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

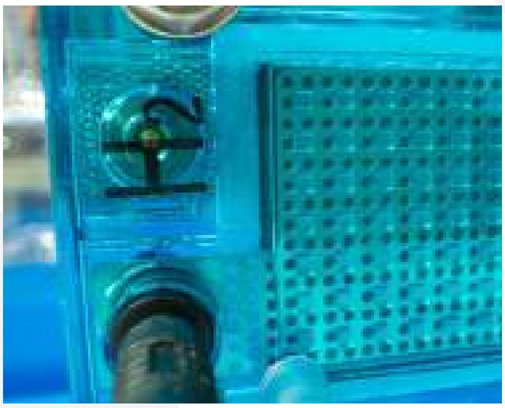
The greatest single barrier to the production of green hydrogen is its cost – it is currently two to three times more expensive to produce than grey hydrogen (see Box 1.2).

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

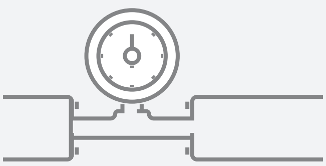
3.2. POLICY SUPPORT FOR **HYDROGEN INFRASTRUCTURE**

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

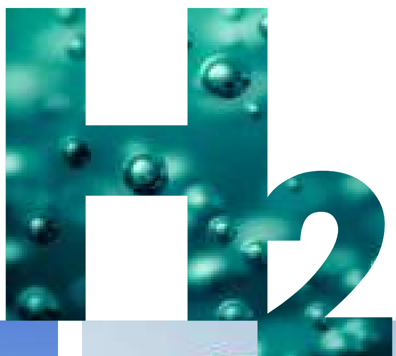
Realising the potential of green hydrogen will require careful policy attention to meet the challenges of transport and storage. It is important to begin now to plan the infrastructure of the future; similar to the planning of the power grid, the effects of such planning will be seen decades from now.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

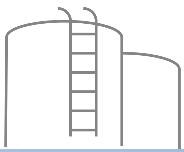
- **Kicking off international collaboration on global trading of hydrogen.** Importing hydrogen from regions with low-cost renewables might be attractive for some countries. There is currently limited infrastructure for this and it is not yet clear how to best transport hydrogen over long distances. 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.



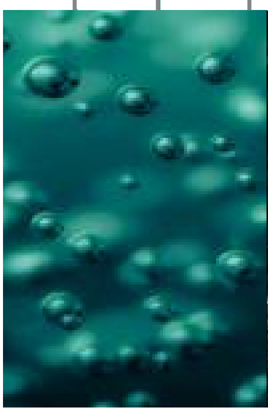


3.3. POLICY SUPPORT FOR HYDROGEN IN **INDUSTRIAL APPLICATIONS**

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.