostly local to avoid the need for extensive infrastructure while planning for infrastructure expansion. Some existing hydrogen production is retrofitted with carbon capture.

2025

STAGE 2 (2025-2030): Scale-up electrolyser capacity to 40 GW in EU countries and produce up to 10 Mt/yr of renewable hydrogen. An additional 40 GW of capacity may be commissioned in neighbouring regions, via co-operation. Transporting the green hydrogen will require a pan-European grid infrastructure that could be largely based on existing natural gas infrastructure. International trade with neighbouring regions can also be developed. It is assumed that the hydrogen market will be efficient in allocation, with unhindered cross-border trade.

2030

STAGE 3 (2030-2050): Green hydrogen reaches maturity and is deployed at large scale across all hard-to-abate sectors where alternatives have a higher cost. E-fuels made from hydrogen would be used in a wide range of sectors, including aviation and shipping.

2050

Reaching the 2030 goals is estimated to require investment of EUR 24-42 billion for electrolyser capacity, in addition to EUR 220-340 billion for 80-120 GW of additional renewable power generation capacity, EUR 65 billion for infrastructure and EUR 11 billion for retrofitting existing natural gas plants.

P1 National Strategies

FIGURE 2.3. Main aspects and instruments mentioned in the EU hydrogen strategy

SUPPLY

- Use of life cycle CO_2 thresholds
- Threshold for low carbon
- Use of certification schemes
- Adoption of tenders

INFRASTRUCTURE

- Reform of gas market legislation
- Repurposing gas infrastructure
- Provide equal access to all stakeholders

DEMAND

- Revision of ETS
- Introduction of ”Carbon Contract for Difference“
- Market-based support schemes
- Quotas of green hydrogen in end uses

INVESTMENT

Important Projects of Common European Interest (IPCEI); REACT-EU; InvestEU programme; European Regional Development Fund and the Cohesion Fund

RESEARCH AND INNOVATION

Larger and more efficient electrolysers; innovative production technologies; assess the repurposing of natural gas infrastructure; environmental impact; safety and materials

INTERNATIONAL DIMENSION

Partnerships with neighbouring regions; IPHE, CEM, MI, IEA, IRENA; global trading; trade policy to avoid market distortions; Euro as benchmark for hydrogen trading

Notes: CEM = Clean Energy Ministerial; ETS = emissions trading system; IPHE = International Partnership for Hydrogen and Fuel Cells in the Economy; MI = Mission Innovation; REACT-EU = Recovery Assistance for Cohesion and the Territories of Europe.

Source: European Commission, 2020.

2.2. POLICY PILLAR 2: **ESTABLISH POLICY PRIORITIES FOR GREEN HYDROGEN**

P2

Establish Policy Priorities

Individual countries have specific conditions. As a result, national green hydrogen policy makers should carefully assess, in order to set up their policy priorities, key factors for each segment of the hydrogen value chain. These include the size of the country's renewable resources, the maturity of its energy sector, the current level of economic competitiveness and the potential socio-economic effects.

For example, a region with good renewable energy resources could use electrolysis to make green hydrogen cost-competitive, while in other cases policy makers may identify more value in importing hydrogen instead and focusing their efforts on other technologies underpinning the energy transition.

As countries develop their net-zero emission and green hydrogen strategies, it may be useful to remember three basic concepts to set up policy priorities.

1. Hydrogen is not a full substitute for fossil fuels

The first concept to be kept in mind is that, despite the great promise of green hydrogen and its suitability to replace fossil gases, it is not a complete substitute for fossil fuels. Instead, it is just one of several possible decarbonisation alternatives (Figure 2.4) that should be carefully weighed when setting priorities. Similarly, the selection of the supporting policies must take into account the relative costs and benefits of green hydrogen compared to other decarbonisation solutions for specific end uses, especially given continuing progress in competing technologies.

In many cases, direct electrification using renewable energy, along with energy efficiency, will be a faster and more cost-effective solution to decarbonising the energy system than using green hydrogen. In the transport sector, for example, the rapidly declining cost and technological improvement of batteries have made electric vehicles a very attractive solution for the decarbonisation of the sector. Use of hydrogen in FCEVs will still be possible for specific uses, for example where the electricity grid is unavailable. The two transport subsectors where fewer low-carbon alternatives to green hydrogen exist are international aviation and shipping, so it will most likely be part of a low-carbon future for these subsectors.

FIGURE 2.4. Hydrogen as a complement to alternative ways to decarbonise end uses

	RENEWABLES	DIRECT ELECTRIFICATION	ENERGY EFFICIENCY	GREEN HYDROGEN
HEATING	• Solar water heaters, direct geothermal use, biomass (low-grade heating)	• Heat pumps	• Retrofit of buildings • Technological advancement	• High-grade heating
INDUSTRY	• Solar drying, biomass (productive uses)	• Electric industrial application (e.g. arc furnaces)	• Use of best available technologies	• Steelmaking refineries • Chemical industry
LAND TRANSPORT	• Biofuels	• Battery electric vehicles	• Performance standards • Travel avoidance • Engine design	• FCEVs
SHIPPING	• Biofuels • Wind energy	• Short-distance shipping	• Ship design • Operation optimisation • Travel avoidance	• Green ammonia • Methanol
AVIATION	• Biojet fuels	• Short-distance aviation	• Plane design • Travel avoidance	• Hydrogen and synthetic fuels for aviation

Based on: IRENA, IEA and REN 21, forthcoming, and IRENA, 2020b.

2. The need to identify the highest-value applications

Once the decision to promote green hydrogen has been made, policy decisions include what applications should be prioritised and how quickly to make the shift from fossil fuels to green hydrogen. Policy makers should identify the highest-value applications for a given amount of green hydrogen, in order to focus their policy efforts where they could provide the most immediate advantages and enable economies of scale.

One potential role for green hydrogen policy is to support and then accelerate a shift to green hydrogen in industrial applications where hydrogen is already used, such as refining and the production of ammonia and methanol. Notably, the demand from these facilities is large enough to enable economies of scale in production and infrastructure, making the shift to green hydrogen even more cost-effective in these applications compared to distributed applications.

For example, 2 250 tonnes per day of green hydrogen could be used to meet the heat demand for buildings in a city with more of a million people. Instead, the same amount could be used to power a single green ammonia plant. In this case, using the hydrogen to make ammonia would avoid the high infrastructure costs and large amount of time needed to convert thousands of homes to hydrogen. At the same time, heat demand in residential buildings can be met more easily by other solutions such as heat pumps powered by renewable electricity (IRENA, IEA and REN21, forthcoming).

Another option to consider is to combine various uses that can benefit production by achieving larger economies of scale. These synergies can be found in industrial clusters, ports and cities (Roland, 2018). The synergies in such clusters help create a virtuous circle between supply and demand where large-scale production decreases costs, which in turn encourages demand within the same area. Higher demand then enables production to expand, further reducing costs and enabling even greater use.

Finally, when setting priorities, policy makers must carefully weigh both the economic gap compared to incumbent fossil fuel options and the urgency of the need to reduce emissions, in particular where options other than green hydrogen are virtually non-existent. For instance, green hydrogen used for the direct reduction of iron (DRI)[10] is one of the few options for zero-emission steel production. But the technology is only in pilot stage and may take several years to reach the commercial stage. Similarly, synthetic fuels are one of the few options for decarbonising aviation, but are currently far away from reaching cost parity with fossil jet fuel. Yet, despite this high cost, efforts need to start today to reduce production costs and scale up production.

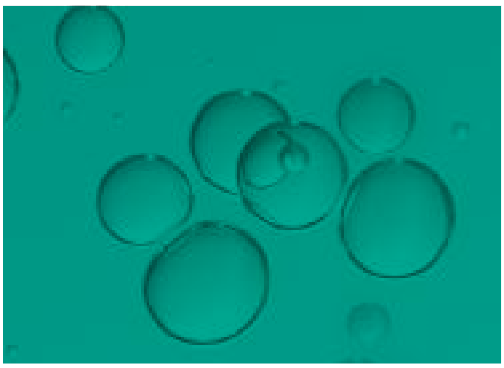
P2

Establish Policy Priorities

3. The principle of renewable energy additionality

Finally, the principle of additionality is crucial for the renewable energy used for green hydrogen production. In other words, if there are other productive uses for the electricity being generated from renewable sources, that electricity should not be diverted from those uses to produce green hydrogen. Instead, green hydrogen should be produced only from additional renewable energy capacity that would not otherwise be commissioned and electricity that would not be otherwise consumed.

Failing to follow this principle of additionality would slow down the electrification of buildings, industry and transport with renewable energy that is critical for a successful energy transition, and actually cause more fossil fuels to be brought into the power mix. At the same time, as more renewable capacity is constructed, more periods of excess generation will occur, which could either lead to VRE curtailment or be productively used to make green hydrogen. In this case, not only would the hydrogen then be used to decarbonise hard-to-abate sectors, its production would also increase the value of those generating assets and make it easier to integrate large amounts of VRE into the electricity grid.



10 Iron is found in nature in combination with oxygen. The removal of this oxygen is called reduction. This reduction is done today with a mix of carbon monoxide (CO) and hydrogen (H_2) in various proportions: the oxygen combined with CO and H_2 then produces CO_2 and H_2O. Hydrogen can provide the same function alone, thus avoiding CO_2 production.

2.3. POLICY PILLAR 3: **GUARANTEE OF ORIGIN SCHEME**

Molecules of green hydrogen are identical to those of grey hydrogen. For this reason, once hydrogen has been produced, a certification system is needed that allows end users and governments to know the origin and quality of the hydrogen.

The schemes used to track origin are usually referred to as providing a "guarantee of origin" (GO).[11] One example in the case of hydrogen is the CertifHy project in the European Union. The scheme issued over 76 000 GOs for green or low-carbon hydrogen, out of which 3 600 were used by 2019.

This was a pilot project covering less than 0.05% of the total EU market and less than 4% of the certificates were actually from renewable energy. Table 2.1 presents this and other examples of GO certification schemes. In particular, such schemes should be used to track CO_2 emissions from the production to the use of hydrogen, in order to recognise when and where the use of hydrogen can be more effective for decarbonisation purposes than direct electrification or the use of bioenergy.

P3
Guarantee of origin scheme

Table 2.1. Examples of guarantee of origin schemes

	BODY	REFERENCE	THRESHOLD	QUALIFIED PROCESSES
France	AFHYPAC	None	100% renewable	All renewable-based solutions
California	Low Carbon Fuel Standard	Well-to-wheel emissions from new gasoline vehicles	30% lower GHG, 50% lower NO_x	Green hydrogen, catalytic cracking of biomethane or thermochemical conversion of biomass, including waste
EU	CertifHy	Grey hydrogen	60% lower GHG than reference (36.4 gCO_2/MJ)	Two labels: • "Green hydrogen" if the hydrogen is made from renewable energy • "Low carbon hydrogen" otherwise Hydrogen must meet the threshold with 99.5% purity
Germany	TÜV SÜD	Grey hydrogen	35-75% lower than reference depending on process	Renewable electrolysis; biomethane steam methane reforming; pyro-reforming of glycerine
Germany	Clean Energy Partnership	Grey hydrogen	100% renewable	Renewable electrolysis; biomass
EU	REDII[12]	Transport fuels	70% reduction	Renewable transport fuels of non-biological origin
EU	Technical Expert Group on Sustainable Finance	None	5.8 tCO_2/tH_2 or 100 gCO_2/kWh used as input	Water electrolysis

Notes: REDII = Renewable Energy – Recast to 2030; NO_x = nitrogen oxides; gCO_2/MJ = grams of carbon dioxide per megajoule; gCO_2/kWh = grams of carbon dioxide per kilowatt hour; tCO_2/tH_2 = tonnes of carbon dioxide per tonne of hydrogen.

Sources: Jensterle et al., 2019; Velazquez Abad and Dodds, 2020.

11 For the purpose of this report, GO is used to define all schemes quantifying the GHG emissions of hydrogen or its derivatives.
12 This is applicable to all advanced renewable fuels, including hydrogen and its derived products.

The previous examples show that there is still no single definition for the certification of hydrogen, meaning that schemes may be incompatible. For example, the CO_2 threshold limit below which hydrogen would be considered "green" or "low-carbon" varies widely (35-100%). Some of the schemes cover multiple hydrogen production technologies (e.g. Low Carbon Fuel Standard, CertifHy), while others focus specifically on green hydrogen (e.g. AFHYPAC).

The schemes also vary when it comes to end uses. Some cover all possible sectors (e.g. CertifHy), while others focus on a particular application. For example, the Low Carbon Fuel Standard only applies to use in vehicles. In addition, the references can be different: for example, the TÜV SÜD uses as baseline the production of grey hydrogen, while the REDII compares emissions against the reference values of the incumbent technology (fossil fuels for transport). Finally, it should be noted how some of the schemes presented above are part of a legislative requirement to obtain incentives or to be accounted as renewable energy (e.g. LCFS and REDII – both related to the transport sector), while others are voluntary schemes adopted by producers to guarantee their sustainability.

To be useful for producers, policy makers and end users, all GO schemes should provide a clear label for the hydrogen product to increase consumer awareness and accurately describe the value of the commodity (Veum *et al.*, 2019, Mehmeti *et al.*, 2018). The information provided should clearly differentiate between the various hydrogen production pathways.

A GO scheme should also be based on life cycle GHG emissions, from upstream activities such as electricity generation to transport (see Figure 2.5). That would ensure consistency and compatibility with GHG emission certification schemes for other commodities, such as electricity or fossil gas.

Green hydrogen solutions could then be compared with other hydrogen shades, fossil fuels, direct electrification and use of bioenergy.

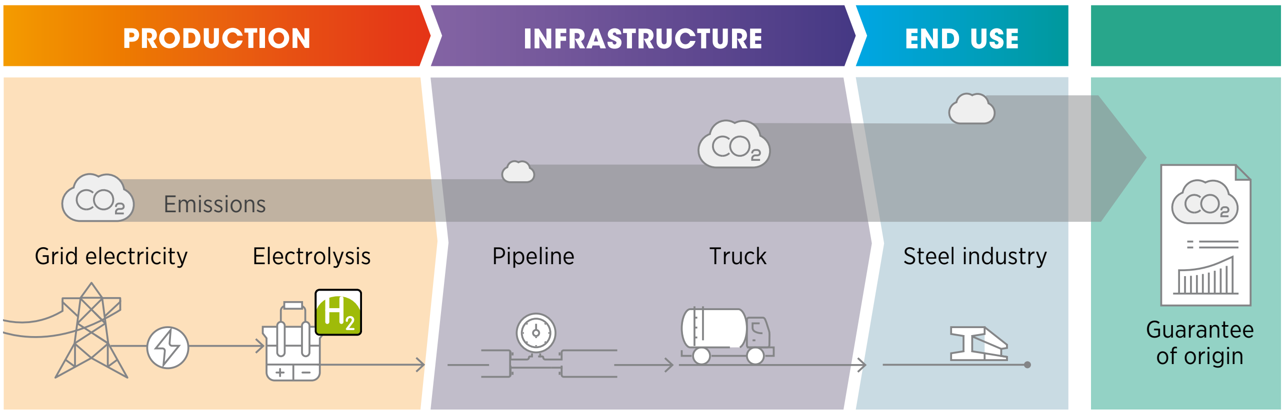
Biofuel certification schemes offer lessons on how to track and certify hydrogen. In biofuel certification schemes, some parts of the production chain can have default CO_2 reference values. In this way, the process of certification is accelerated for new applications. The default values are regularly updated to reflect technological changes. Producers may still apply for specific audited values, if they believe they have achieved better values than the reference ones.

The transport of biofuels is also accounted for in biofuel certification schemes by considering how and how far feedstocks and biofuels have been transported. Hydrogen GO schemes need to do this as well, since hydrogen produced from a dedicated wind farm and then transported with diesel trucks may have a greater carbon footprint then hydrogen produced with grid electricity that is transported in a pipeline.

Lastly, GO schemes should be designed to allow the international trading of green hydrogen, helping to create a global market. An example of international collaboration is the Hydrogen Production Analysis Task Force from the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE, 2020). The task force is aiming to develop a harmonised methodology and terminology to define and standardise clean hydrogen across different countries and to facilitate the creation of a common scheme for GO.

GO schemes will be a key element of a green hydrogen system, at least until carbon-intensive hydrogen is no longer produced. Other enabling policies will still be needed, however, to drive growth in green hydrogen.

FIGURE 2.5. Guarantees of origin lifecycle emissions (Illustrative)



2.4. POLICY PILLAR 4: **GOVERNANCE SYSTEM AND ENABLING POLICIES**

As green hydrogen transitions from niche to mainstream, the policies that drive the transition must not only cover the deployment of green hydrogen (presented in Chapter 3), but also its integration into the broader energy system. It is economy-wide policies that affect the sustainability and pace of the transition. Civil society and industry must be involved in this new sector in order to reap its benefits.

A broad base of support can create an enabling environment for green hydrogen actors to provide their value to the whole energy and social system. With these goals in mind, concrete actions that policy makers can take include:

- **Seeking advice from civil society and industry.** Civil society and industry can provide advice to policy makers on proposals, actions and amendments to the strategy depending on progress. An advisory council of experts who can provide high-quality input to government could be created. The council should include a diverse range of actors from academia, business and civil society to ensure that all interests are considered. The council could use sectoral or thematic tables to gather input from a broader range of stakeholders. Outcomes of the tables would be summarised and used as inputs for the council's recommendations to government. Italy's "Hydrogen Table" is an example of this policy. It involves companies and other stakeholders operating in the institutional and research world, with the objective of keeping the government updated on technological progress, identifying possible projects in the hydrogen value chain and their potential socio-economic effects, and maintaining international collaboration (MISE, 2020).
- **Implementing measures to maintain industrial competitiveness and create export opportunities.** Policy makers can assess which elements of the green hydrogen value chain can be manufactured domestically. This would include an assessment in each country of its existing national capacity compared to other countries and the actions needed to achieve leadership. In some cases, as in Canada, Germany and South Korea, the strategy could also set a national goal of becoming a first mover to develop a domestic industry, thus enabling exports of the technologies to other regions. Countries (such as Australia, Chile, Portugal and some members of the Gulf Cooperation Council region) may also focus on using their vast domestic renewable resources to establish an exporting hydrogen sector and promote domestic economic growth.
- **Identifying economic growth and job creation opportunities.** As part of a strategy, policy makers should assess the value that the hydrogen sector would add to the economy and its effect on associated industries, quantifying the number of jobs generated in equipment manufacturing, construction and operation, and indirectly in the supply chain and supporting industries. Examples of analyses of the employment impact of green hydrogen within an economy are common across first-mover countries, and they are used to inform national strategies. This was the case, for example, in the Netherlands (CE Delft, 2018; Government of the Netherlands, 2020). In addition, the local workforce needs to be able to perform the new jobs that will be created in these activities, and even in regulating the industry. Countries will therefore need education and training programmes to ensure a match between the skills needed and those currently available.

P4

Governance system and enabling policies

P4

Governance system and enabling policies

- **Introducing hydrogen as a part of energy security.** Not all countries enjoy the presence of large reserves of fossil fuels, meaning that the continuity of supply is governed by ever-changing political and economic factors. The production of green hydrogen can ease the demand for fossil fuels, in particular for industry and hard-to-abate sectors, increasing the energy security of a country.

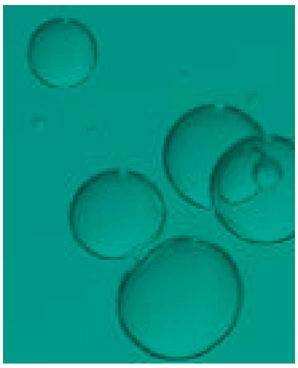
- **Setting international codes and standards.** International standards make it possible not only to execute cross-border projects, but also to reap the benefits of learning-by-doing from foreign companies that design and construct the equipment. This will enable costs to decrease more rapidly and will enhance safety as a result of applying best practices, among other benefits for end consumers.

- **Building or repurposing infrastructure.** Policy makers should assess the potential for repurposing existing natural gas pipelines to transport hydrogen, and thus decrease overall costs. They also need to guide the development of the hydrogen network by considering the locations of potential demand clusters and supply centres. Transparent plans and timelines for hydrogen network backbones, storage, fuelling stations and port infrastructure can be useful at the early stages to indicate the future routes and identify possible hurdles. Plans to repurpose grid infrastructure can be found in the EU hydrogen strategy (European Commission, 2020).

- **Ensuring access to financing.** Policy makers can provide direct dedicated funding from state budgets, or assist access to private capital by creating guidelines or new facilitating mechanisms. Public support may be needed for initial investments, in order to attract private capital. Given the versatility of hydrogen, there are multiple ways to expand existing funding programmes to cover its development.

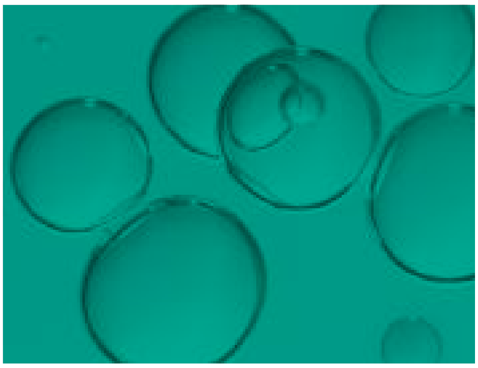
- **Collecting statistics.** Hydrogen is not currently included in national energy balances, because it is considered to be a chemical product. Including hydrogen supply and demand as a separate category in national energy balances (similar to electricity, fossil fuels or bioenergy) will allow better identification of energy flows and provide a solid basis for further analysis. Maintaining a central repository of data on hydrogen deployment across different sectors (such as MW of electrolysis or number of FCEVs) can make market information (such as prices, traded volumes and share of green and low-carbon hydrogen) openly available to promote transparency. This action will also require international co-operation to align the methodology and ensure mutual comprehension.

- **Setting research priorities.** By identifying technology needs, policy makers can prioritise the actions needed to close innovation gaps. A regular review of funding, progress and priorities should be part of the process. Since many of the hydrogen pathways needed over the long term are still in their early stages, policy makers should ensure the research agenda includes key demonstration projects to bridge the gap to commercialisation.



- **Implementing carbon pricing.** Green hydrogen will bring major GHG emission reductions when used to replace fossil fuels for many end uses. However, in many cases this benefit is not reflected in commodity prices, reducing the economic incentive to produce green hydrogen. By internalising the externalities (such as the impacts of extreme weather events, including damage to crops and other assets) in the form of either a carbon tax (i.e. a predetermined price path) or a trading system (i.e. a predetermined limit on emissions with a variable price), policy makers will contribute to valuing this benefit and closing the economic gap with fossil fuel pathways.
- **Phasing out fossil fuel subsidies.** Fossil fuel subsidies are responsible for various fiscal, social and environmental problems. These problems include harmful impacts on energy markets and greater fiscal burdens on governments, as well as environmental impacts. By phasing out fossil fuel subsidies, policy makers will help to close the economic gap with green hydrogen, while reducing market distortions and making the real price of fossil fuels clearer. When energy subsidies are used to assist energy-vulnerable populations or to guarantee competitiveness of national companies, careful planning of their phase-out should include measures to avoid energy price spikes or excessive burdens on family and company budgets.

While the measures described here can facilitate the deployment of green hydrogen, supporting mechanisms may still need to be put in place. The next chapter provides examples of such measures.



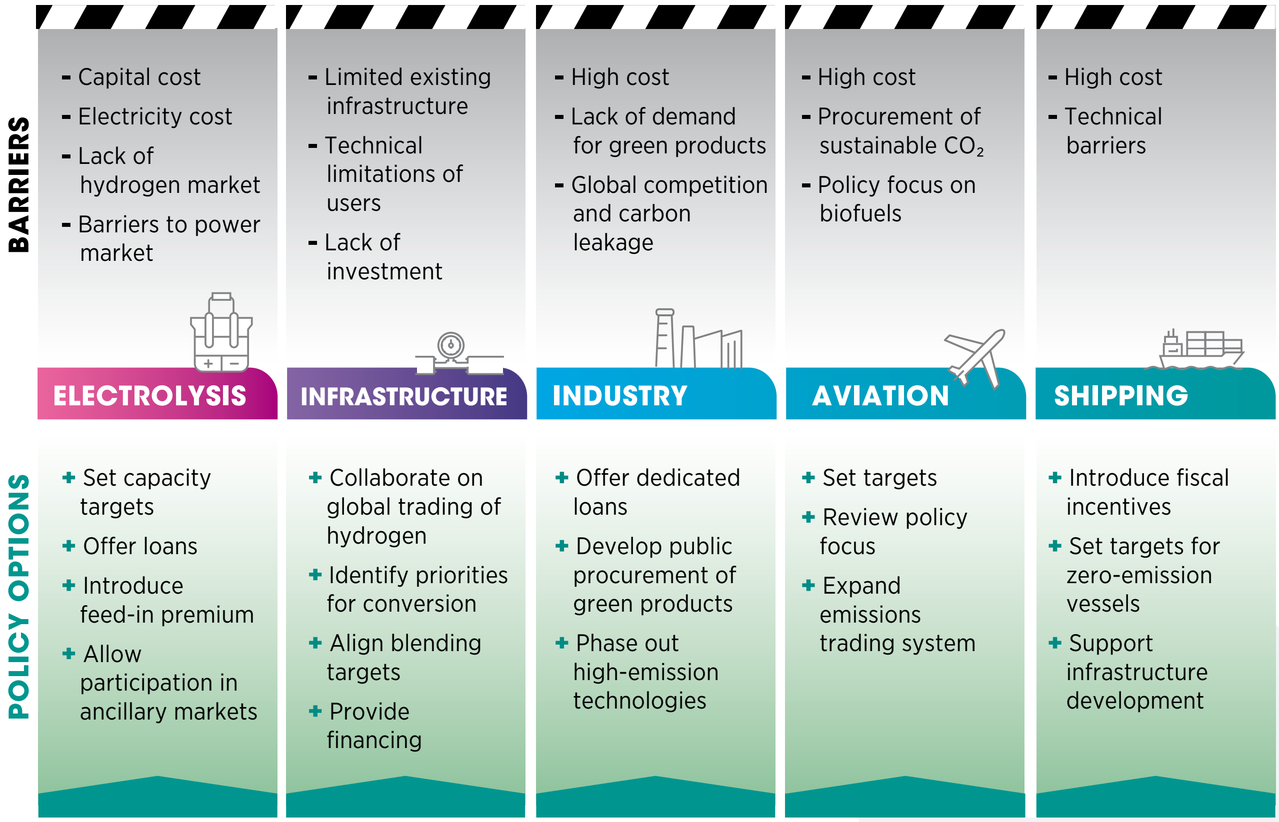
3 SUPPORTING POLICIES FOR GREEN HYDROGEN

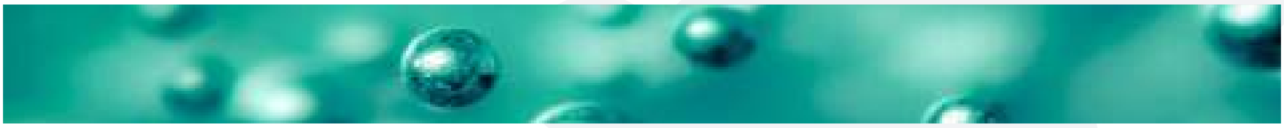
This chapter will present insights and recommendations for policy makers who are considering kickstarting the green hydrogen sector in their jurisdictions. Green hydrogen is at an early stage in most applications and needs policy support to advance from niche to mainstream and be part of the energy transition. Some barriers to the deployment of green hydrogen in various sectors are relatively consistent across end uses (as discussed in Section 1.3), the cost barrier being the main one.

Other barriers are more sector-specific and call for a tailored approach (Figure 3.1).

Once priorities are set, policy makers need to address the barriers specific to the sectors where green hydrogen is expected to be deployed. In this chapter, specific policies and measures are presented for selected segments of the hydrogen value chain. The policy briefs that are due to follow this publication will delve in greater detail for each of the mentioned elements.

FIGURE 3.1 Selected barriers and policies for segments of the hydrogen value chain





3.1. POLICY SUPPORT FOR **ELECTROLYSIS**

Green hydrogen is produced via electrolysis from renewable electricity. Electrolysis is a developed and commercialised process, with various technologies available, each with benefits and barriers to uptake (IRENA, forthcoming). While electrolysis technology is mature, about 95% of all the hydrogen used today is still produced from fossil fuels through SMR or coal gasification (grey hydrogen). Water electrolysis for the production of green hydrogen is limited to about 200 MW of electrolyser capacity in few hundreds demonstration projects.

But green hydrogen production has the potential to grow quickly. The manufacturing capacity to build electrolysers is increasing rapidly, and multiple projects have been announced with a gigawatt scale (IRENA, forthcoming).

Barriers

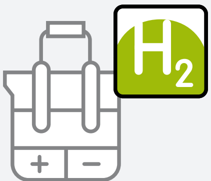
The greatest single barrier to the production of green hydrogen is its cost – it is currently two to three times more expensive to produce than grey hydrogen (see Box 1.2).

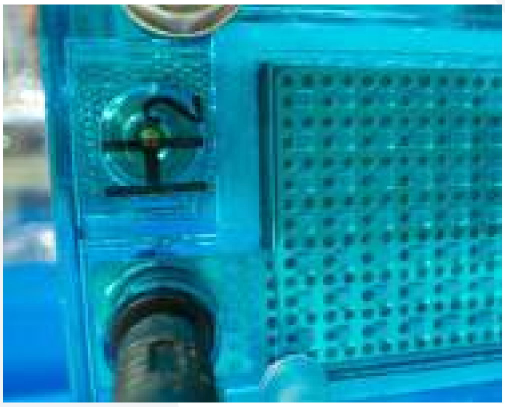
Another barrier to the wider use of green hydrogen is the lack of recognition of the value that it can provide. Hydrogen is not publicly traded: the hydrogen currently being used comes mostly from on-site generation and bilateral agreements between companies.

A market for green hydrogen thus needs to be created to enable cross-border trading and to harness the power of market forces. This market will need to incorporate the value of sustainable production, which would in turn accelerate the uptake of electrolysers as green hydrogen becomes a valuable asset.

Policy recommendations

All these barriers can be overcome with carefully designed policies. Costs can be brought down through economies of scale, innovation, efficiency gains and improvements in the manufacturing of electrolysers. Several policies can accelerate the growth in electrolyser capacity and green hydrogen production, and thus help achieve these cost reductions. Meanwhile, other policies can increase the financial incentives for green hydrogen production by closing the current large gap between the costs of producing green and grey hydrogen. These policies include:





- **Setting targets for electrolyser capacity**, such as the European Union's goal of increasing electrolyser capacity to 80 GW (40 GW in Europe, 40 GW in neighbouring countries) by 2030 (European Commission, 2020). Similar to renewable energy targets, these goals will inform the private sector of the countries' commitments and help attract investment.
- **Tackling high capital cost.** Government loans, capital grants and other forms of financial assistance can make the business case for the installation of electrolysers. For example, the United Kingdom has awarded USD 9.8 million for a feasibility study to scale up the size of electrolysers to 100 MW and to increase manufacturing capacity to 1 GW/yr by 2025 (Element Energy, 2020).
- **Improving tax schemes for electrolysers.** The cost of green hydrogen production could be lowered by reducing the taxes and fees on the electricity used by electrolysers. Lowering corporate, business and sales taxes on green hydrogen could also improve revenues and the rate of return on projects.
- **Paying a premium for green hydrogen** through feed-in tariffs or other subsidies. Subsidies for renewable biogas and biomethane are already in place in six European countries, and could potentially be extended to green hydrogen. The SDE++ programme in the Netherlands is set to provide subsidies for the production of hydrogen from electrolysis (RVO, 2020).
- **Ensuring additionality of renewables generation.** As the production of hydrogen grows, measures must be put in place to ensure that the electricity used by electrolysers is as low carbon as possible and that enough renewable electricity is available for both the direct electrification of end uses and the production of hydrogen. Policy makers may need to set ambitious targets for the growth of renewable generation capacity. In addition, policy makers could consider incentives and market rules that encourage electrolyser operators to use renewable electricity that would otherwise be curtailed; one strategy would be to locate electrolysers in areas with recurrent grid congestion.
- **Increasing support for research** to improve electrolyser efficiencies and to optimise and standardise designs for large-scale electrolysers to bring down electrolyser cost

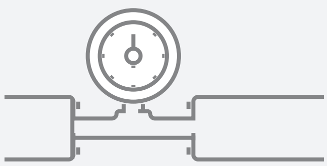
3.2. POLICY SUPPORT FOR **HYDROGEN INFRASTRUCTURE**

Vast renewable resources are available to be exploited to produce green hydrogen. A large share of the potential, however, such as that of solar PV, is found in deserts at great distances from where the hydrogen could be used. Even when electrolysers are located closer to demand, the hydrogen may still need to be transported. As a result, various forms of infrastructure will be needed to store and transport green hydrogen and hydrogen-based synthetic fuels.

Hydrogen can be transported by truck, ship or pipeline. Hydrogen has a low energy content by volume in the gaseous state (three times less than methane for example), but, once pressurized, it can be transported through pipelines with the same energy flow as natural gas. To ship hydrogen, it can be liquified or converted to ammonia or liquid organic hydrogen carriers (LOHC), for greater energy content by volume. Those conversions require additional energy consumption for liquefaction and continuous cooling.

As for storage, hydrogen can be stored in steel tanks or in underground geological formations. While not all countries have suitable underground formations, the overall available capacity is vast. For example, the potential hydrogen storage capacity in Europe is about 2 500 Mt, or 82.8 petawatt hours (Caglayan *et al.*, 2019). Moreover, when hydrogen is converted to LOHCs, green methanol or synthetic hydrocarbons, the fuels can be stored and transported using existing tanks, pipelines and other infrastructure.

The use of existing natural gas infrastructure for the transport and storage of green hydrogen would lower the overall cost of the transition, both in terms of reduced investment in hydrogen infrastructure and avoided investment in the expansion of the electricity grid. In fact, in the early stages of the energy transition, green hydrogen could be blended at low shares with natural gas in existing pipelines and uses. As green hydrogen production and use increases, however, new infrastructure will be needed.



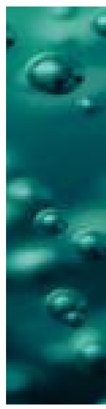
Barriers

Challenges in transporting and storing hydrogen will continue to evolve as the production of green hydrogen expands.

In early stages, the possibility could exist to blend most of the hydrogen produced into existing natural gas infrastructure or use it on-site or close by. Even these uses come with challenges and costs, however. While some parts of the gas grids can deal with high shares of hydrogen, many pipelines can handle only limited percentages. Similarly, many downstream gas applications, such as turbines, cannot handle high shares of hydrogen, and a pipeline fit for hydrogen would still be useless if end uses are not ready. Similarly, countries currently have different blending limits, for example, which hinders transport across borders.

Later stages would require the widespread conversion of gas networks, appliances and industrial users to hydrogen. Germany is already planning to convert 5 900 km of its natural gas pipelines to hydrogen (around 15% of the total national network), with the first 1 200 km to be completed by 2030 (DW, 2020). Such conversion requires investment in new compression stations and pressure regulators.

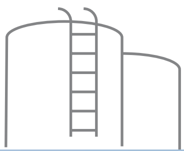
In addition, new hydrogen pipelines might still be needed to connect the hydrogen production centres to the demand centres. When renewable resources are located at great distances from the demand centres, it might be preferable to turn the green hydrogen into ammonia on the spot and then transport the ammonia, rather than the hydrogen. To achieve that, facilities will be needed to convert hydrogen to ammonia and other energy carriers and fuels.



Policy recommendations

Realising the potential of green hydrogen will require careful policy attention to meet the challenges of transport and storage. It is important to begin now to plan the infrastructure of the future; similar to the planning of the power grid, the effects of such planning will be seen decades from now. Policy makers should consider:

- **Kicking off international collaboration on global trading of hydrogen.** Importing hydrogen from regions with low-cost renewables might be attractive for some countries. There is currently limited infrastructure for this and it is not yet clear how to best transport hydrogen over long distances. Agreements and co-operation are needed in the short term to start piloting routes and carriers to make sure a global supply chain is established over time.
- **Identifying priorities for conversion programmes.** The hydrogen blending limit is defined by the least tolerant elements in a gas network. Some end uses are more sensitive to low levels of blending. These need to be surveyed to determine the extent of potential pipeline conversion programmes, which could also promote the use of hydrogen-ready equipment.
- **Aligning standards and blending targets.** Gas composition, and hydrogen content in particular, needs to be harmonised among neighbouring countries to facilitate trading across borders. It will be necessary to create international standards for the operation and design of ships and other facilities needed to transport green hydrogen and related products. Those standards should include sustainability criteria, operational safety standards, pipeline integrity requirements, fuel specifications and appliance compatibility standards. If blending targets are being considered, aligning them across countries will facilitate trading.
- **Financing infrastructure development.** To achieve significant expansion, the capital needs might be beyond the capabilities of the operator, and additional funds from public and private capital sources may be needed. Policies should be put in place to facilitate capital flows for this network expansion and repurposing.

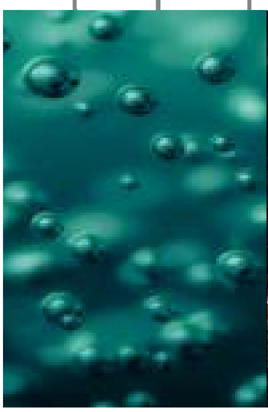


3.3. POLICY SUPPORT FOR HYDROGEN IN **INDUSTRIAL APPLICATIONS**

Converting to green hydrogen can significantly reduce carbon emissions from the industrial sector, which is currently responsible for about one-quarter of all energy-related CO_2 emissions (or 8.4 $GtCO_2$/yr). Four industries in particular – iron and steel, chemicals and petrochemicals, cement and lime, and aluminium – account for around three-quarters of total industrial emissions (IRENA, 2020b).

Grey hydrogen is currently used as a feedstock to produce methanol and ammonia. Green hydrogen could replace much of it with no changes in equipment or technology, eliminating the emissions associated with the production of grey hydrogen.

Over 70% of global steel is produced via the blast furnace/basic oxygen furnace (BF-BOF) route, which relies mostly on coal. Most of the remaining steel is produced from direct reduction of iron (DRI) or steel scrap in an electric arc furnace (EAF), with fossil fuels providing both the reducing agent and energy for DRI and the electricity for the furnace. A structural shift in iron and steel making is needed, with renewables displacing fossil fuels for both energy and reducing agents. One option is to apply alternative processes that can use renewable energy and green hydrogen (IRENA, 2020b).



Barriers

The principal barriers to the greater use of green hydrogen in industry are high costs, investors' confidence, competitiveness and a lack of policy focus

The cost differential between hydrogen-based and fossil fuel-based processes will vary by location and application. But at present the use of green hydrogen is significantly more expensive than fossil fuels, unless a carbon price or other adjustment is applied. Green ammonia (ammonia made from green hydrogen) is two or three times more expensive than grey ammonia, and green methanol is three to four times more expensive than grey methanol. Hydrogen-based industrial processes, moreover, are not yet fully proven at scale. Investors making large capital investment decisions typically lack sufficient information to fully assess the risks associated with investing in green hydrogen activities.

Commodities such as steel and chemicals are traded globally and are often important components of national trade policies. The competitiveness of national industries is therefore a major concern for both governments and companies. If some, but not all, countries impose emission limits on industrial processes, thus raising costs in those countries, industrial production may shift to areas without the same rules, reducing production costs but causing GHG emissions to increase (this phenomenon is also known as "carbon leakage"). Industrial energy policies tend to focus on energy efficiency. While improved energy efficiency is needed, policy makers should move their focus onto the fuel shift that is required for the uptake of green hydrogen – a policy that is often missing.

Policy recommendations

To overcome these barriers, policy makers must adopt measures to close the cost gap between current industrial processes and the use of green hydrogen, encourage markets for green hydrogen and address problems like carbon leakage. Such policies include:

- **Adapting industrial policy for green hydrogen.** The adaptation includes two steps. First, making sure there are policies that promote fuel shifts and do not just focus on marginal improvements, which are not enough to achieve net-zero emissions on their own. This could be done, for instance, by setting ambitious long-term targets for GHG emission reductions by type of industry that cannot be achieved by energy efficiency alone, and including green hydrogen in the supported technologies. Governments might also combine decreasing CO_2 emission targets with a carbon trading scheme, allowing companies that cut emissions below the target to sell the surplus to companies with higher emissions. For example, Canada's output-based pricing system sets targets of 80-95% GHG emission reductions for the steel, chemical and refinery industries. Facilities that are below the thresholds are given surplus credits that can be traded (Turcotte, Gorski and Riehl, 2019).
- **Planning to phase out high-emission technologies.** Governments can develop strategies to transition industries in stages. The steel industry could begin reducing emissions by using an increasing share of green hydrogen in existing blast furnaces, but then switch to fluidised bed furnaces to enable that share to reach 100%.
- **Providing loans, grants or dedicated funds.** These measures are needed to make investment in green pathways more financially attractive. For example, the Energy and Climate Fund in Germany has allocated EUR 45 million to help decarbonise the steel, cement and chemical industries, and Germany's 2020 budget includes EUR 445 million specifically to support greater industrial use of green hydrogen by 2024 (BMU, 2020; BMWi, 2020). In Sweden the HYBRIT project has benefited from a contribution from the government to build a pilot green hydrogen steel plant (HYBRIT, 2020).
- **Recognising the value of green products.** Policy makers should recognise the higher social value of these products and reward them accordingly. Available policy tools for the early stages include price premiums, feed-in-tariffs or carbon contracts for difference in price, which can guarantee investors a higher price for CO_2 emission reductions than the prevailing price in current CO_2 trading schemes.
- **Kickstarting markets for low-carbon products.** Governments could, through public procurement, preferentially buy steel or other products made sustainably through the use of green hydrogen, or require a higher share of those products in the overall material mix.
- **Addressing carbon leakage.** Policies to support green hydrogen should go in tandem with policies to address carbon leakage that take into account fair international competition, ease of implementation and the risk of windfall profits, while still providing demand-side abatement incentives (*e.g.* material efficiency and replacement). Possible policies include cross-border adjustments or tax rebates to reduce or eliminate the competitive advantages of industrial facilities that have lower production costs and higher emissions than "greener" facilities.

3.4. POLICY SUPPORT FOR SYNTHETIC FUELS IN **AVIATION**

Aviation accounts for 2.5% of global energy-related emissions. It is dependent on high energy density fuels due to the mass and volume limitations of aircraft.

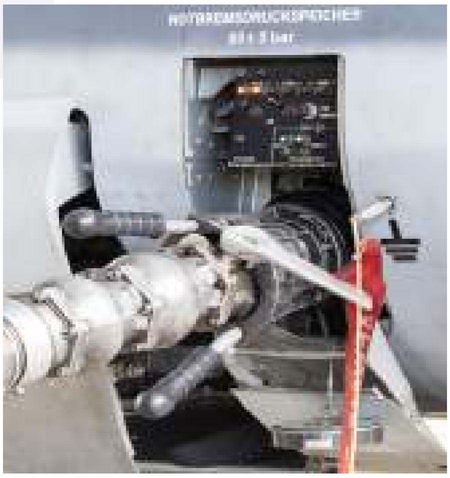
Synthetic jet fuels produced from green hydrogen could play a role as drop-in fuels, complementing biojet fuels in decarbonising the aviation sector (IRENA, 2020b). Synthetic jet fuels are produced from hydrogen and a source of carbon (usually in the form of CO or CO_2) and are hydrocarbons with the same physical properties of refined products from fossil fuels.

The amount of synthetic fuel needed for aviation (and thus the overall cost of the energy transition of the aviation sector) could be reduced further through greater aircraft energy efficiency, lower demand for long-distance travel (*e.g.* through shifts to trains or reduced air travel, wider use of teleworking and teleconferencing), and direct electrification of short-haul flights. Electric propulsion could be feasible for small planes and short-haul flights. The direct use of hydrogen in airplanes is also under consideration.

Barriers

Synthetic fuels for aircrafts are very expensive, currently up to eight times more expensive than fossil jet fuel. The cost components include electricity costs, the cost of electrolysers and synthesis plants, operational costs and the costs to procure the carbon needed. At the time of writing there is no market that values the sustainable low-carbon character of molecules that are otherwise indistinguishable from fossil-derived ones. In addition, the sustainability of synthetic fuels depends on the source of the carbon used (CO and CO_2captured from emission streams, biogenic sources or directly from the air), which could increase costs.

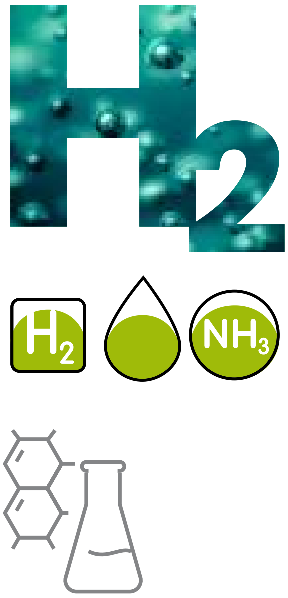
Most countries have mitigation targets for the transport sector as a whole. This might focus efforts on other modes of transport, delaying the preparation for mitigating emissions from aviation. Moreover, targets focus mostly on biofuels, missing the opportunity to promote the use of synthetic fuels, which would widen the technology portfolio and potentially decrease costs in the long term.



Policy recommendations

To take advantage of the opportunity to cut emissions from aviation using synthetic fuels, policy makers can consider:

- **Setting explicit targets for reducing emissions in aviation.** Renewable fuels for aviation should be explicitly counted towards meeting transport sector decarbonisation targets. They could also be given extra weight to reflect their higher costs and give them a slight priority, as in the EU REDII, which has a multiplier of 1.2 for renewable fuels used for shipping and aviation when calculating performance against the targets (European Parliament, 2018).
- **Focusing more on synthetic fuels.** Efforts to reduce CO_2 emissions have focused so far on energy efficiency (which delivers lower fuel consumption, lower fuel costs and higher profits), and on biofuels. Sustainable aviation fuels, as a concept, include both biofuels and synthetic fuels. Policies should aim to promote both energy carriers.
- **Providing financial incentives to reduce the cost gap between fossil fuels and synthetic fuels.** Possible strategies include eliminating subsidies for fossil fuels, providing grants for investing in synthetic fuel production and expanding existing emissions trading systems, such as the EU ETS, to cover aviation. The policies should be aimed at creating a market that values the emission reductions from using synthetic fuels. Even in the long term, however, synthetic fuels might not reach cost parity with fossil fuels, so blending mandates could be a practical interim option.
- **Guaranteeing a sustainable carbon source.** The environmental impact of synthetic fuels is defined by both the electricity and CO_2 source. CO_2 sources that are compatible with a net-zero emissions system, namely biogenic or directly captured from the air, should be promoted. Ensuring that synthetic fuels are environmentally sustainable requires a certification system for both the hydrogen and the CO_2 used in the production process.



3.5. POLICY SUPPORT FOR HYDROGEN USE IN **MARITIME SHIPPING**

Maritime shipping is already the most efficient form of freight transport; it uses 30% less energy for a given weight and distance than rail transport and 90% less than heavy-duty trucks. But the 95 000 ships currently in use, which carry 80-90% of all global trade, emit substantial amounts of CO_2 – 930 $MtCO_2$ in 2015, equivalent to 2.8% of total global energy-related emissions. With heavy fuel oil providing more than three-quarters of the fuel used by ships, ships are also major emitters of sulphur, particulates and other air pollutants (IRENA, 2020b).

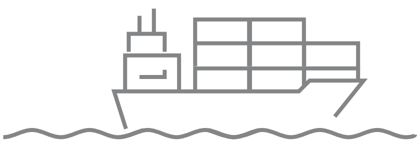
Around 20% of the global shipping fleet is responsible for 85% of the net GHG emissions associated with the shipping sector. Therefore, a limited number of interventions might have a large impact in decarbonising the shipping sector. Electrification via batteries or fuel cells could play an important role for short-distance vessels. Biofuels are an immediately available option to decarbonise the shipping sector, either in blends or as drop-in fuels. However, their potential is currently limited (IRENA, 2020b).

Green hydrogen could play an important role, but its adoption would require substantial adaptations to existing onboard and onshore infrastructure. In addition, green ammonia is emerging as one of the most feasible low-carbon fuel pathways. Leading manufacturers are working on engines that can run on ammonia and are anticipated in 2024.

Barriers

As in other sectors, higher costs are a barrier. A recent study indicates that at least USD 1 trillion in investment is needed to decarbonise international shipping, using green ammonia as the main fuel (Raucci *et al.*, 2020). Beyond costs, there also are technical and practical barriers. For the same amount of energy, ships would need fuel tanks three to four times larger than existing tanks in order to use ammonia, and 40% larger for liquid hydrogen. Larger tanks would cut into cargo space, reducing the amount of cargo that could be carried by ships by about 10-15% in typical bulk carriers.

In addition, ammonia is caustic and corrosive, and thus requires special fuel handling, while liquefying hydrogen requires considerable additional energy. These fuels would also require a new bunkering infrastructure.

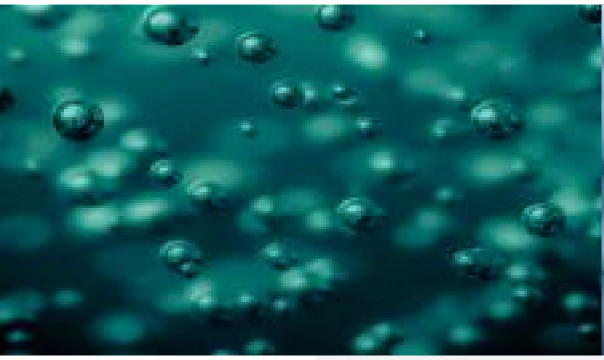


3.5.2. Policy recommendations

Many of the policies already described in this report to reduce the cost gap between fossil fuels and green hydrogen and its related fuels will also help make these green synthetic fuels more economically viable for use in ships, from carbon taxes to economies of scale that bring down the price of renewable electricity and ammonia plants.

Beyond those general policies, there are specific steps that governments can take to accelerate the decarbonisation of maritime shipping. While these policies can be implemented either domestically or internationally, they will have the greatest impact at the international level. Policy makers should consider:

- **Implementing fiscal incentives.** Taxes based on the tonnage of cargo could be set lower for cargos carried by ships that have lower GHG emissions, as Norway and Portugal have done. In addition, 28 of the 100 largest ports in the world charge port fees that vary depending on ships' environmental impacts, with five of them including GHG emissions among those impacts (ITF, 2019). Other possible policy instruments could be charging all ships a fixed levy based on their fossil fuel consumption, or adding shipping to emissions trading systems, as the European Union will do in 2022 (Reuters, 2020). Such financial incentives would help close the cost gap between fossil fuels and green alternatives.
- **Creating demand for green maritime fuels.** Governments can set targets for a required number of zero-emission vessels, for example. Or they could mandate increasing levels of synthetic fuels to be blended into current ship fuels, or ambitious levels of market-based measures.
- **Support infrastructure development.** Making supplies of green hydrogen, ammonia or methanol available at just a few ports around the world would be enough to bring large reductions in global emissions, since just seven countries are currently responsible for nearly 60% of global bunker fuel sales (the largest being Singapore, the United States and the United Arab Emirates) (IRENA, 2019c). That could simplify the logistics and lower the costs of making alternative fuels available. Ports would need to be adapted to deliver hydrogen or ammonia.
- **Support international policy and regulations.** If only one or a few countries enact policies to limit maritime emissions, then much of the shipping business would simply move to other countries. As a result, coordinated action by many countries is needed to cut emissions from international shipping. In addition, an international regulatory framework for these alternative fuels needs to be put in place. It should include GOs and accurate measurements of GHG emissions for the fuels.



4 CONCLUSIONS

H
Hydrogen 1.01

National pledges to achieve net-zero emissions

Broader use of hydrogen

Maturity of relevant technology

Power system flexibility benefits

Low renewable energy cost

Extensive base of interested stakeholders

Global interest is rising in green hydrogen as one of the solutions for an energy transition toward zero or net-zero emissions. There have been several waves of interest in hydrogen in the past. However, this new wave places a broader focus on creating a link between renewable electricity and hard-to-electrify end uses. Its drivers include: low renewable electricity costs, the maturity of relevant technology, power system flexibility benefits, national pledges to achieve net-zero emissions, and a more extensive base of interested stakeholders.

Indeed, the last two years have witnessed increased momentum for green hydrogen, with many countries around the world implementing national hydrogen strategies or announcing their intentions to do so. Measures to support green hydrogen have even been included in post-COVID-19 recovery packages. Although interest in green hydrogen is reaching unprecedented levels, several barriers are still impeding its full contribution to the energy transition. The primary obstacle is the high cost of green hydrogen compared to grey hydrogen and fossil fuel sources. Other barriers include the lack of dedicated infrastructure, the lack of value recognition for reduced GHG emissions, and other barriers related to the development of an emerging industry.

While the hydrogen sector has received attention from governments, more dedicated policy support is needed to ensure technology readiness, market penetration and market growth. IRENA has identified four pillars for green hydrogen policy making: national hydrogen strategies, policy priorities for green hydrogen, guarantee of origin systems, and enabling policies.

National hydrogen strategies define a country's level of ambition for hydrogen and outline the amount of support required to achieve such ambition. They serve as a reference for private actors in the hydrogen industry, helping to encourage increased levels of financing. Effective national strategies should lay out a clear pathway to increasing hydrogen uptake.

A wide range of end uses can utilise green hydrogen. To avoid diluting efforts, national policy makers should identify the applications that provide the highest value and prioritise action towards them. By doing so, governments can ensure their policy efforts provide more immediate benefits, creating higher demand for green hydrogen.

Guarantee of origin schemes should be based on lifecycle GHG emissions. They should be designed to allow policy makers and end users to understand the impact of this energy carrier, ensure consistency and compatibility with GHG emissions for other commodities, and allow comparison with other energy sources.

Enabling policies are economy-wide policies that can help to level the playing field between hydrogen and fossil fuels. These policies should be applied to allow hydrogen actors to provide value to the entire energy system, and to broader economic and social systems.

This guide lays out key recommendations to accelerate the proliferation of green hydrogen. A series of sectoral briefs will follow this publication. The first brief will be dedicated to the supply side (electrolysis and infrastructure), followed by briefs focusing on the hard-to-abate sectors (industry and long-haul transport). These briefs aim to guide policy makers in designing and implementing policies to support green hydrogen. They will analyse the status of associated technologies, outline sector-specific barriers and costs, and provide a wide range of policy recommendations according to the stage of implementation.

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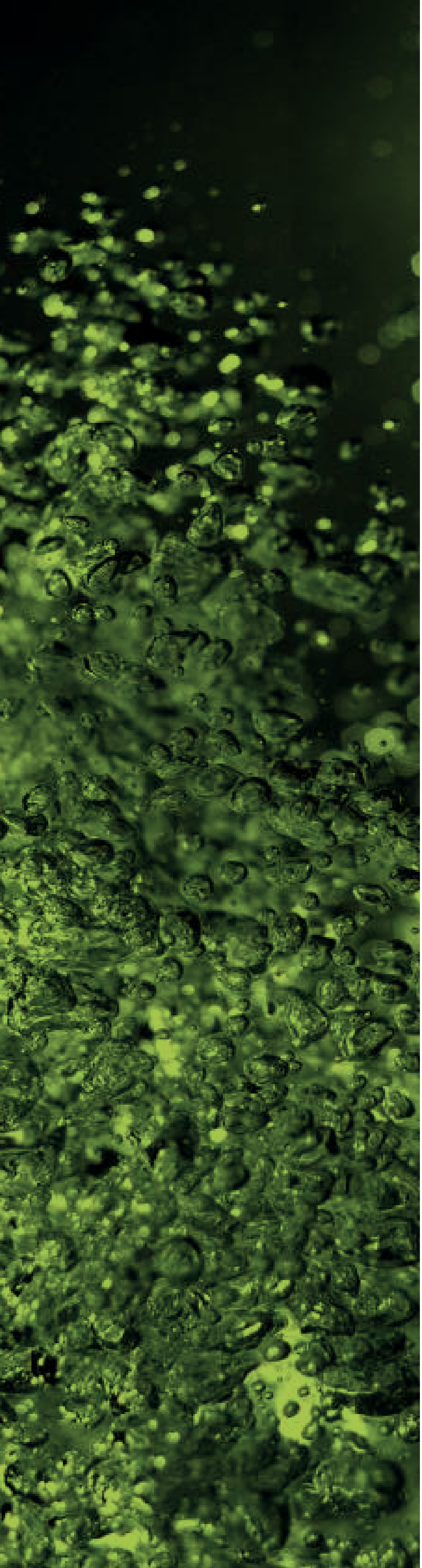

ABBREVIATIONS

ATR	Autothermal reforming
CCS	Carbon capture and storage
CCUS	Carbon capture, use and storage
CEM	Clean Energy Ministerial
CO_2	Carbon dioxide
DRI	Direct reduced iron
ETS	Emissions trading system
FCEV	Fuel cell electric vehicle
GO	Guarantee of origin
H_2	Hydrogen
IEA	International Energy Agency
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IRENA	International Renewable Energy Agency
LOHC	Liquid organic hydrogen carriers
MI	Mission Innovation
NECP	National energy and climate plan
REACT-EU	Recovery Assistance for Cohesion and the Territories of Europe
VRE	Variable renewable energy

UNITS OF MEASURE

EJ	Exajoule
g	Gram
GJ	Gigajoule
Gt	Gigatonne
GW	Gigawatt
kg	Kilogram
km	Kilometre
kW	Kilowatt
kWh	Kilowatt hour
Mt	Million tonnes
MW	Megawatt
MWh	Megawatt hour
t	Tonne
TWh	Terawatt hour

IRENA

International Renewable Energy Agency

H_2

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