IRENA
International Renewable Energy Agency

GREEN HYDROGEN FOR INDUSTRY

A GUIDE TO **POLICY MAKING**

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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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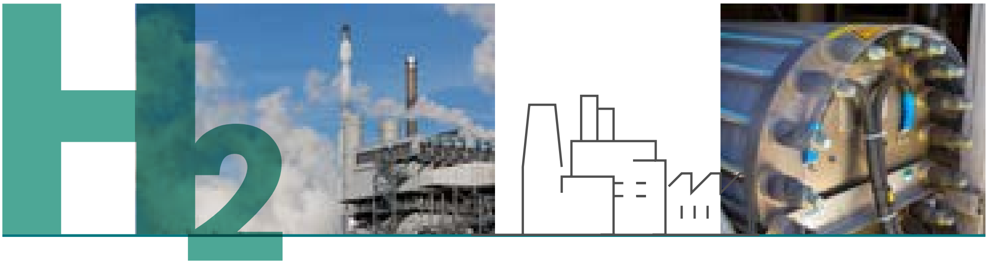

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ABBREVIATIONS

BCA	Border carbon adjustment
BECCS	Bioenergy with carbon capture and storage
BF	Blast furnace
BF-BOF	Blast furnace-basic oxygen furnace
CCfD	Carbon contract for difference
CCS	Carbon capture and storage
CCUS	Carbon capture utilisation and storage
CO_2	Carbon dioxide
COP	Coefficient of performance
DAC	Direct air capture
DRI	Direct reduction of iron
EAF	Electric arc furnace
ETS	Emissions trading system
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
FIP	Feed-in premium
FIT	Feed-in tariff
GHG	Greenhouse gas
H_2	Hydrogen
NO_x	Nitrogen oxide
OBPS	Output-based pricing system
PtH	Power-to-heat
PV	Photovoltaic
SMR	Steam methane reforming
SPP	Sustainable public procurement
WTO	World Trade Organization

UNITS OF MEASURE

EJ	Exajoule
GJ	Gigajoule
Gt	Gigatonne
GW	Gigawatt
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt hour
m^3	Cubic metre
Mt	Megatonne
MW	Megawatt
MWh	Megawatt hour
PWh	Petawatt hour
t	Tonne
TWh	Terawatt hour
yr	Year

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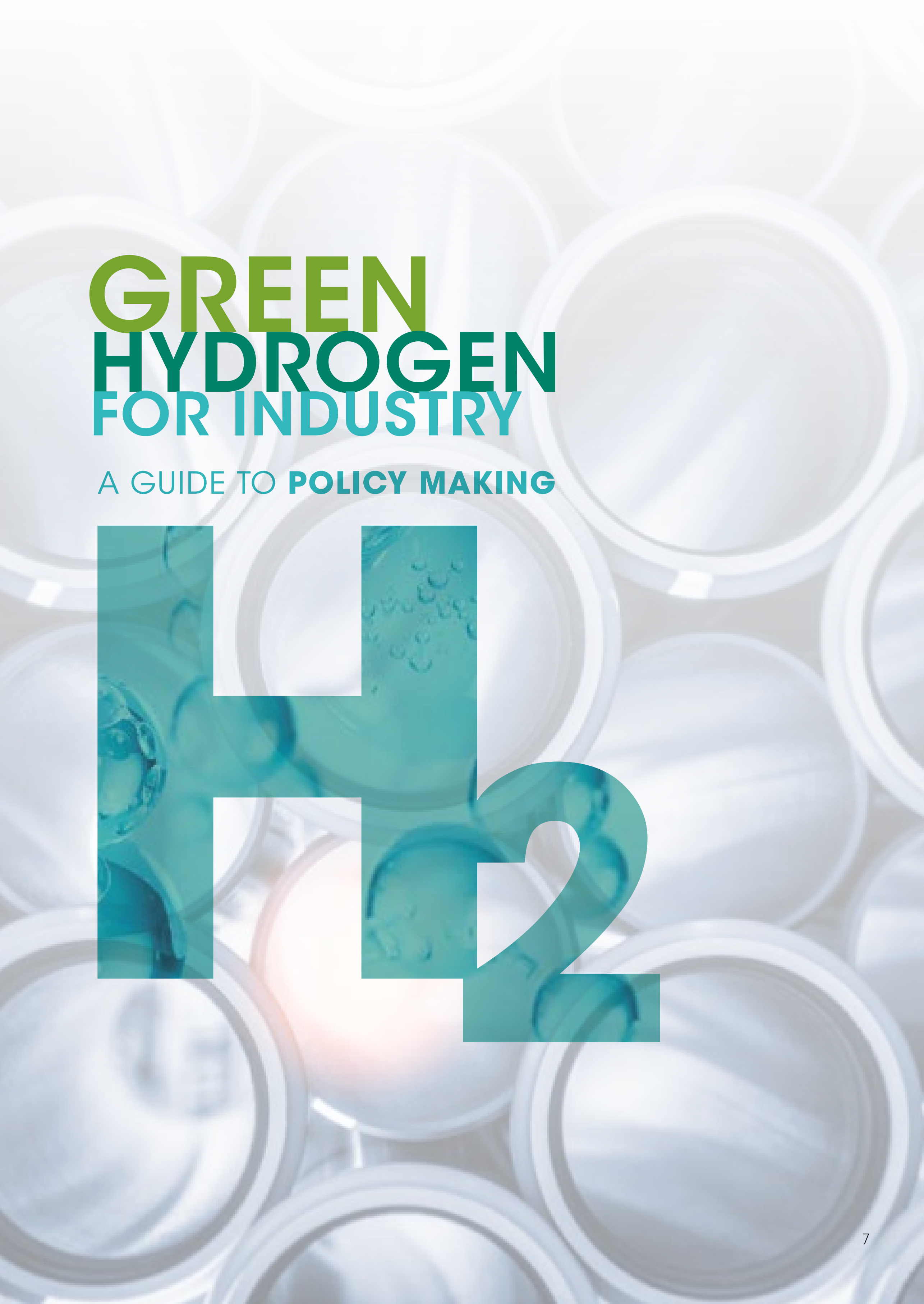


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INTRODUCTION

ABOUT THIS REPORT

Green hydrogen[1] is benefiting from a new wave of interest due to its potential to make a significant contribution to meeting climate goals and advancing the energy transition. In response, IRENA has been analysing options for the production and consumption of green hydrogen, along with devising policies to support and accelerate its commercialisation and wide adoption (see Box i.1).

In 2020 IRENA published an initial report focusing on green hydrogen policies: *Green hydrogen: A guide to policy making* (IRENA, 2020a). It outlines the main barriers to the uptake of green hydrogen and the key pillars for effective policy making. It also creates a framework for discussion about green hydrogen policy making.

The green hydrogen value chain, from production to consumption, consists of multiple elements that are interlinked with the broader energy sector. Each of these element can face specific barriers and challenges. IRENA, therefore, conceived a series of reports focusing on these challenges and the options to overcome them. The IRENA report, *Green hydrogen supply: A guide to policy making*, examines the policy options to support the production of green hydrogen by water electrolysis, its transport, and the options for storage (IRENA, 2021a).

The present report explores the challenges that green hydrogen faces in the industrial sector and the policy options available to policy makers to address these challenges.

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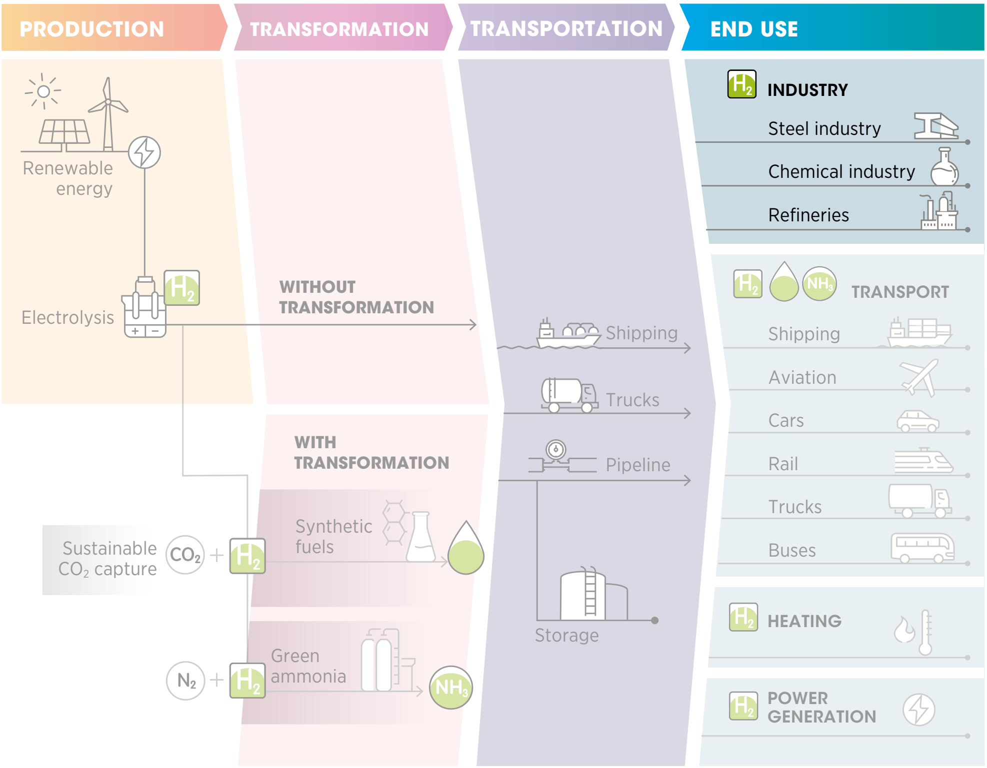
[1] Green hydrogen is hydrogen produced from renewable energy. Since the most established technology options for producing green hydrogen is water electrolysis fuelled by renewable electricity, it will be the focus of this report.

Figure i.1 Green hydrogen value chain and the focus of this report



Sources: IRENA (2020a)

Box i.1 IRENA's work on green hydrogen and hard-to-abate sectors

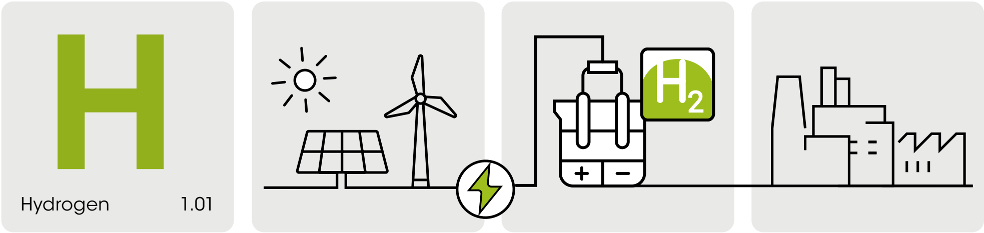
This report is part of IRENA's ongoing programme of work to provide its member countries and the broader community with expert analytical insights into the potential options, the enabling conditions and the policies that could deliver the deep decarbonisation of economies. IRENA's World Energy Transitions Outlook provides a detailed roadmap for emission reductions on a pathway consistent with a 1.5°C goal, alongside assessments of the socio-economic implications (IRENA, 2021b). Building on this, IRENA is analysing specific facets of that pathway, including the policy and financial frameworks needed.

Recent IRENA publications on green hydrogen include:

- Hydrogen from renewable power (2018)
- Hydrogen: A renewable energy perspective (2019)
- Reaching zero with renewables (2020) and its supporting briefs on industry and transport
- Green hydrogen: A guide to policy making (2020)
- Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5°C climate goal (2020)
- Renewable energy policies in a time of transition: Heating and cooling (2020)
- Green hydrogen supply: A guide to policy making (2021)
- Enabling Measures Roadmap for Green Hydrogen (2021), with the World Economic Forum.
- Geopolitics of the Energy Transformation: The Hydrogen Factor (2022)

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 Framework on Green Hydrogen. These initiatives bring together a broad range of member countries and other stakeholders to exchange knowledge and experience.



HARD-TO-ABATE SECTORS AND GREEN HYDROGEN

Energy-intensive industries producing basic materials, such as iron and steel and chemicals, are responsible for a large share of greenhouse gas (GHG) emissions. The iron and steel and chemical sectors alone emitted about 8% and 5% respectively of the 36.9 Gt of global energy- and process-related GHG emissions in 2017 (IRENA, 2020b).

The emissions from these energy-intensive industries have increased steadily with the growing global demand for materials, driven in turn by increased global wealth and urban populations, and associated infrastructure development (Lamb *et al.*, 2021). Reversing this trend and aligning the industrial emissions trajectory with the goals of mitigating the climate crisis is an urgent and challenging task.

Material industries are an integral part of our society; the related policies and social institutions co-evolved with them, often aiming to keep them competitive in a global market. As a result, these industries have become highly efficient but fossil-fuel dependent in their production systems, resulting in “carbon lock-in” (Åhman, 2020). In the iron and steel industry, for example, 40% of the 21 EJ consumed in 2019 came from coal, 33% from fossil gases and 20% from electricity (IEA, 2021a). In addition, demand for basic materials is expected to continue increasing, driven by economic growth and the infrastructure needs of a net zero future.

It has become common to list the iron and steel and chemical industries among the “hard-to-abate” sectors. This is because of their process energy needs and emissions, for which the abatement challenges are many, including the current material use model (with limited recovery after use), the fact that the thermodynamic efficiency of core processes has been maximised without an increase in GHG efficiencies, and the low technology maturity of the electric alternatives (Bataille, 2020).

As its production has become cheaper, with great promise of further cost reduction (IRENA, 2020c), green hydrogen has emerged as a shared decarbonisation solution for some hard-to-abate processes. However, a transition away from fossil fuels is a gradual process, and various policies and measures will be needed along the way (IRENA, 2021b; Rissman *et al.*, 2020).

Policy makers, when supporting the energy transition, have various solutions they can use, with green hydrogen being one of them alongside electrification, energy efficiency, greater material efficiency, a circular economy approach, higher energy efficiency and carbon capture measures. These solutions are not in competition with each other. Instead, they can complement each other when proactive policy making is in place. Still, policy makers need to set priorities and carefully assess the extent of the solutions available. When developing supportive policies, they should consider the relative costs and advantages of green hydrogen compared with other decarbonisation options for certain end uses, especially in view of the ongoing advancement of competing technologies.

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PRIORITY SETTING IN GREEN HYDROGEN POLICY MAKING

Technically, hydrogen can be used in many different sectors, as shown in Figure i.1. However, despite hydrogen's great potential, it must be kept in mind that its production, transport and conversion all require energy, as well as significant investment (IRENA, 2021a, 2020c). As a result, its extensive use may not be in line with the requirements of a decarbonised world, where energy consumption and capacity deployment will have to be carefully managed. In particular, the production of green hydrogen requires dedicated renewable energy that could be used for other end uses. Indeed, indiscriminate use of hydrogen could then slow down the energy transition. This calls for priority setting in policy making.[2]

Priority setting for green hydrogen strategy relies on assessing different factors (IRENA, forthcoming). Some of these factors can be similar between different countries globally, while others are country- or region-specific.

Among the global factors are the **technological readiness of the decarbonisation solutions** and **the potential size of local hydrogen demand**.

Technological readiness of the decarbonisation solutions: Alternatives to green hydrogen, competing as decarbonisation options, are already available for many end uses. For example, heat pumps and direct use of renewable energy are options for residential heating that have been commercially available for decades. In many other cases, alternatives to hydrogen such as fuels for long-haul aviation (*e.g.* biojet fuels) have not yet been demonstrated at a large scale for commercial use. Finally, there are no alternatives to the use of hydrogen for feedstock.

Potential size of local hydrogen demand: Large demand centres can kickstart economies of scale in green hydrogen, making the shift even more cost-effective compared to distributed or new applications. For example, 475 t per day of green hydrogen could be used to power a single ammonia plant with a production capacity of 1 Mt of green ammonia a year, or to meet the demand for refuelling around 6 700 trucks a day (Siemens *et al.*, 2020; Transport & Environment, 2020). Using the hydrogen to make ammonia would avoid the high infrastructure costs of building the refuelling infrastructure. In general, higher, continuous and long-term demand enables hydrogen production to expand, further reducing costs and enabling even greater use. For this reason, "hydrogen valleys" are an option to kickstart regional hydrogen demand (Section 2.2).

These two factors are plotted in Figure i.2. Industrial uses of hydrogen are among the highest priority end use, as alternatives are still missing in the foreseeable future and demand from these facilities can be large enough to allow economies of scale in production and infrastructure, making the shift to green hydrogen even more cost-effective in these applications. High-grade heat is placed in the medium-priority area, where both electrification and green hydrogen can be used. A range of options to produce high-temperature heat via electricity (with resistance, infrared, induction, microwave and plasma heating) can be more energy-efficient than the burning of green hydrogen (Agora Energiewende and AFRY, 2021; Friedmann, Fan and Tang, 2019; Madeddu *et al.*, 2020).

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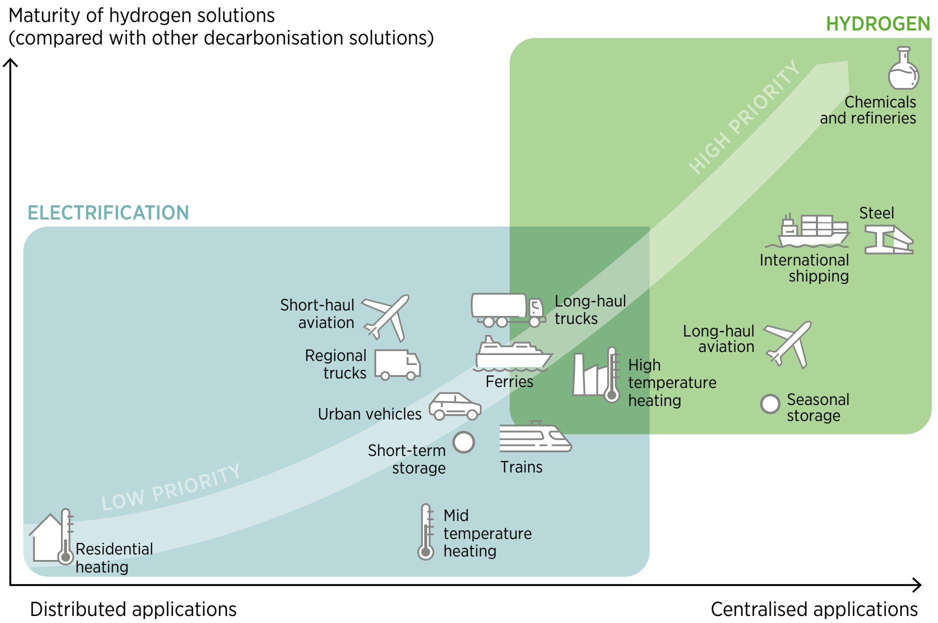
[2] Priority setting is one of the policy pillars listed in IRENA (2020a). The other three are guarantees of origin, national hydrogen strategy, governance system and enabling policies.

Figure i.2 Green hydrogen policy priority

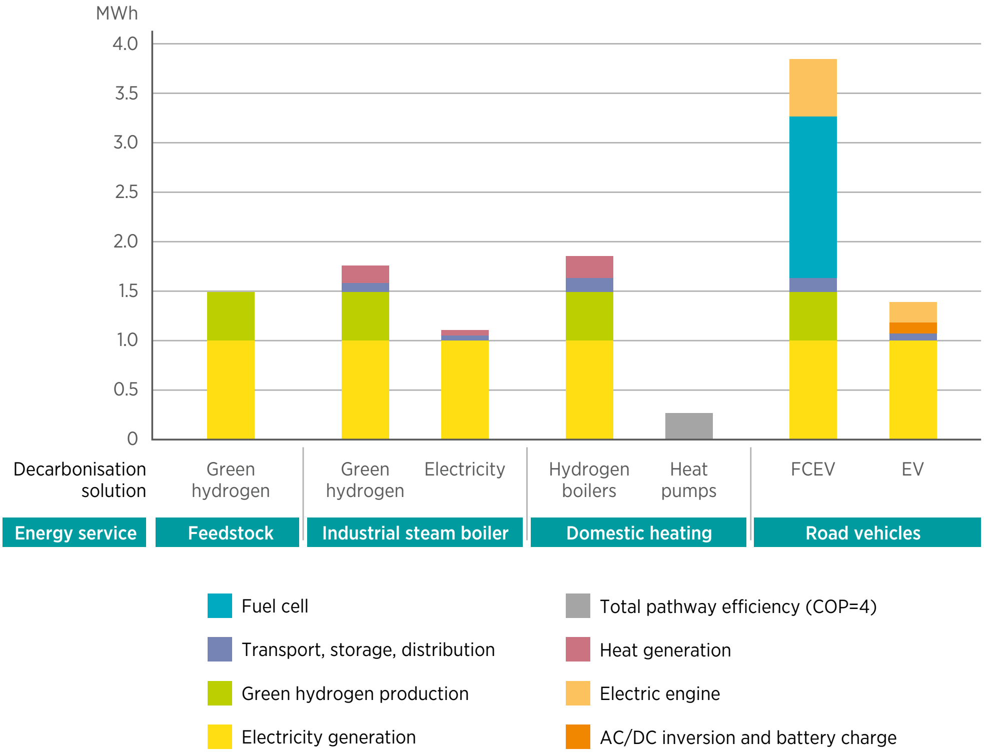


Source: IRENA analysis based on Agora Energiewende (2021a); Belmans and Vingerhoets (2020); Liebreich (2021); IEA (2021b); Natuur & Milieu (2021); Ueckerdt et al. (2021).

Note: On the x-axis the end uses are placed according to the estimated average daily hydrogen demand for industry, refuelling stations and combustion devices, with a power relationship. On the y-axis the end uses are placed according to the differences between the technological readiness levels of hydrogen-based vs electricity-based solutions.

To complement the assessment, when electricity-based alternatives are available the electrical efficiency pathway metric can be used to assess how much more electricity the use of hydrogen would entail compared to direct electrification. This can inform policy makers on the estimated additional power capacity needed to power a certain sector with green hydrogen (examples are in Figure i.3). Furthermore, in considering this aspect, industrial applications have a better outlook than distributed applications. Green hydrogen could still be a preferred option in industrial heat applications, notwithstanding the higher power capacity needed, because of other considerations (*e.g.* energy density, cost, technology maturity and existing assets).

Figure i.3 Estimation of renewable electricity generation needed for 1 MWh by energy services and by transformation passage



Notes: COP = coefficient of performance; EV = electric vehicle; FCEV = fuel cell electric vehicle.

However, energy and industrial sector conditions differ greatly between countries. These different conditions can pivot the priority setting. Country conditions that may change the priority setting can be the maturity level of its industrial sectors, its current level of economic competitiveness, the age of its industrial assets, the presence of a large specific sub-sector (for example, ferries in archipelagic countries), wider political objectives and the potential socio-economic effects, such as job creation and air pollution.

THE EXPERIENCE IN THE POWER SECTOR

Policy making for the energy transition in the industrial sector can look to the cumulated experience of the power sector, where many policies have successfully enabled once niche technologies to become the default option for investors. At the same time, the sectors' different nature should be remembered.

In particular, the energy transition in the power sector has been initiated by new actors participating in the power sector with new technologies, like solar photovoltaic (PV) and wind energy. Electricity is largely produced within the same country it is consumed; import and export are limited by interconnections, mostly under long-term contracts, and electricity is only exchanged with neighbouring countries. Finally, in the power system the participation of smaller actors with limited production, down to self-consumers, is possible.

In the industrial sector it is anticipated that change will be driven by established players with current fossil fuel-dependent facilities being converted to renewable energy. While new players may appear with decarbonised processes, this is unlikely to occur to the extent of replacing current players. Steel and chemicals are widely traded across borders and across long distances, exposing these sectors to global competition. Finally, industrial applications are large and do not have the modular nature of power plants.

Policy makers can devise new policies to support green hydrogen and the energy transition in the hard to abate sectors and can do so through a careful assessment of the experiences in the renewable energy sector as well as by considering the distinctive nature of the industrial sector.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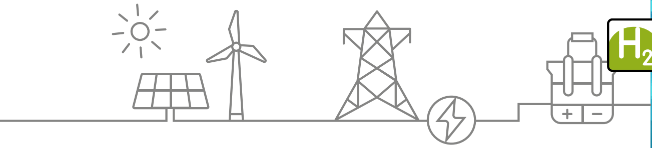

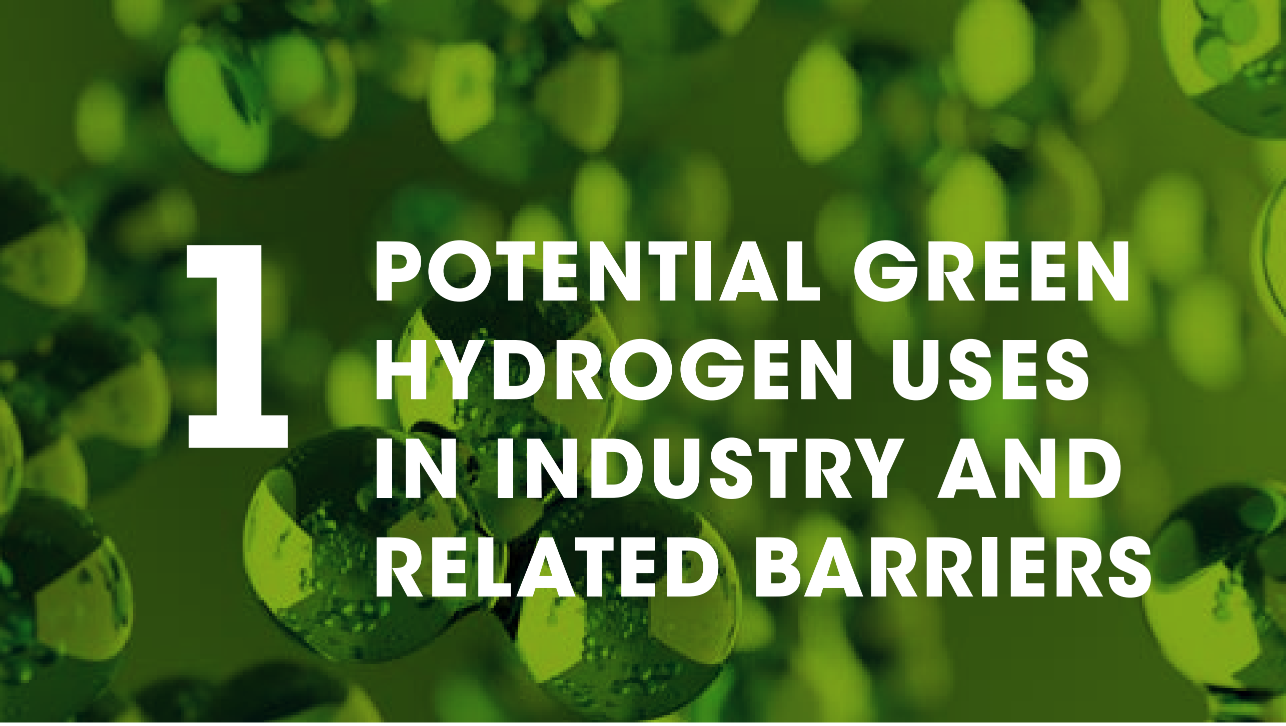

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POTENTIAL GREEN HYDROGEN USES IN INDUSTRY AND RELATED BARRIERS

1.1. CURRENT STATUS AND POTENTIAL USES

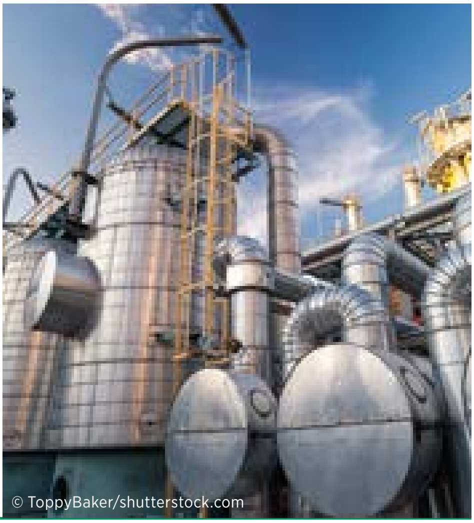
Current hydrogen supply for industrial uses can be separated into three distinct pathways: captive, merchant and by-product hydrogen (Connelly, Elgowainy and Ruth, 2019):

- Captive hydrogen is produced by the consumer for internal use and is the most common method for large hydrogen consumers.
- Merchant hydrogen is generated in an external production facility and delivered to large-scale and retail hydrogen consumers.
- By-product hydrogen is produced in another process where it is not the primary product; it can be consumed as captive hydrogen or sold as merchant hydrogen.

In Europe captive hydrogen production is the most common option, comprising around two-thirds of all hydrogen production (FCHO, 2020).

Hydrogen is currently used in oil refineries to remove impurities and upgrade heavy oil fractions (see Box 1.1), as a feedstock for chemical production (such as ammonia and methanol), and as a reducing agent[3] in iron making. Industry demand for hydrogen was 87.1 Mt in 2020 (Figure 1.1).

The following sections briefly present how hydrogen has or can have a role in the chemicals and steel sectors, focusing on the main applications for the foreseeable future; since a sharp reduction in fossil fuel use is needed to achieve the 1.5°C target, this report does not focus on the decarbonisation of hydrogen production in oil refineries (see Box 1.1).



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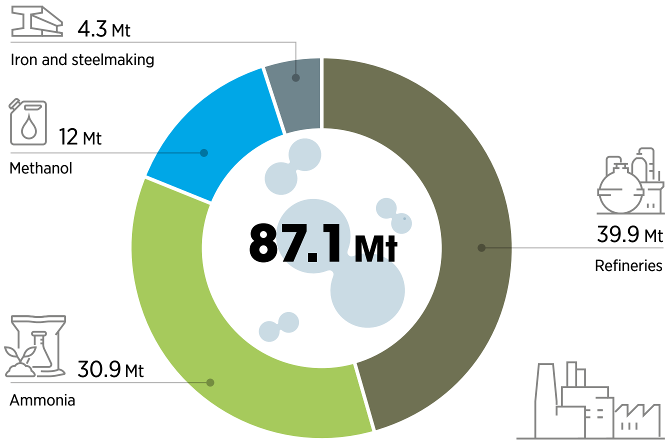
[3] Reduction is the necessary process of removing oxygen from iron ore to create iron.

Figure 1.1 Pure hydrogen demand in industry, global, 2020



Box 1.1 Hydrogen in oil refineries

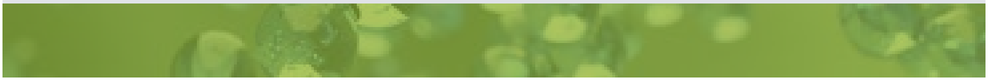
In oil refineries, almost 40 Mt of hydrogen produced in 2020 was used in two processes: hydrocracking and hydrotreating.

Hydrocracking is the process of converting heavy and low-quality gas oil into more valuable fuels such as diesel, gasoline and jet fuel in the presence of hydrogen and a catalyst. Hydrocrackers are used in refineries to maximise diesel production while reducing residual fuel oil.

Hydrotreating is the process of mixing hydrogen (and a metal catalyst) with fossil gas or refined petroleum products (*e.g.* gasoline, jet fuel, diesel) to remove sulphur and other contaminants.

Hydrogen is produced as a by-product in oil refineries, for example in catalytic naphtha reforming. However, by-product hydrogen is not sufficient to cover the hydrogen demand of larger refineries, so around two-thirds of demand is supplied through captive and merchant hydrogen. Refineries' hydrogen demand has grown substantially in the last few decades. Hydrogen production can represent a sizeable amount of the total CO_2 emissions of a refinery, at around 15% in the United States and Europe (Pilorgé *et al.*, 2020; Soler, 2019).

When forecasting future trends for hydrogen demand in oil refineries, it is essential to note that global production from refineries is expected to decrease due to the replacement of fossil fuels in the global economy. According to IRENA's 1.5°C Scenario, the primary energy supply from oil will need to fall from 140 EJ in 2018 to 14 EJ in 2050 (IRENA, 2021b).



1.1.1 Chemical industry

In the chemical industry, hydrogen is used to produce ammonia, methanol and other chemicals. Since hydrogen is already an essential component of these chemicals, the integration of green hydrogen requires limited modification, based only on changing the process for obtaining hydrogen from fossil fuels reforming or gasification to water electrolysis.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Ammonia

Ammonia is produced from hydrogen and nitrogen. It is the second most widely produced chemical commodity by volume, with global production of more than 183 Mt in 2020 (Hatfield, 2020). Fertiliser manufacturers are responsible for using more than 85% of global ammonia production, making the agricultural sector the most significant ammonia consumer (Brightling, 2018). Global population growth is set to increase the demand for fertiliser; this, combined with the prospective use of ammonia in international shipping and power generation, is foreseen to increase the demand for ammonia to almost 600 Mt by 2050, of which around 55% can be produced with green hydrogen (IRENA, 2021b; Saygin and Gielen, 2021).

Ammonia production plants typically use hydrogen from steam methane reforming (SMR). This process alone is associated with 90% of the CO_2 emissions related to ammonia production (The Royal Society, 2020).

Green hydrogen is the solution to deeply decarbonising the production of ammonia. Since there are energy requirements associated with the remaining ammonia production processes, they must also be powered by renewable energy for all ammonia to be truly zero carbon.

Methanol

Methanol is a versatile molecule used to synthesise heavier alcohols, gasoline and many other complex chemicals. The synthesis of chemicals accounted for more than 60% of global methanol production in 2019. It can be used in internal combustion engines as an alternative to conventional transport fuels, where it can function as a stand-alone product or be converted to other chemicals that can be blended with gasoline. In 2019 the use of methanol as a fuel represented about 31% of global methanol production (IRENA and the Methanol Institute, 2021).

Methanol production through the conventional route entails the transformation of fossil gas or coal into synthetic gas (syngas), a mixture of hydrogen and carbon monoxide, and then the conversion of syngas into methanol.

Global production of methanol reached around 98 Mt in 2019 and has more than doubled in a decade. Virtually all of the carbon needed came from fossil fuel resources (fossil gas and coal), with less than 0.2 Mt produced using biomass (IRENA and the Methanol Institute, 2021). Methanol consumption is forecast to grow in a net zero world; production could reach 401 Mt per year by 2050, of which around 73% can be produced with green hydrogen (IRENA, 2021b; Saygin and Gielen, 2021).

Green hydrogen can be used to replace coal and fossil gas to produce green methanol.[4] However, to be "green", the carbon content of the methanol molecule must be obtained sustainably from bioenergy with carbon capture and storage (BECCS) or captured from the atmosphere with direct air capture (DAC) technologies.

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[4] *Where methanol is produced with green hydrogen, it is sometimes called e-methanol to distinguish it from biomethanol (methanol produced from biomass).*

1.1.2 Steel production

Steel has been produced for millennia. In 2020 steel production reached 1.878 billion tonnes, with China accounting for over half of global production. Thanks to its wide range of applications and its versatility, steel is the basis for a variety of industries. In 2019, 52% of steel was used in buildings and infrastructure and 17% in transport applications (worldsteel, 2021).

Nowadays, it is produced mainly in two ways: the **blast furnace-basic oxygen furnace (BF-BOF)** route to produce primary steel (from iron ore) and the **electric arc furnace (EAF)** to produce secondary steel (from scrap).

The BF-BOF is the leading production method, with a share of 71% of global steel production, mostly in Asia (Fan and Friedman, 2021). It is composed of the blast furnace (BF), where iron ore is reduced to cast iron using coke, and the basic oxygen furnace, where the hot metal is converted into steel. The BF-BOF route is the more energy intensive, with one tonne of crude steel consuming 21.4 GJ of final energy on average (BNEF, 2021).

An EAF produces secondary steel by melting steel scrap with the heat generated by an electric arc, using additives to adjust the chemical composition of the steel. This production method is used for 24% of steel production, but the availability of recycled steel limits its market share. Steel scrap availability is typically limited by the long lifespan of steel products, such as bridges and buildings (BNEF, 2021; Fan and Friedmann, 2021; IRENA, 2020b).

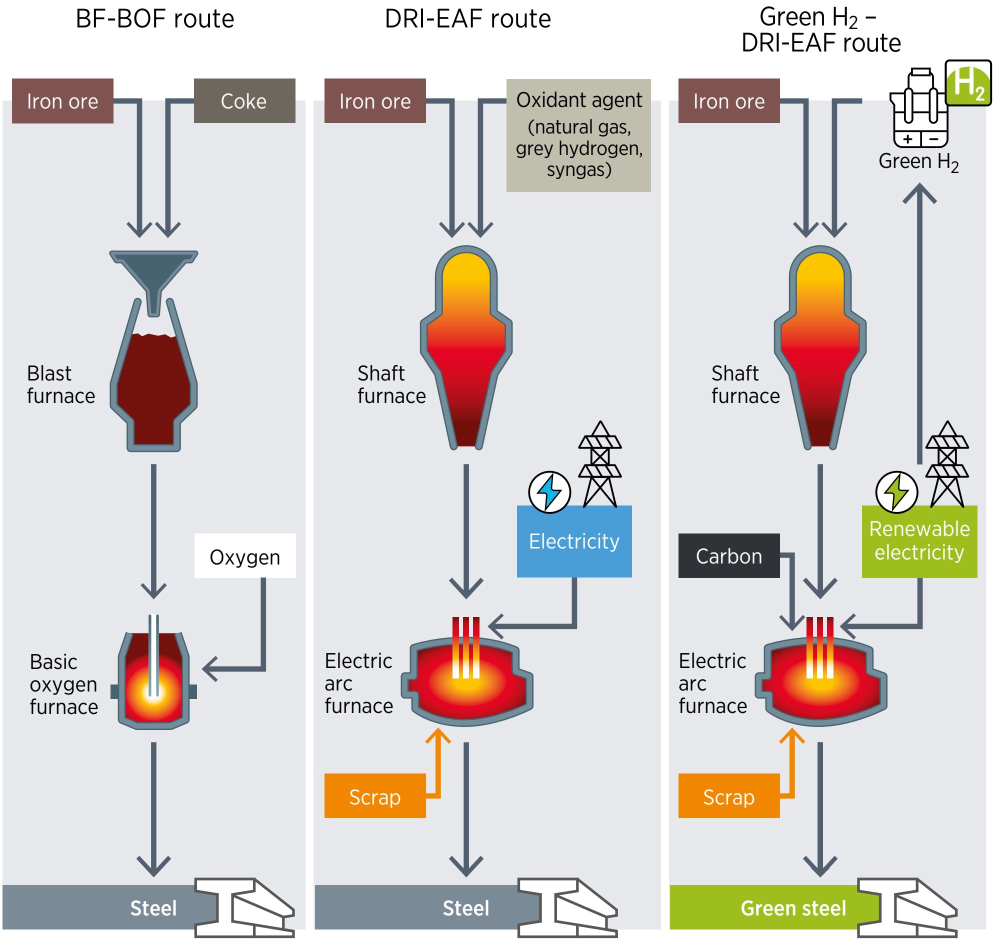
In the absence of steel scrap, the **direct reduction of iron (DRI)** can be used to feed the EAF. DRI is the group of processes for making iron from iron ore, typically using a syngas. No BF is needed to produce primary steel with this method. It is more energy-efficient than the BF-BOF, with 17.1 GJ consumed per tonne of steel. The DRI-EAF method is used for 5% of current steel production and consumed around 4.3 Mt of hydrogen in 2020 (BNEF, 2021; Fan and Friedmann, 2021).

The BF-BOF route is the more carbon-intensive steelmaking process, with emissions reaching 1.7-2.2 t CO_2/t_{steel} (Agora Energiewende, 2020; BNEF, 2021; Fan and Friedmann, 2021). Most of the emissions are from the BF process and the production of coking coal, which is used as a source of heat and a reducing agent for iron. Hydrogen can be used in the BF as a reducing agent, decreasing the amount of coking coal required. However, hydrogen cannot fully replace coking coal. In fact, green hydrogen injection into a BF can only reduce emissions by about 21% (Yilmaz, Wendelstorf and Turek, 2017). Therefore, decreasing the BF-BOF emissions to net zero levels will require the deployment of carbon capture and storage (CCS) technologies. Applying CCS to iron and steelmaking, however, has significant uncertainty surrounding its costs, applicability and carbon offset credibility; as carbon capture will be partial, steelmakers will need to buy carbon offsets if an emissions cap towards net zero is implemented in the local jurisdiction.

While different players around the world are considering the use of hydrogen in DRI-EAF processes (see Box 1.3), there has been no announcements to use CCS in steel production. The only carbon capture utilisation and storage (CCUS) unit in the steelmaking sector is capturing the flue gas from a DRI-EAF plant in the United Arab Emirates, and injecting the CO_2 for enhanced oil recovery in nearby oil fields. The capture capacity is 0.8 Mt CO_2/yr (Agora Energiewende, 2021b). Pilot and demonstration CCS projects in the steelmaking sector have also been commissioned and are operational in Belgium, France, Japan and Sweden, for a total estimated of 0.022 Mt CO_2/yr (BNEF, 2022).

While hydrogen is only an auxiliary reducing agent in a BF, it can be the primary reducing agent in the DRI process. However, a carbon source is still required to produce steel from the EAF. Biogenic carbon sources may be used in lieu of fossil fuels, but the presence of carbon means that emissions cannot be entirely avoided – although they can be reduced sizeably, down to 0.025 t CO_2/t_{steel}. The process still requires iron ore pellets, whose production can cause significant emissions (Berger, 2020; BNEF, 2021; Fuel Cells and Hydrogen 2 Joint Undertaking, 2019).

Figure 1.2 Main steel production pathways



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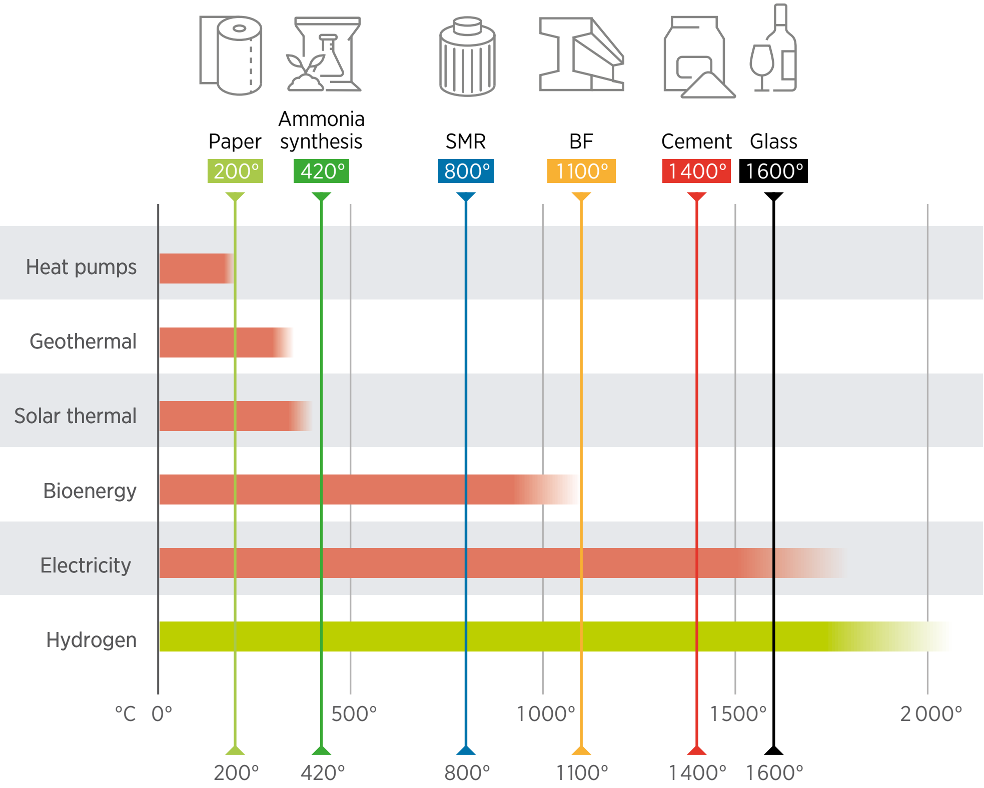
The consumption of green hydrogen in the steel industry is currently limited to demonstration projects. Similar to the chemical industry case, hydrogen consumption would be at sufficient scale to justify the co-location of electrolysers and steelmaking plants without the need for infrastructure to transport hydrogen.

1.1.3 High-temperature heat

Industries need heat for various processes. Industrial heat can be classified as high, medium or low, with high-temperature heat above 400°C, medium-temperature heat between 100°C and 400°C, and low-temperature heat below 100°C. Many decarbonised solutions exist to produce low- and medium-temperature heat without resorting to hydrogen (IRENA, IEA and REN21, 2020). Hydrogen combustion produces high-grade heat that meets almost all heavy industrial applications (Figure 1.3).

Figure 1.3 Working temperatures for selected renewable heat technologies and temperature requirement of selected industries



Sources: Adapted from Friedmann, Fan and Tang (2019); IRENA, IEA and REN21 (2020).

More than 85% of industrial heat is consumed in iron and steel, chemicals and cement. Around 95% of the high-temperature heat is currently provided by the combustion of fossil fuels or combustible by-products (IEA, 2019). Small amounts of biomass are used in specific sectors, such as in the pulp and paper industry.

Electricity can also be used for high temperature heat, generating heat via resistance, infrared, induction, microwave and plasma heating (Agora Energiewende and AFRY, 2021; Madeddu *et al.*, 2020). The advantages of electrical heating include its capacity for precise temperature regulation and lower maintenance costs. Given that the performance factor[5] of high-temperature heat from electric heating is at the very least comparable to burning hydrogen from electrolysis (0.5-0.9 for electrical heating vs 0.55-0.8 for hydrogen burners), power-to-heat technologies should be considered as the first choice, before green hydrogen.

However, the electrification of high-grade heating entails redesigning industrial equipment and, therefore, capital expenditure. Industrial operators may thus prefer less invasive options, such as hydrogen, that involve minimal redesign; substantially modifying existing processes may be considered less viable without financial support (Friedman, Fan and Kang, 2020).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[5] *Expressed as kWh heat output per kWh electricity input.*

1.2. BARRIERS

This section presents the main barriers to the consumption of green hydrogen for the production of green materials and goods.[6] These include the cost barrier, technical barriers, the lack of a real market for green products, policy uncertainties and the carbon leakage risk.

This section does not assess the main barriers to the production and transportation of green hydrogen itself, such as the high cost of production, sustainability issues, unsuitable power system structures and the lack of technical and commercial standards. These aspects are covered in the previous guide entitled Green hydrogen supply: A guide to policy making (IRENA, 2021a).

1.2.1 Cost of green materials and investments

Green production processes for materials cost more than the default fossil fuel-based mature processes (see Box 1.2).

Steel and chemicals industries are very capital intensive with low profit margins, depending to the cost of raw materials and the economic growth. Economies of scale and low raw material and energy prices are crucial to profitability. As long as green products compete against established higher-carbon – but lower-cost – options, they will struggle to charge prices that recover their production costs while remaining competitive against their grey counterparts, also because the product is perceived and buyers focus primarily on final price.

However, the issue is not only the higher cost of the final product. When processes are changed, companies experiment with different technologies which can cost billions of US dollars. Without support schemes or a clear demand for green materials or goods, the investment could be too great for a single firm (Gross, 2021).

It should be noted that basic materials are further processed downstream, so the cost impact on end-product prices is expected to be low. For instance, a 20-30% higher steel cost translates into a 0.5% increase in the cost of a car (Bataille *et al.*, 2018; Material Economics, 2019).

1.2.2 Technical barriers

As hydrogen molecules are the same independent of the production route, processes that use hydrogen produced from fossil fuels can use green hydrogen without technical challenges if the flow remains unchanged.

However, in the petrochemical and chemical sector the SMR processes used to produce grey hydrogen[7] also work as a heat sink, increasing the overall efficiency of the process. Electrolysis is not a heat sink and thus it cannot use waste heat from other processes, potentially reducing the overall efficiency.

Without storage, green hydrogen from variable renewable energy will similarly have a variable production pattern. Industrial processes have limited experience with continuous load adjustment for supply variation. So hydrogen storage could ensure a steady supply, working as a buffer for the electrolysers, but also increasing the overall green hydrogen costs. Assuming 30 years of useful life, pressurised tanks add costs of USD 0.2-0.85/kg (BNEF, 2019; IRENA, 2021a). The processes themselves could become more flexible to cope with solar and wind variability. For example, the ammonia production process can become more flexible by adopting different types of machinery or operating at different pressures (Armijo and Philibert, 2020).

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[6] *Across this report, "green materials" refers to steel, ammonia and methanol produced using green hydrogen. "Green goods" refers to goods (cars, fertilisers, etc.) produced using green materials. "Green products" refers to both when appropriate.*

[7] *Grey hydrogen is produced with fossil fuels, from methane using SMR or coal gasification.*

Box 1.2 Costs of green hydrogen and materials

Green hydrogen and green products share the barrier of cost with other energy transition-related technologies. The cost barrier has always been higher at the inception of a new technology and gradually decreased as experience and economies of scale are accumulated for a given technology. After high initial costs, solar PV and wind energy are now cheaper than the operational costs of existing coal-fired generators (IRENA, 2021c). These costs do not take into account the externalities related to the consumption of fossil fuels, which would reduce the cost gap and ultimately make green solutions always more attractive than traditional approaches.

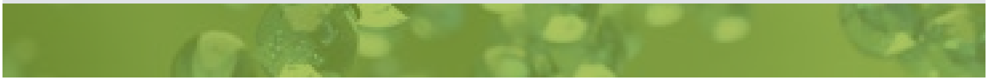
Green hydrogen is currently more expensive than grey hydrogen. IRENA estimates that current green hydrogen costs are in the range of USD 4-6/kg, compared with USD 1-2/kg for grey hydrogen (IRENA, 2020c). The use of green hydrogen therefore increases the cost of the goods produced with such a carrier. Many first movers in green hydrogen solutions present the cost gap as the main obstacle (IRENA Coalition for Action, 2021).

Estimates indicate that while grey ammonia costs stood in the range of USD 250-450/t in the past decade, **green ammonia** can be two to three times more expensive. However, it is estimated that green hydrogen technology can cover this gap by 2030 as the cost of electrolysers and renewable electricity declines, even with dedicated ammonia synthesis facilities. According to estimates, green ammonia may be produced term at a competitive cost of between USD 500/t and USD 625/t in areas heavily endowed with renewable resources by fine-tuning the size of hydrogen storage and synthesis equipment, and taking advantage of resource complementarity (Armijo and Philibert, 2020; Fasihi *et al.*, 2021; IRENA and AEA, forthcoming; Saygin and Gielen, 2021; Valentini, 2020).

The cost of producing grey methanol is in the range of USD 100-400/t. The current production cost of **green methanol** is estimated to be USD 800-1600/t assuming the CO_2 is sourced from BECCS at a cost of USD 10-50/t. If the CO_2 is obtained by DAC, where costs are currently USD 300-600/t, green methanol production costs would be USD 1200-2400/t. With anticipated decreases in renewable power prices, the cost of green methanol is expected to decrease to levels between USD 250-630/t by 2050 (IRENA and The Methanol Institute, 2021).

Green steel investment and operating costs are in the order of 30-50% higher compared to the principal route, including the electrolyser. Energy consumption for green steel is around 15% lower, but the electricity for electrolysis is much more expensive than coal, which costs around USD 10/MWh (IRENA, 2021a). Market prices for steel fluctuate; during 2015-2020 average prices were in the range of USD 400-600/t, while during the 2021 global supply chain crisis they achieved USD 800/t. Early assessments of the production price of full-scale hydrogen-based direct reduction indicate a 20-30% higher cost with the price of electricity below USD 60/MWh (Koch Blank, 2019; Rissman, 2020; OECD, 2021; Vogl, Åhman and Nilsson, 2018).

The conversion cost of equipment to produce **high-temperature heat** from green hydrogen depends on the existing equipment and its size. It has been estimated that the conversion cost ranges from USD 52/kW (steam boilers in the chemical industry) to around USD 100/kW (for example, for paper drying) in the United Kingdom of Great Britain and Northern Ireland (UK) context (Hy4Heat, 2019).



For hydrogen to replace fossil fuels in certain processes, such as in steelmaking, a complete change of technology will be necessary. Shifts in technology are not unprecedented. For example, in the 1950s open-hearth furnaces were the dominant technology in US steelmaking (producing up to 90% of US steel), but were completely phased out in 50 years by EAF and BOF technology (Manning and Fruehan, 2001). However, the energy transition will require a more rapid and global phase-out of current technologies.

Critical challenges to using hydrogen for high-temperature heat include changes in heat transfer characteristics and flue gas composition, including higher nitrogen oxide (NOx) emissions. Furthermore, fossil gas equipment must be modified to operate on hydrogen because of different combustion characteristics. As of today, hydrogen uses in industry for high-temperature heat are still at the prototype stage for some technologies like steam boilers.

For methanol to be carbon neutral and sustainable, the CO_2 has to be from BECCS or DAC technologies. Sequestration of carbon from biomass can already be applied today. DAC, although promising, is still at the early stages of development (IRENA and The Methanol Institute, 2021).

Finally, a large amount of electricity would be needed to satisfy the demand for green hydrogen in industry. If green hydrogen provided 16.8 EJ to chemicals and steel only by 2050, this would require total electricity of almost 6.81 PWh/yr (IRENA, 2021b).[8] For comparison, this is close to the world's entire renewable electricity production in 2020 (7 PWh). The issue, however, is not the total electricity needed, since the global renewable resource potential is in orders of magnitude higher than hydrogen demand, but whether the annual pace of development of renewable electricity will be fast enough to meet the needs of both end-use electrification and the development of a global supply chain in green hydrogen (IRENA, 2020a, 2021b).

1.2.3 Lack of value recognition and low demand

The current production and use of sustainable materials and plans for green materials are driven mainly by climate ambition or speculation on their demand rather than immediate economic gain. While stakeholders may believe that economic gain will happen in the future, currently an established means of placing a monetary value on the benefits of green goods does not exist. Indeed, there is no widespread compensation for the higher costs that green goods entail, nor are there adequate economic barriers to non-climate-friendly solutions.

While interest in the idea of green materials and goods is growing, little to no actual demand exists. Despite increased public concern about climate change, the "intention-action" gap in purchases exists and resists (Joshi and Rahman, 2015; Song *et al.*, 2019); public-sector procurement rules may focus more on corruption avoidance and cost reduction, leaving environmental concerns aside.

The lack of demand is accompanied by a substantial lack of production and infrastructure (IRENA, 2020a), creating the so-called **chicken and egg problem** of green hydrogen: green hydrogen solutions are cost-prohibitive today, but without demand, investment remains too risky for wide-scale production that could reduce costs. Without a change in this dynamic, costs will remain too high to kickstart actual large-scale demand for green hydrogen.

Despite the absence of incentives for green products in industry and the lack of market demand for these products, progressive private-sector entities have been making decarbonisation efforts (Box 1.3 presents some prominent examples). Their approach is to build electrolysers within the facility using the energy carrier or creating "hydrogen valleys", meaning regions where centralised hydrogen production serves multiple industries. These cluster enough demand to achieve economies of scale, leading to lower costs and justifying common infrastructure development.

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[8] *Assuming an overall production and transport efficiency of 68% by 2050.*

Box 1.3 Industrial companies with hydrogen-related decarbonisation targets – selected examples

HYBRIT (Hydrogen Breakthrough Ironmaking Technology) is a consortium formed in April 2016 by three Swedish companies: the steelmaker SSAB, the iron ore mining company LKAB and the energy company Vattenfall. The consortium's goal is to transition to fossil-free iron and steel production in the Swedish and Finnish markets by 2035. The objective is to have a complete low-carbon process across the entire value chain, from the mine to finished steel. LKAB, the largest iron ore producer in Europe, will be replacing coal with green hydrogen for the DRI process, while SSAB will convert to EAFs. Vattenfall will provide the fossil-free electricity required for both processes and develop the technology for large-scale underground hydrogen storage. In June 2021 HYBRIT successfully completed the test production of sponge iron. The first steel made with HYBRIT technology was rolled by SSAB in July. The partners aim to demonstrate the technology on an industrial scale as early as 2026 (Arens and Vogl, 2019; HYBRIT, 2021; Vattenfall, 2021).

Voestalpine is an Austrian steel-based technology and capital goods company. The company's stated goal is to achieve carbon-neutral steel production by 2050. Its strategy is based on achieving a 30% reduction in emissions by 2030 through the gradual phase-out of coal-based steel production to production based on fossil gas and renewable electricity, increasing the share of green hydrogen, and delivering carbon-neutral steel by 2050. In 2019 Voestalpine and five other companies in the EU flagship project H2FUTURE developed a large polymer electrolyte membrane electrolyser pilot facility, located at Voestalpine's steel plant in Linz, Austria. The plant has run successful trials and can produce around 100 kg of green hydrogen per hour (Arens and Vogl, 2019; Voestalpine, 2021).

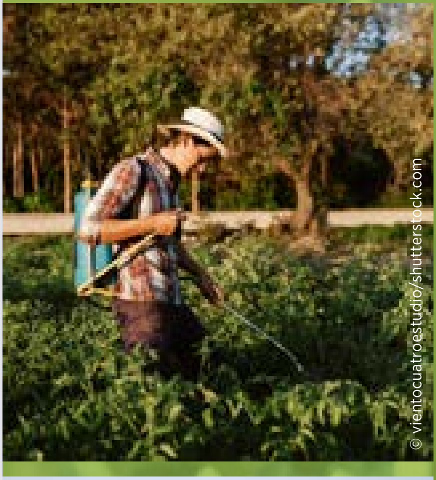
HBIS Group, also known as Hesteel Group, is one of the largest steel producers in China and the third-largest globally. In March 2021 the company announced its Low Carbon Green Development Action Plan, detailing its carbon reduction ambitions. According to the plan, HBIS aims to be carbon neutral by 2050. To achieve its target, HBIS Group has set the short-term targets of reaching a peak in emissions by 2022, then cutting emissions by 10% and 30% by 2025 and 2030, respectively. The company's plan for decarbonisation is separated into two phases. In the first phase, which is scheduled to begin in late 2021, the company will produce blue hydrogen to feed the process of producing 600 000 t of iron per year, reducing emissions by at least 40%. The second phase foresees the use of green hydrogen (Steelguru, 2021).

©voestalpine Linz (Hafen)

Fertiberia is a Spanish chemical manufacturing company and one of the largest producers of fertilisers and ammonia in the European Union. In 2020 the company signed an agreement with the Spanish electric utility company Iberdrola to install 800 MW of green hydrogen production capacity over the next seven years, equivalent to 20% of Spain's target of 4 GW of electrolyser capacity by 2030. The agreement entails a combined investment of EUR 1.8 billion and is predicted to create 4000 jobs. The first of their four planned hydrogen plants comprises a 100 MW solar PV system, a 20 MWh lithium-ion battery system and a 20 MW electrolyser. The hydrogen produced from the first plant will be used at Fertiberia's green ammonia plant in Puertollano, Spain. The first molecules of green hydrogen were produced in December 2021 (Iberdrola, 2020).

The **Westküste 100** project is a cross-industry consortium made up of multiple entities, including EDF Germany, Holcim Germany, OGE, Ørsted, Raffinerie Heide, Stadtwerke Heide, Thyssenkrupp Industrial Solutions, Thüga, the Region Heide development agency and the Westküste University of Applied Science. The project aims to create an industrial-scale regional hydrogen economy on the west coast of Schleswig-Holstein, Germany, integrating regional industries' needs while demonstrating green hydrogen's potential. Initially, a 30 MW electrolyser powered by an offshore wind farm is to be installed at Heide Refinery. Building on the experience from the initial 30 MW electrolyser, the consortium plans to scale up hydrogen production capacity to 700 MW. The hydrogen produced is to be combined with the CO_2 captured from a cement plant, to produce methanol (Westküste100, 2021).

The HYBRIT, Fertiberia and Westküste 100 examples are featured as case studies in the IRENA Coalition for Action report, "Decarbonising end-use sectors: Practical insights on green hydrogen" (2021).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1.2.4 Lack of sufficient policy ambition

Significant investment in green hydrogen technologies and infrastructure will be more complex without clear, binding policy commitments. Regardless of the policy mechanism, stable and long-term frameworks are necessary to realise the potential of green hydrogen (IRENA, IEA and REN21, 2020).

When implementing policies that will translate climate commitment into reality, the risk is the adoption of sub-optimal policies. The short timeframes of the energy transition imply that a technological change must happen as soon as possible. However, decarbonisation policies often promote a gradual pathway for each sector (for example, gradual use of renewable-based solutions or energy efficiency measures).

The goal of reaching zero emissions requires a very different mindset compared to an objective of gradually reducing emissions and, in some cases, progressing with the "gradual reduction" mindset risks locking in emissions.

The "gradual reduction" mindset, in fact, enables a market for less carbon-intensive but still fossil fuel-based solutions. Blue hydrogen with partial CCUS could be an example, and electrolytic hydrogen fuelled by fossil-based electricity could offer a lifeline for fossil fuels. These solutions create additional transitional barriers, as adopters of the more efficient (but still fossil fuel-based) solutions aim to complete their investments' lifetime instead of changing technology as new, more restrictive policies are adopted. This situation will require additional actions to eliminate the remaining emissions when more ambitious climate change objectives are later adopted, creating additional government expenditure and stranded assets that pile up as the infrastructure of the fossil fuel era.

Investment decisions in industry have a long-term impact due to the high capital costs and long useful life of industrial assets. These investment decisions are also urgent: 71% of blast furnaces will need major refurbishment before 2030, and the remainder will need it before 2040 (Agora Energiewende, 2021b). The average lifetime of chemical plants is around 30 years; the average ammonia plant is 15 years old, and the oldest are located in Europe and Asia (IEA, 2020). Therefore, only one investment cycle exists before 2050, and new low-carbon technologies must be the next recipient of investment to avoid carbon lock-in within the limited timeframe to avoid climate catastrophe.

A step change, whilst expensive, may be the only option for specific industries to achieve a net zero emission system. For hard-to-abate industries, the technological shift must also be timed with the deployment of the renewable power needed to produce green hydrogen. This would reduce the risk of locking in emissions in the power sector.

The size of these challenges led some governments in Glasgow to sign the Glasgow Breakthroughs, which cover steel and hydrogen among other sectors (Box 1.4).

Box 1.4 The Glasgow Breakthroughs

To better frame the action needed to reduce emissions, the UN High Level Climate Champions presented the 2030 Breakthroughs at COP26 in Glasgow in November 2021. These are time-based sectoral objectives across the energy sector that provide a path to reducing emissions. The Glasgow Breakthroughs were presented as five government-backed targets for 2030 for strategic sectors. Steel and hydrogen are among them: for steel, the target is "to make near-zero emission steel the preferred choice in global markets, with efficient use and near-zero emission steel production established and growing in every region by 2030". For hydrogen, "to make affordable, renewable and low-carbon hydrogen globally available by 2030" (UNFCCC, 2021). This initiative aims to mobilise governments to co operate in establishing demonstration projects and collaborate in addressing the main challenges faced by these sectors.

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1.2.5 Carbon leakage risk

"Carbon leakage" describes the situation where, due to higher costs incurred to comply with climate policies, companies relocate facilities to jurisdictions with laxer emission constraints, possibly leading to an increase in total emissions. Explicit carbon pricing or mandates targeting industry can cause carbon leakage, but other policies may also indirectly hamper a company's business case (*e.g.* increased energy costs due to renewable energy surcharges) (Cosbey *et al.*, 2019; Marcu *et al.*, 2013).

Carbon leakage can become a barrier to the use of green hydrogen if businesses decide to relocate to jurisdictions where its use is not necessary, decreasing global demand. Moreover, producers who decide to comply with climate requirements may face competition from producers that prefer to move their operations to countries with lax climate policies.

Carbon leakage also becomes a barrier to green hydrogen when, to avoid leakage effects, governments implement measures to reduce the impact of climate change policies on heavy industry, such as technology-specific free allocation of emission allowances, shielding them from the burden of a step change that could require the use of green hydrogen.

2

POLICIES TO PROMOTE GREEN HYDROGEN IN INDUSTRY

The energy transition calls for the phase-out of fossil fuel-based technologies used to produce basic materials and the adoption of low-carbon technologies. As the previous section has shown, there are multiple barriers to overcome and individual investors, when they are not required to do so, have no clear incentive to deploy green technologies, in particular where these technologies are not competitive with incumbent processes. Some investors may see a long-term advantage in becoming first movers, but even in these cases deep decarbonisation of the processes may be hard to achieve without a change in the enabling environment.

The fossil fuel dependency of the hard-to-abate sectors can be unlocked by concerted effort and a long-term vision. This unlocking will require changes to many aspects of traditional industrial policy making, which evolved in most of the world with the prime objective of keeping the industrial sector local and competitive.

Creating new policies and regulations to decarbonise industry will have to face the national role played by industry, particularly heavy industry. Industrial policies aiming to reinvigorate developed countries' industries resurfaced in response to the 2008 financial crisis, reintroducing policies supporting local industry in contrast with the previous decades' pro-globalisation policy trend. At the same time, for developing countries, industrialization is a way to promote development, create higher domestic value-added, and create higher-value jobs (Åhman, 2020).

For the world to achieve net zero carbon emissions by 2050, investment in green materials and progress along the learning curve must start as soon as possible. New measures will be required to overcome the policy and cost barriers that impede the conversion of traditional material industries, support the creation of a green materials and a green goods market, and overcome carbon leakage (Figure 2.1).

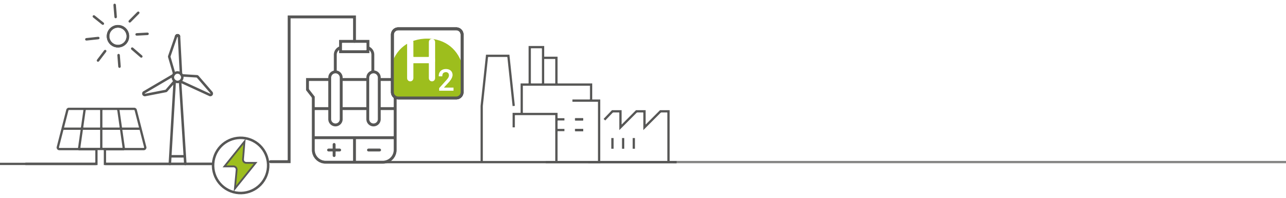
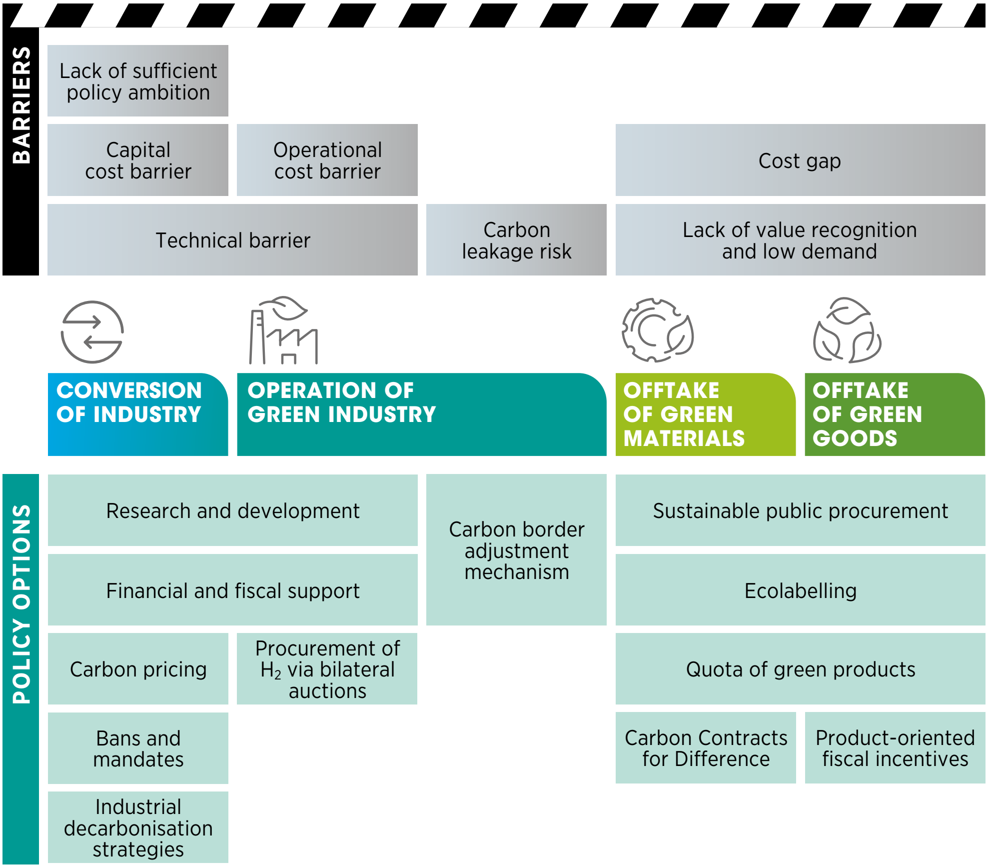


Figure 2.1 Barriers and policies to support green hydrogen uptake in the industrial sector



Policy makers, historically, have heavily influenced the course of industrial activity. Government actions have routinely improved workers' conditions and reduced environmental impacts, and affected other aspects of industrial life. Government actions have included imposing environmental limits on or changes to production processes that would not otherwise have been taken into consideration, support for change, and requests to modify production processes and goods themselves to achieve national objectives.

However, so far industry has been largely shielded from climate policy, which has resulted in GHG emissions remaining high. In particular, the hard-to-abate sectors have been entirely or partially spared from climate policy making due to their dependency on fossil fuels and national importance. This will need to change if green hydrogen's potential is to be realised.

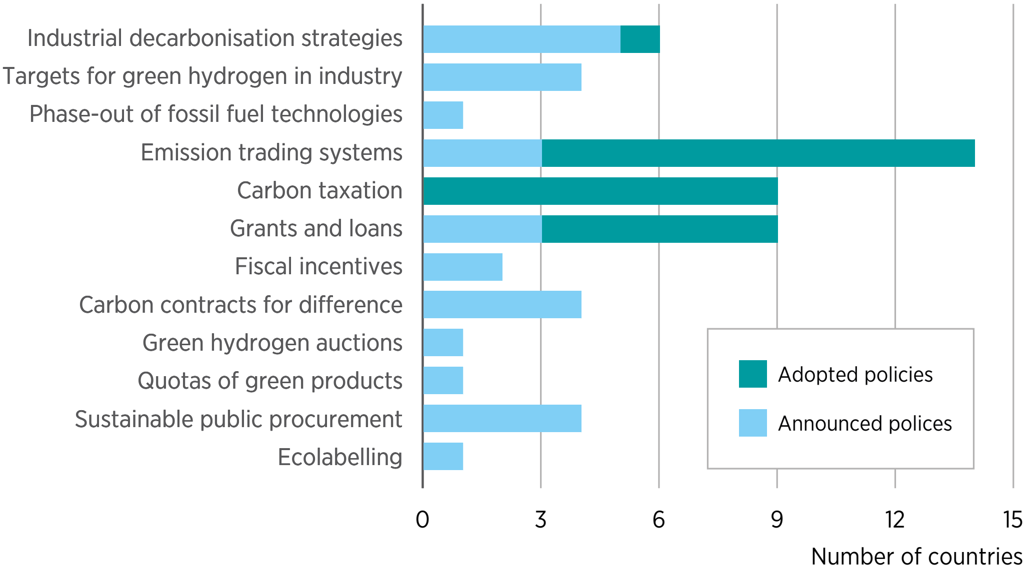
Governments have begun to recognise the need for greater intervention in industrial policy making as the need to find a feasible solutions for hard-to-abate sectors in the next decade has become increasingly apparent.

In fact, when published national hydrogen strategies describe actions to support green hydrogen, they also presents the options governments are considering to support industrial decarbonisation (as well as hydrogen use in other sectors), complementing measures announced in other policy documents and policies already adopted (IRENA, forthcoming) (Figure 2.2).

In particular, countries with a focus on importing green hydrogen have an interest in creating a demand for it, and for this reason have announced more policies to support its use in the industrial sector. One example is the German hydrogen strategy, which includes various measures targeting the industrial sector (Box 2.1). The principal instrument already used that can support green hydrogen for industry are carbon pricing mechanisms, already adopted in many countries (Section 2.4) and support systems in the form of grants, in particular for pilot projects (Section 2.5.1).

This chapter presents the options to support green hydrogen in the industrial sectors. Chapter 3 then provides a roadmap of actions to support the movement of green hydrogen in industry from niche to mainstream.

Figure 2.2 Green hydrogen industrial policies by status, selected countries, 2022



Source: World Bank (2022) and IRENA

Note: Policy announcements are extracted from the published hydrogen strategies and announcements of Canada, Chile, Colombia, France, Germany, Hungary, Japan, Luxembourg, the Netherlands, Norway, Paraguay, Portugal, Republic of Korea, Spain and the United Kingdom. Information in this figure is as accurate as possible at the time of writing; however, more policies may have been announced or adopted.

Box 2.1 German hydrogen strategy

The German hydrogen strategy supports two green hydrogen phases and aims to kick-start a hydrogen market in the country. The first phase (until 2023) lays the foundations for a domestic market for green hydrogen, which will enable growth in subsequent phases. The second phase (from 2024) envisages the consolidation of the domestic market and the development of European and international markets.

On the supply side, the strategy focuses on the production of green hydrogen. However, it suggests that by linking the national market to the European and international markets, there could be some use of imported blue hydrogen or other low-carbon alternatives. On the demand side, the strategy focuses on applications where green hydrogen is the least in need of economic support, or where there are limited choices for decarbonisation (*i.e.* the hard-to-abate sectors). These include refineries, steel production, the chemical industry, aviation and shipping.

In the industrial sector, the strategy is based on replacing grey hydrogen with green hydrogen in the chemical industry and substituting blast furnaces for iron reduction with hydrogen DRI in the steel industry. To promote hydrogen in industrial processes, the government will provide investment grants and launch a carbon contracts for difference (CCfD) programme, which is mainly aimed at the steel and chemical industries. The German government is considering establishing a demand quota for materials such as green steel to increase the demand for industrial products manufactured using green hydrogen and other low-emission processes. The strategy recognises that facilitating this increased demand would require the creation of an ecolabel to differentiate sustainable products.

The strategy is implemented through a committee of state secretaries supported by a national hydrogen council (with 25 representatives from business, science and civil society). A hydrogen co ordination centre monitors progress. There will be annual reports with performance indicators and a main report every three years to re-evaluate the overall strategy and adjust targets depending on market developments.

To pursue its strategy, Germany allocated USD 10 billion to create a demand-driven market for hydrogen (as part of the USD 156 billion stimulus package for economic recovery from the COVID-19 crisis), plus USD 2.4 billion dedicated to partnerships with countries where hydrogen can be produced.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Sources: BMWi (2020a); Reuters (2020).

2.1. GREEN (HYDROGEN) INDUSTRIAL POLICIES

Industrial policy can be defined as the variety of policy interventions aimed at guiding and controlling the structural transformation process of an economy (Bianchi and Labory, 2006).

Industrial policy became less popular in countries where neoliberalism emerged as a dominant theory. It was seen as an inefficient government practice to control the private sector (Johnstone *et al.*, 2021). However, the need for an economic recovery after the 2008 financial crisis enabled a 'renaissance' of industrial policy making in many parts of the world, including in regions where a that embraced the idea of a minimal role of the state in the market (Ahman, 2020; Alami and Dixon, 2019; Ciurak, 2011; Johnstone *et al.*, 2021).

In this renaissance of industrial policy, the latter been seen and used as also a way to achieve a number of societal objectives, including the need to move towards low-carbon and a resource efficiency to address the urgent necessity to accelerate the energy transition, *i.e.* "Green industrial policy" (Johnstone *et al.*, 2021).

Green industrial policy intervention is also required in achieving decarbonisation in the hard-to-abate sectors, in order to enable for a change that cannot otherwise happen at the scale and speed needed to avoid the climate crisis.

The focus of this report is green hydrogen industrial policy. The green hydrogen industrial sector is still at the "infant" one, still not competitive with grey hydrogen, and therefore, as for many infant industries, is a good candidate for industrial policy making.

Industrial policies can take many forms; they can actively force the hand of industrial stakeholders to change the status quo, make the fossil fuel solution unattractive for investors, or vice versa, provide support policies to green hydrogen to attract investment. Supportpolicies in particular have been widely used in the energy sector to support the deployment of renewable electricity through support schemes, and these can offer many lessons for green hydrogen. (IRENA, IEA and REN21, 2018).

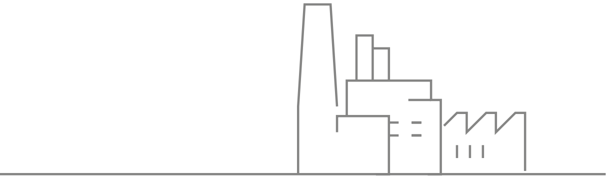
Designing green hydrogen industrial policies may involve the following:

- **Industrial decarbonisation strategies.** Policy makers should ensure the adoption of policies occurs in a way which takes into account national circumstances, clearly signalling to stakeholders the forthcoming changes, and considering the broad impact of a policy. This can be achieved through proactive planning, as presented in Section 2.2.
- **Regulatory action that mandates a change**. Introducing punitive measures such as fines or confiscation of property in case of non-compliance. Technological mandates and forced green hydrogen quotas can direct the industrial sector to reduce or eliminate the use of carbon-intensive practices. Options are presented in Section 2.3.
- **Internalisation of climate change externalities** makes the use of carbon-intensive technologies less financially sustainable in the long term. This can be achieved, for example, by creating a carbon pricing instrument that will enable green hydrogen technologies to become more financially attractive. There is no strict obligation in this second case, but the cost of the carbon-intensive technologies may become unbearable. These options are assessed in Section 2.4.
- The idea behind mandates and carbon pricing is that operators comply following a cost-benefit assessment where green hydrogen becomes more attractive. Stricter penalties lead to faster compliance and a diminishing role for fossil fuels as the expected costs of consuming the latter rises. However, these policies may increase the risk of carbon leakage or loss of competitiveness leading to lower economic activity. Therefore, specific **carbon leakage policies** may be needed to avoid such a situation (see "In focus" section).

- **Financial and fiscal support** to help first movers overcome high investment costs and bridge the cost gap between green hydrogen and mature fossil fuel technologies. Options are presented in Section 2.5.
- **Creating demand for green materials and goods.** An anchor demand for green products can push entrepreneurs to change their processes to meet this demand and gain first advantage as it increases. Policies to nudge businesses and consumers towards more sustainable patterns of consumption are presented in Section 2.6.
- **Research and Development (R&D) support**. Public R&D funding can pivot research activities to encourage technology development that will benefit national industry. The status of R&D funding for green hydrogen industry is presented in Section 2.7

2.2. INDUSTRIAL DECARBONISATION STRATEGIES

The energy transition creates challenges for the industrial sector, increasing costs and potentially placing the national industry at a disadvantage compared to competitors elsewhere in the world where decarbonisation is less of an immediate priority. Policy makers can introduce an **industrial decarbonisation strategy** to understand and present the size of these challenges while proposing ways to address them. This requires drawing up a plan to decarbonise the industrial sector, reflecting the nuances of the country's industrial sectors and taking into consideration actions to keep them internationally competitive.



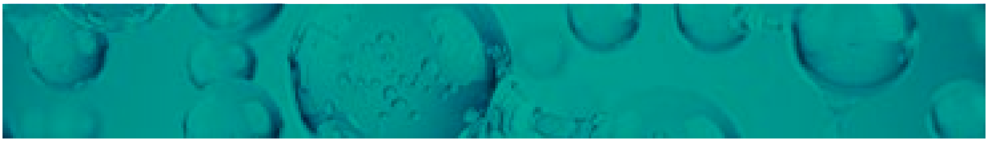
To establish an industrial decarbonisation strategy, governments will need data on current country emissions. Facility-level data may be missing **Mandatory GHG reporting programmes** impose a requirement on industries to provide credible information about their GHG emissions and their sources, enabling the establishment of a solid foundation to support mitigation policies. These programmes allow governments to understand their emissions-related risks and opportunities, assisting them in creating dedicated decarbonisation policies.

Mandatory and standardised reporting brings consistency and allows policy makers to track their progress and support those industries that are improving their carbon footprint. Mandatory GHG emission reporting is now widespread in the Global North (Singh and Bacher, 2015).

Tailored sub-sector planning is essential because of industrial equipment's capital-intensive and long-lasting nature and the fact that specific industries have strict feedstock specifications.

To achieve net zero targets, gradual or moderate changes, such as in fuel efficiency standards, are unlikely to be enough. Decarbonisation strategies should aim at a step change in technology that reduces the risk of locking in emissions and of stranded fossil fuel assets in the future. A planned step change will help bring in the processes needed for deep decarbonisation and align the actions of investors and businesses with the interests of the public. Both electrification and green hydrogen technologies would benefit from such step change planning, to avoid companies investing in short-sighted efforts that are not helpful in achieving carbon neutrality by 2050 (IRENA, 2020b; Agora Energiewende, 2020).

Given the urgency of the energy transition, specific deadlines for the decarbonisation of all end-use sectors are necessary for the coming years. Adopting an industrial decarbonisation strategy can mark these deadlines in the calendars of industrial stakeholders, informing them years in advance about when the new emission limits will kick in and when a new supporting policy will be in place. The drafting and updating of industrial strategies can also allow bilateral information exchange to take place.



An industrial decarbonisation strategy should inform and be informed by the national hydrogen strategy, if in place or under development, providing a harmonious plan for both. It should also be the opportunity to identify no-regret options for industrial uses of hydrogen, prioritising actions in those sectors and avoiding the identification of hydrogen as a complete substitute for fossil fuels (IRENA, 2020a). Industrial decarbonisation strategies should assess current hydrogen demand, potential additional hydrogen uses, high-temperature industrial heat demand suitable for hydrogen use, and opportunities to co-locate hydrogen production and use across different industries (IRENA, 2020a; IRENA, IEA and REN21, 2020), identifying potential **hydrogen valleys** in their jurisdictions.

A hydrogen valley is a geographical area where several hydrogen users or potential users are present and can be combined to create a local system that covers the entire value chain from production, storage and distribution to final use. Industries already tend to be co-located within industrial clusters (*e.g.* ports) or regions, making it possible to combine various uses to benefit hydrogen production by achieving more significant economies of scale.

Hydrogen valleys present an opportunity to create a large, stable and long-term source of demand that can be used as an anchor for future hydrogen producers. Hydrogen valleys have the potential to reduce electrolyser project risk, as a variety of off-takers for green hydrogen production can be identified upfront. The synergies in such clusters help create a virtuous circle between supply and demand, where large-scale production decreases costs, encouraging further demand within the same area. Co-location also reduces the immediate need for long-haul transport infrastructure, while potentially taking advantage of existing infrastructure for the transport of green hydrogen (*e.g.* pipelines and shipping). Finally, even small-scale hydrogen valley projects can shed more light on the feasibility of a hydrogen economy encompassing various industries at the same time.

To assist the creation of a hydrogen valley, policy makers can identify target industrial clusters where green hydrogen supply and demand can be co-located. After identifying the area, policy makers can bring together key industry players to co-develop a local plan for the hydrogen valley. This would be the opportunity to assess the whole range of appropriate technologies for decarbonisation, including electrification, system efficiency and circularity (IRENA and WEF, 2021).

Hydrogen valleys should be seen as a means to achieving national objectives, so the targets for the region and sectors involved should be in line with national net zero goals.

Finally, such strategies are an opportunity to set targets for green products, planning the phase-out of technologies (see Section 2.3), introducing government public procurement targets, announcing funds (Section 2.5.1) and introducing other policies, such as those presented in this report. The United Kingdom has published its Industrial Decarbonisation Strategy (Box 2.2), which includes a staged approach similar to the one presented in Chapter 3.

Box 2.2 UK Industrial Decarbonisation Strategy

In March 2021, before the publication of a hydrogen strategy, the United Kingdom released its Industrial Decarbonisation Strategy, which covers the full range of domestic industry sectors, with a view to aligning them with its ambitious target of reaching net zero emissions by 2050. According to the strategy, to keep the United Kingdom in line with its nationally determined contribution under the Paris Agreement, emissions from industry must fall by around two-thirds by 2035 and at least 90% by 2050, compared with 2018 levels.

To remain on track, the strategy lays out the following milestones: 3 Mt CO_2 of industrial emissions captured through CCUS each year by 2030, four major industrial clusters linked up to the necessary CCUS and hydrogen infrastructure by 2030, and a minimum of 20 TWh of fossil fuel use replaced with low-carbon alternatives in 2030.

To overcome the range of barriers faced by industry along the way, the strategy recognises that government efforts will be imperative, and a shift in the policy landscape must take place. The strategy identifies the following policy principles, which will serve as the basis of government action:

- Government intervention should be technology-neutral and focus on addressing market failures or barriers to decarbonisation.
- Government should mitigate the risks of carbon leakage.
- Government should play a key role in delivering large infrastructure projects for critical technologies where cost or risk is too high for the private sector.
- Government should intervene to deliver specific strategic outcomes in line with broader green growth priorities.

It should be noted that the strategy does not make a difference between blue[9] and green hydrogen, combining them under the "low-carbon hydrogen" name as in the subsequent UK Hydrogen Strategy. Low-carbon hydrogen is earmarked to assume a central role. According to the strategy scenarios, low-carbon hydrogen consumption in the industrial sector alone will be 10-16 TWh per year by 2030 and 24-86 TWh per year by 2050. For comparison, the United Kingdom produced around 23 TWh of grey hydrogen in 2019 (or 700 000 t). The oil refining and chemical sectors are considered important drivers of the transition to low-carbon hydrogen.

The strategy recognises that it is critical to solve the chicken and egg problem. It aims to solve it by promoting fuel switching to hydrogen in industrial sites parallel to ramping up hydrogen production. Opportunities for hydrogen are identified in heat production for chemicals, oil refineries and the paper industry. Possible conversion of furnaces in the steel industry is earmarked from 2035.

The UK government will look to develop business models and fuel standards to cover the cost gap between hydrogen and fossil fuels. Hydrogen projects can also access government co-investment through the USD 425 million Industrial Energy Transformation Fund, USD 230 million Industrial Decarbonisation Challenge and the USD 13.5 million Green Distilleries Fund. Additionally, the government has confirmed that a USD 324 million Net Zero Hydrogen Fund will be created to provide capital co-investment for early hydrogen production projects.

Source: Lambert and Schulte, 2021; UK Government, 2021a, 2021b

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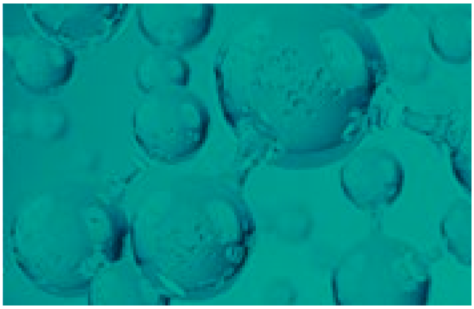
[9] *Blue hydrogen has the same production processes of grey hydrogen coupled with CCS.*

2.3. TECHNOLOGICAL MANDATES

While some industrial players may be proactive in decarbonising their processes (see Box 1.3), this may not be the case for all. If left unchecked, the industrial sector may keep its status quo, avoiding addressing its global responsibility toward climate change. Policy makers can change the prevalent practice with "stick" policies imposing a change that may not happen on its own. These policies can be accompanied by carrots (see Sections 2.5 and 2.6) to financially and politically assist such change.



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2.3.1 Bans and mandated phase-outs of fossil fuel technologies

Mandated fossil fuel bans and phase-outs set a deadline for the commissioning of new fossil fuel-based technologies and the operation of existing assets.

Bans on fossil fuel technologies are not a novelty and have been adopted in the power sector (particularly for coal plants). Similarly, mandates to push a new energy carrier are not uncommon in the power and transport sector (*e.g.* green certificates and biofuel mandates).

Industrial assets can have decades-long lifetimes: if these assets are installed today, their useful lifetime would exceed the 2050 deadline, making their premature retirement economically unattractive (Agora Energiewende and Wuppertal Institut, 2019).

The adoption of bans and phase-out mandates would make it possible for green solutions to be adopted in the soonest industry investment cycle, avoiding a lengthy carbon lock-in. Regarding the steel industry, blast furnaces can use hydrogen, but ultimately they cannot operate purely on hydrogen since the furnace design needs coke. To achieve full decarbonisation, therefore, a phase-out of blast furnaces will be needed, to be substituted with DRI.

The phase-out of technologies could happen automatically if a country or region has already adopted plans and policies to decarbonise the whole energy sector.

To accelerate the switch, policy makers could announce, and later enforce, bans on specific technologies to avoid the creation of early stranded assets and inform industry and academia of the need to adopt low-carbon technologies by a specific year. Similarly, the early phase-out of existing fossil fuel technologies could be announced, and later enforced. This may require sectoral industrial decarbonisation strategies (see Section 2.2) that include all decarbonisation options for hard-to-abate sectors. It would present the opportunity to bring together key industry players and policy makers to co-develop a phase-out strategy, which could be assisted by dedicated funds and tax rebates (Section 2.4.2) (IRENA and WEF, 2021).

2.3.2 Targets and binding green hydrogen quotas

Targets for green hydrogen can be introduced specifying a set share of overall gas consumption to be from renewable gases. These targets can focus on the industrial use of hydrogen (or solely on grey hydrogen, which is used mostly in industry) to provide an indicative level of future green hydrogen consumption and, therefore, of future procurement needs. This is the case proposed in the Spanish hydrogen strategy, in which the government included a 25% minimum contribution of green hydrogen to the total hydrogen consumed in 2030 by all industries, both as a feedstock and as an energy carrier. The equivalent of 25% of current hydrogen consumption in Spain is about 125 000 t per year.

The European Commission "Fit for 55" proposal package includes targets that would give a significant boost to the development of green hydrogen in industry. The target is to have a 50% green share in total hydrogen consumption by industry – or around 5 Mt – by 2030.

Binding quotas move the implementation of targets a step ahead, imposing an obligation on selected industries to reach a share of green hydrogen in their total amount of hydrogen or total gas demand. Virtual blending could complement this approach, *e.g.* by buying certificates for the equivalent consumption of green hydrogen while not necessarily carrying out the physical use (IRENA, 2021a). This idea is already used in green certificate systems for renewable electricity and could be explored for green hydrogen. This would require a robust certification system, along with a central repository to allow the trading of certificates (Agora Energiewende, 2021c; IRENA, 2021a).

The growing demand created by a quota system would reduce investment risk and financing costs for green hydrogen facilities, facilitating investment in electrolysis while at the same time putting all the industrial companies within the jurisdiction under the same obligation and similar additional costs.

A binding quota with a certificate system can only be adopted at the beginning of the transition, as in the long term net zero emission systems will need all users to achieve physical reductions in their emissions. Setting targets and quotas at an achievable level in the short term requires robust and comprehensive national and regional assessments of hydrogen production capacity and the competitiveness of the domestic industry.

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2.4. CARBON PRICING

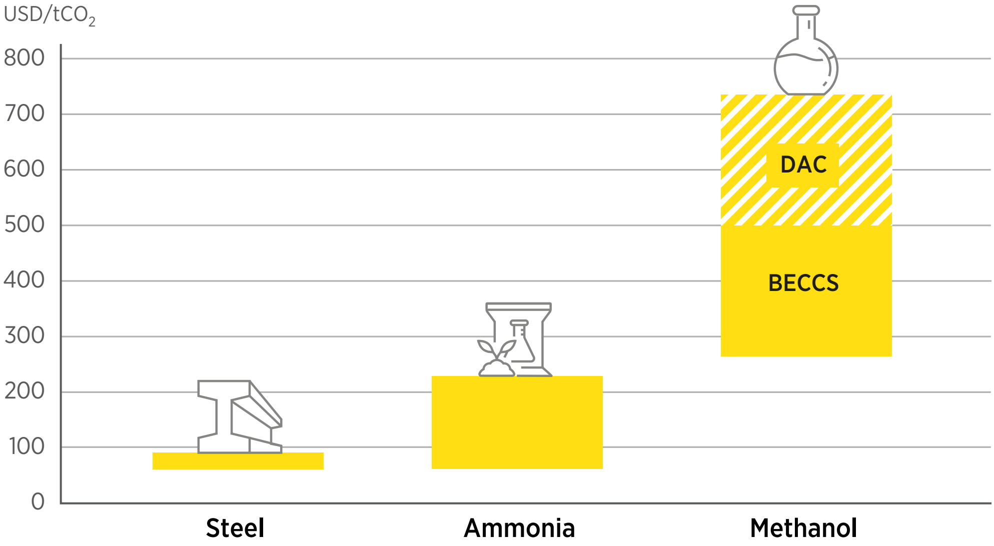
Green hydrogen will bring major GHG emission reductions to industry. However, in many cases this benefit is not reflected in commodity output prices, reducing the economic incentive to produce green products. By internalising the carbon externalities in the form of either an emissions trading system (ETS) or a carbon tax, policy makers can assist in valuing this benefit, closing the economic gap with fossil fuel pathways.

Investment in low-carbon technological innovations, including green hydrogen, can be stimulated by carbon pricing. But to support green hydrogen investment, carbon pricing would need to cover the cost gap between green and grey materials (Figure 2.3).

If carbon pricing does not achieve such levels, supplementary policies such as those presented in other sections (Sections 2.5 and 2.6) will be needed to make green hydrogen technologies economically viable. The alternative of waiting until carbon prices reach high enough levels may result in capital turnover that is too slow, which will not achieve the energy transition in the industrial sector within the 2050 deadline.

An ETS and carbon taxes, presented below, do provide important signals to the market to decarbonise processes. In 2021 these initiatives are estimated to have already covered 11.65 Gt CO_2-eq, representing 21.5% of global GHG emissions (World Bank, 2022).

Figure 2.3 Estimated carbon prices needed to cover the cost gap between green and grey materials



Notes: Estimated costs of green steel production (between USD 650 and 715/t) are compared to a grey steel cost of USD 550/t. Avoided CO_2 emissions/per tonne of steel are assumed as 1.87 t. Estimated costs of green ammonia production (between USD 500/t and USD 900/t) are compared to a grey ammonia cost of USD 350/t. Avoided CO_2 emissions/per tonne of ammonia are assumed as 2.4 t. Estimated costs of green methanol production (between USD 800/t and USD 1200/t with BECCS and between USD 1200/t and USD 1600/t with DAC) are compared to a grey methanol cost of USD 350/t. Avoided CO_2 emissions per tonne of methanol are assumed as 1.7 t (see Box 1.2).

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Moreover, they generate significant revenue flows that can be used to boost investment in renewable energy and energy efficiency, to align infrastructure and the general economy better with climate goals, or be deployed in support of a fair transition strategy. Revenues from the policy can also be earmarked to support technology demonstrations and close the economic gap for the first few plants using green hydrogen.

2.4.1 Emissions trading systems

An ETS is a market-based approach that aims to provide incentives to reduce emissions. Different systems exist worldwide (in California, the European Union, New Zealand and the Republic of Korea, for example), with different design elements and various degrees of success. China introduced its own nationwide ETS in 2021 (ICAP, 2021a).

An ETS with a cap-and-trade system requires a public body to set an emissions cap for the emitters in one or more sectors, which become obliged parties. Obliged parties must at the end of a period hold allowances in an amount equal to their emissions; if they emit more than allowed, they have to buy allowances from other obliged parties that had total emissions below the cap. This creates an incentive to reduce emissions while making polluters pay. The cap ensures that allowances have a value. The number of allowances should be reduced over time so that total emissions fall. The obliged parties may receive from the same body a limited number of allowances to emit a specific amount of emissions for free ("free allowances") (See "In focus" section). In the European Union, manufacturing industry received 80% of its allowances for free in 2013; these then decreased gradually, down to 30% in 2020. The amount not covered by free allowances, in the European Union, can be bought on national auctions or from secondary markets. Allowance prices, based on actual and projected emissions, depend on general economy activity. In early 2020 many ETSs experienced a sharp price reduction during the onset of the pandemic, due to falling emissions from COVID-19 related restrictions. Prices had recovered by the second half of 2020. Following the economic recovery, EU ETS prices kept increasing, reaching USD 100/t CO_2 in December 2021 and February 2022 , to decrease by 30% in early March 2022 (ICAP, 2021a, Ember, 2022) (Figure 2.4).

An output-based standard disengages the ETS price from the general economy. The principle is similar to the cap-and-trade design, but it does not involve an absolute cap. Instead, the limit

Figure 2.4 Carbon allowance price in the European Union, 2008-2020

Source: ICAP (2021b), Ember (2022).

is put at facility level and based on its output (*e.g.* the amount of ammonia produced). As such, it is not affected by economic downturns and does not penalise industry in case of economy growth. The output-based standard then sets a performance standard for different industrial activities. Facilities that produce more emissions than the sectorial standard have to compensate for the excess.

An example of an industrial output-based standard is the output-based pricing system (OBPS) introduced by the federal government of Canada. This system determines the facilities whose emissions are in excess of the standard, which must then compensate for the excess. Facilities whose emissions are below the standard receive surplus credits, which may be sold or kept for a later date. Facilities can also comply by paying the carbon price. The OBPS includes steelmakers, chemical plants and refineries (ICAP, 2021b; Turcotte, Gorski and Riehl, 2019).

Investments in green hydrogen technologies require a high, long-term and predictable allowance price, in the absence of other measures to support the technological change. High allowance prices may also trigger the purchase of merchant green hydrogen, as green hydrogen would be cheaper than its counterpart. But in this case prices also need to be constantly and predictably at remunerative levels. Manufacturers should be exposed to their carbon costs as much as possible and in an expedited way, or the incentive to switch processes to reduce carbon may fall beyond the 2050 deadline.

2.4.2 Carbon taxation

Carbon taxation is the fiscal measure used in various jurisdictions to capture the estimated external costs of GHG emissions of selected emitters. Carbon taxes are now adopted in 27 countries, covering around 5% of global emissions (World Bank, 2022).

Carbon taxation, is a source of revenue for governments and has also the advantage of providing more certainty on the final revenue compared to the ETS, as the carbon pricing is administratively set and issued to a selected range of emitters. Moreover, carbon taxes can be easier to adopt than ETS systems, since they can be implemented via existing taxation systems, such as levies or other excise taxes on fuels.

Carbon taxation may take different forms depending on the targeted sector. In particular, performance standards can be considered a form of carbon taxation in industry. Under this policy, an emissions reduction trajectory is set for each industry, together with an economic penalty for any CO_2 emissions above the target.

Performance standards can be imposed on industries currently consuming grey hydrogen, requiring them to start decarbonising their hydrogen consumption. This may create a market for green hydrogen if the carbon price imposed is above the cost gap between grey and green hydrogen. This option also provides better certainty of price compared to the allowance trading, where the price is defined according to the supply of and demand for allowances. It is also a more transparent scheme in which citizens (who will be the final payers of the cost increase in the final good) can be aware of the reason for these higher costs and how this extra expenditure is used.

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IN FOCUS: ADDRESSING CARBON LEAKAGE

As climate policies started being implemented, countries around the world also began considering measures to avoid carbon leakage. For example, under the EU ETS industrial installations considered to be at high risk of carbon leakage receive special treatment to support their competitiveness. The European Commission defines sectors at high risk of carbon leakage as those where production costs are seen to increase by 5% due to the direct or indirect effects of climate policies and the sector's trade intensity with non-EU countries (imports and exports) is above 10%. This section presents policies in place or planned to avoid or minimise the risk of carbon leakage.

Free allowances and exemptions under an ETS

Under an ETS, the most common policy mechanism that policy makers have used to address leakage to date is through the provision of free allowances.

The allocation of free allowances can follow three methodologies: grandfathering, output-based allocation and fixed sector allocation (PMR, 2015):

- **Grandfathering** is the allocation of free allowances to specific firms based on their historical emissions. The allocation does not vary with annual changes in output and only changes when the policy is reviewed. This is usually applied in the early stages, with a move towards output-based or fixed sector benchmarks following later. Grandfathered emitters still have the incentive to produce fewer emissions than historically, but have no immediate constraints. In the first phase of the EU ETS, free allowances were allocated almost exclusively through grandfathering (ICAP, 2021a).
- **Output-based allocations** are mechanisms through which firms receive allowances based on their recent production levels. If production increases, the next round of free allocations will also increase, and if production declines, allowances will be removed. Since allowance allocation adapts to the output, this kind of free allowance allocation can act as a subsidy and encourage additional production at the margin. This methodology also provides firms with an incentive to reduce emissions by improving emissions performance, rather than reducing production. The New Zealand ETS provides output-based allocations to industries considered emissions intensive and trade exposed (Ecofiscal, 2017; ICAP, 2021a).
- **Fixed sector allocations** are distributed according to evaluation of sector-wide benchmarks developed for each product, based on the best-performing installations producing that product. All installations in a given sector receive the same allocation of free allowances per unit of activity. Under this methodology, allocations are independent of the technology or fuel used and the size of the installation. In the third phase of the EU ETS, this benchmarking approach was used based on the best-performing 10% of installations producing a given product (European Commission, 2020; ICAP, 2021a).

Among the various solutions to prevent carbon leakage, the more immediate one is fully or partially **exempting** some sectors from the ETS. This solution may be used for cases where a policy application might be difficult or too expensive. In particular, small enterprises and strategic sectors may benefit from exemptions.

With carbon prices at around USD 100/t, green hydrogen could already become competitive with fossil fuels in EU industry, for example in the steel sector. However, manufacturing industry, such as steelmaking and oil refining, has been shielded from climate policies, and these free allowances and exemptions have the effect of the removal of industry accountability towards climate change in favour of competitiveness.

Border carbon adjustments

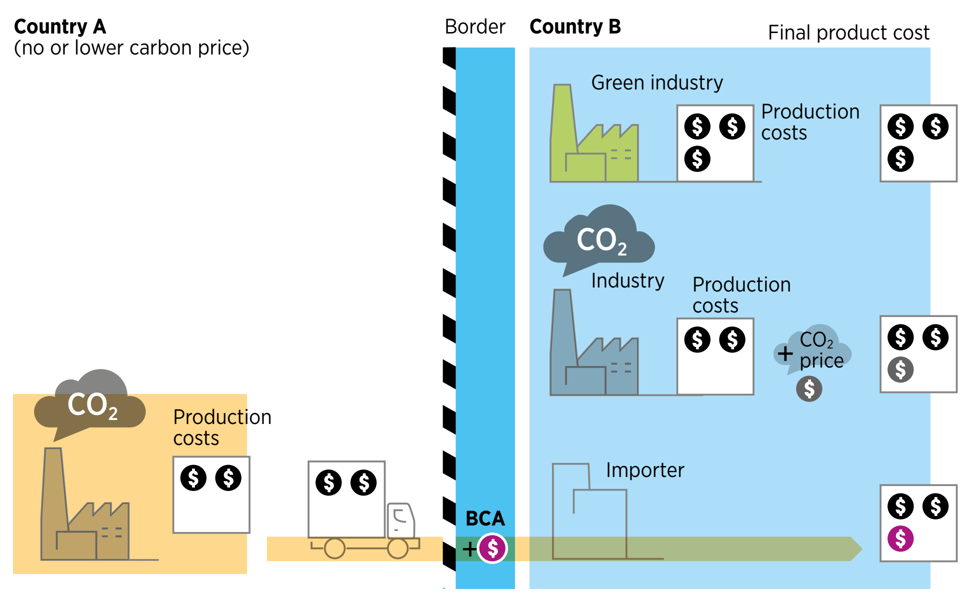
Border carbon adjustments (BCAs) are alternative systems to avoid carbon leakage but that still expose local industry to the carbon costs. BCA are import taxes that account for the difference in carbon pricing policies between countries. The objective is to make polluters, even outside the importing jurisdiction, pay the same (or a similar) carbon price paid by local industry, discouraging carbon leakage and levelling the playing field between industry regardless of the local carbon policy (Figure 2.5). A BCA on incoming products means domestic producers will not be at competitive disadvantage compared to their foreign counterparts.

BCAs have been widely discussed in academic and policy circles for two decades, and there is now a rich literature analysing how they can be designed to overcome the significant legal, technical and political challenges. However, there is so far limited experience of BCA implementation (Cosbey *et al.*, 2019; OECD, 2020).

Although broader coverage has been advocated, in practice, most BCA proposals have focused on energy-intensive sectors, which may be at risk of carbon leakage. The carbon leakage protection of a BCA is expected to vary from sector to sector, depending on characteristics such as the commercial balance of a specific product (Fischer and Fox, 2012).

Some of the issues to consider in the policy design of a BCA are how to determine the CO_2 emissions associated with imported products, ensuring fair competition, the sectors covered and the treatment of exported goods.

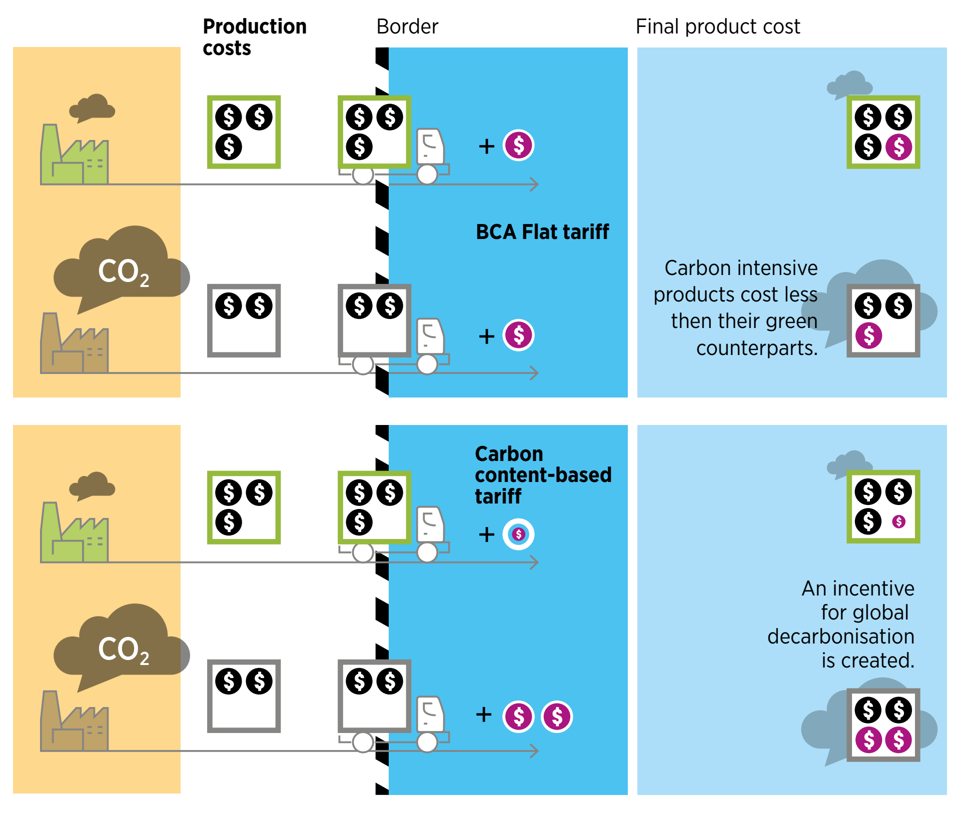
Figure 2.5 Schematic of a BCA



A BCA tariff can be "flat" – meaning it would be the same for a given imported good[10] – or it can be based on the actual carbon content – meaning the tariff would consider the actual emissions in the life cycle of the specific good. The application of a carbon content-based tariff at the border may have important implications for green hydrogen-based products, as shown in Figure 2.6. A flat tariff would naturally benefit the more cost-competitive solution, regardless of the process used and the emissions incurred. An imported product produced with green hydrogen could not compete within the region that has a flat BCA tariff. By contrast, a carbon content-based tariff would be lower for green products and higher for blue or grey products, incentivising carbon reduction during manufacture (Euractiv, 2020).

An important challenge for a BCA is the fact that, as a border tax, it should be compliant with the World Trade Organization (WTO) General Agreement on Tariffs and Trade (GATT). Generally speaking, the GATT mandates that any imported goods taxation

Figure 2.6 Flat vs carbon content BCA tariffs



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10 A flat tariff can still differentiate between countries' carbon intensity.

cannot result in treatment that is less favourable than the treatment of comparable goods produced domestically. However, WTO case law suggests that a BCA would be allowed if it were based on the carbon content of a product rather than on the goods' country of origin; moreover, the GATT exempts certain cases from obligations where they are based on environmental protection (Acworth, Kardish and Kellner, 2020; Cosbey *et al.*, 2019).

Policy makers will also need to determine whether the scheme adjusts for domestic exports, meaning a carbon cost rebate for exported products to level the playing field in countries with more relaxed carbon policies. However, domestic export rebates reduce abatement incentives in the more export-oriented industries, shielding domestic production from actual carbon costs. Export rebates also put the entire concept of a BCA at risk, since its reason for existing is to push to reduce emissions that have a global effect (Acworth, Kardish and Kellner, 2020; Cosbey *et al.*, 2019; Mehling *et al.*, 2019; PMR, 2015).[11]

A further issue is the different impacts carbon prices and BCAs have on domestic and importing companies. National carbon costs are applied to the entire domestic production, while any BCA would likely apply only to the quantity that foreign producers export to the country with a BCA, hence having the possibility of absorbing such costs throughout their entire production. In other words, a local steelmaker with total production of 5 Mt of grey steel and an average carbon cost of USD 25/t_{steel} pays USD 125 million; at the same time, a similarly sized foreign producer exporting only 50 000 t would face costs of only USD 125 000, which are much easier to absorb, thus making the BCA ineffective.

To avoid such dynamics, BCAs could be adopted by multiple countries (as in the recent EU proposal), co operating to enlarge their market share sufficient to make the extra cost harder to absorb. This co operation is important: BCAs may be seen as a confrontational measure, but it can also offer significant incentives to bring about a common and shared system of climate change mitigation. BCAs would leverage current heterogeneous emissions performance among industries, pushing for a race to the top to decarbonise beyond national borders.

The first carbon content trade agreement was announced in November 2021 when the United States and the European Union agreed to modulate their tariffs on steel and aluminium based on the carbon content of the commodities.

This new arrangement (which will be negotiated over a three-year period) aims to give preference to the trade in low-carbon commodities. It will require a shared methodology for counting carbon content. Lower tariffs will translate into lower costs for consumers, but also in higher costs for high-carbon-content steel from Asia, where most of the coal-fired blast furnaces are located. The European Union and the United States will encourage other jurisdictions to participate in this agreement (White House, 2021a, European Commission, 2021a).

Conclusion

Carbon leakage raises both environmental and socio-economic concerns, putting global decarbonisation efforts at risk. Fundamentally, policies to combat carbon leakage are a method of correcting the asymmetric climate policies of different countries. In order to truly address the issue of carbon leakage, countries could employ a multilateral approach and come to a consensus on the dangers of climate change. A lack of agreement between countries on the associated impacts of increased emissions will only further increase the divide on policies and targets. This divide is what creates the foundation for carbon leakage to take place, as some countries may not enact climate policies, notwithstanding the daunting challenge of climate change. Harmonised global climate policies will ease both addressing carbon leakage and reducing global emissions, creating a demand for decarbonisation solutions at global scale.

Support systems, like those presented in Sections 2.5 and 2.6, can be considered as implicit measures against carbon leakage, providing local industries with a market for green products and the capital to decarbonise their processes.

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[11] *Moreover, it may be more difficult to prove a BCA to be an environmental exception to the GATT if exported goods are not subject to the environmental charge.*

2.5. FINANCIAL AND FISCAL SUPPORT

Currently, green hydrogen is more than twice as expensive as grey hydrogen and green materials face similar or higher premiums. A simple way to support green hydrogen technologies is to provide financial assistance, lowering the high cost barriers to entry. In the early stages, grants and loans can help the first movers cover the high investment costs of the newer technologies. As the market matures, the nature of the financial assistance provided can evolve from direct financial assistance to tax incentives and other kinds of subsidies.

2.5.1 Grants and loans

Funds for green hydrogen projects may be needed at the various project stages, from pre-feasibility studies to commissioning the final facility. Financial assistance can be applied to any industrial decarbonisation solution. Policy makers may need to support all the possible technologies, including those at their inception with great promise, such as green hydrogen technologies, to avoid dedicating funds only to more mature solutions, such as energy efficiency measures, leaving green hydrogen solutions without the needed initial support.

Supporting local industry with grants, convertible loans and similar financing mechanisms is not a novel concept. This kind of financial assistance can be used to reduce the invested costs and the necessary financing. It therefore can and should be used for the conversion of fossil-based processes to climate-neutral solutions (for example, the early phase-out and conversion of BF-BOF). These instruments should be adopted at the inception of an industry's decarbonisation efforts, to assist first movers and to keep the impact on government budgets low. Industrial decarbonisation strategies (see Section 2.2) can inform the nature of the financial assistance and the burden on government budgets. For jurisdictions with an ETS or a carbon tax, part of their revenues could be invested back in low-carbon technologies for industry.

Funds for decarbonisation of the industrial sector are already present in various jurisdictions, and can benefit the hydrogen industry too:

- The **European Union** has established the Innovation Fund for the commercial demonstration of innovative low-carbon technologies. The fund may increase to EUR 20 billion over the ten-year period to 2030 (for all sectors of the energy system), depending on carbon allowance pricing. Large and small hydrogen-based projects can apply for the fund. The HYBRIT project (see Box 1.3) has been pre-selected for a grant.

- The HYBRIT project also benefited from a grant from the **Swedish** Energy Agency, equal to SEK 528 million (USD 57 million), in support of the construction of two pilot plants, covering around 37% of the expected costs. This marked the largest single grant in the history of the agency.

- The Energy and Climate Fund in **Germany** includes EUR 45 million for the transition of the steel, cement and chemical industries, while the 2020 budget set aside EUR 445 million (by 2024) for the use of green hydrogen in the industrial sector. The federal government also plans to close the economic gap for hydrogen through the Industrial Decarbonisation Fund for CO_2 mitigation and use in basic industries. The economic stimulus in response to the COVID-19 crisis includes EUR 7 billion for the hydrogen sector, with support for the shift of industrial processes (Box 2.3) (BMU, 2020; BMWi, 2020a, 2020b; Wehrmann and Wettengel, 2020).

In jurisdictions where the push for the energy transition is strong, there is the possibility that green hydrogen investors may find themselves with multiple possible financing streams and public funds. Applying for them may create a bureaucratic barrier, requiring multiple grant requests that call for a large number of documents to be presented. Creating **a one-stop shop for finance** can be a solution to reduce the burden, connecting stakeholders with funding sources for green hydrogen projects, while allocating funds more efficiently (IRENA and WEF, 2021).

2.5.2 Tax rebates

A tax rebate represents another method of supporting green hydrogen projects. The intention is to promote carbon emission reductions by reducing the overall tax liability faced by industrial firms if they invest in carbon-neutral processes, such as green hydrogen consumption. For industries that buy hydrogen from merchant producers, rebates may be used to support the purchase of green hydrogen. The tax rebate can be determined by CO_2 reduction per unit of output or the adoption of specific new processes that the government wants to support.

Carbon tax rebates are also used to address the risk of carbon leakage, without reducing incentives to cut emissions. In this instance, carbon tax rebates may aim to avoid an industrial firm's overall tax liability increasing if certain conditions are met, for example specific activities to decarbonise processes (*e.g.* the installation of an in-situ electrolyser). In this way, carbon pricing would effectively support the decarbonisation of the same taxed industry, allocating the budget to decarbonisation projects.

Although not related to carbon emissions or green hydrogen, the Swedish tax on NO_x emissions provides an interesting example of a tax rebate that actively supported environmentally friendly activities. In 1988 the Swedish government placed NO_X emission limits on combustion plants through a permitting system. After realising that NO_X emission limits were not sufficient to reduce emission rates, in 1990 Sweden set a tax rate of SEK 40/kg of NO_x emitted from any combustion plant producing at least 50 MWh per year. A refund mechanism was placed in the design of the tax, returning all of the revenues generated (except for a small amount to recover administration costs) to the plants covered by the tax. The tax revenues were returned to the plants in proportion to the amount of energy they produced. In effect, this meant that plants with low rates of emissions per unit of energy produced received a subsidy and those with high rates were the net payers of the tax (Braathen, 2012).

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2.5.3 Carbon contracts for difference

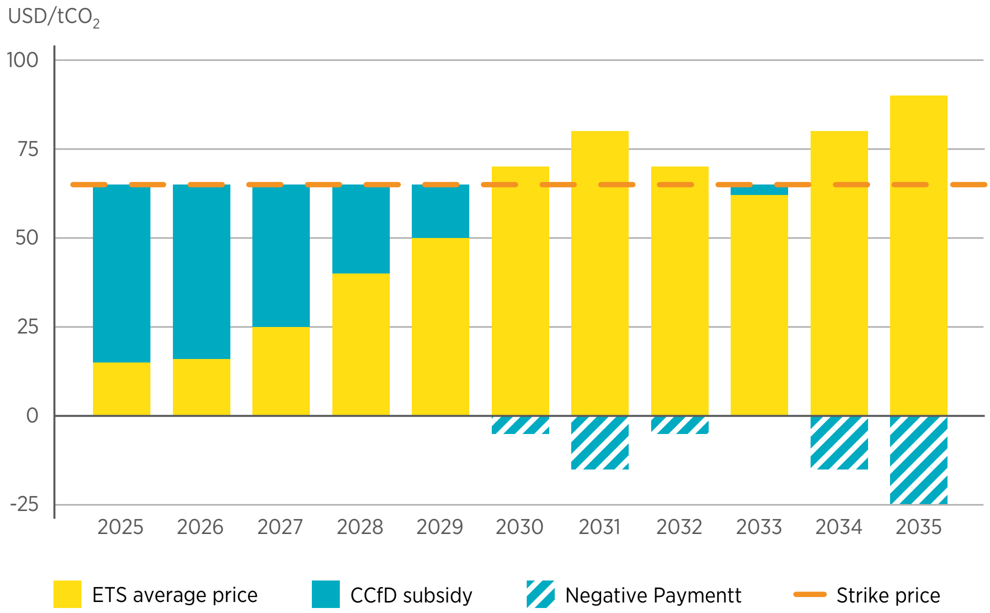
A solution that has worked in recent decades and which is still one of the most widely adopted solutions to accelerate the energy transition is the creation of a premium for each unit of the energy. They are usually called feed-in tariffs (FITs) or feed-in premiums (FIPs). Tariffs and premiums have been introduced in various jurisdictions either administratively or competitively (with auctions).

These systems have been recognised as successful for electricity production and are being considered for green hydrogen too (IRENA, 2021a), but there is a growing consensus around the fact that they could be applied to green materials too, through the use of carbon contracts for difference (CCfDs) that can complement ETS systems.

These CCfDs would be contract between governments and projects that produce materials with reduced carbon intensity. A CCfD would guarantee a fixed "strike price" for tonnes of CO_2 avoided for a predetermined number of years. If at the end of a certain period (*e.g.* a year) the average annual ETS price has been below the strike price, the industrial producer will receive, for each tonne of CO_2 avoided, the difference between the two values.

Figure 2.7 represents how it could work.

Figure 2.7 Relationship between average ETS price and CCfD subsidy at strike price of USD 65/tCO_2



CCfDs would help to ensure that low-CO_2 industry is be in place without needing to wait until a combination of economic conditions is present to justify the investment (*e.g.* high ETS prices, BCA). CCfDs would cover a proportion of the cost difference between a conventional and a low-carbon product. More crucially, they would stabilise revenue streams by removing the risk of CO_2 price volatility for project investors. As a result, they could considerably increase the economic feasibility and bankability of projects, as seen by the outcomes of renewable energy auctions throughout the world. Because of the enhanced certainty of pay-offs, projects can increase the proportion of debt in overall project financing compared to equity. Debt is less expensive, which lowers the cost of capital and, as a result, the breakeven carbon price (Agora Energiewende, 2020, 2021c; IRENA, 2019; McWilliams and Zachmann, 2021). Even if green hydrogen is bought from a merchant producer, a CCfD will increase the maximum price the industrial player can negotiate to buy green hydrogen, allowing green hydrogen merchant producers to compete in markets they would have been otherwise excluded from.

In order to set up a CCfD scheme, policy makers could identify a target industry for a CCfD pilot scheme, where a suitable CO_2 pricing mechanism or ETS is already in place. The design of the CCfD would benefit from the engagement of industry stakeholders and leveraging best practice from renewable electricity contract for difference schemes and floating FIPs. The programme could be then scaled up in line with a national hydrogen or industrial decarbonisation strategy (IRENA and WEF, 2021).

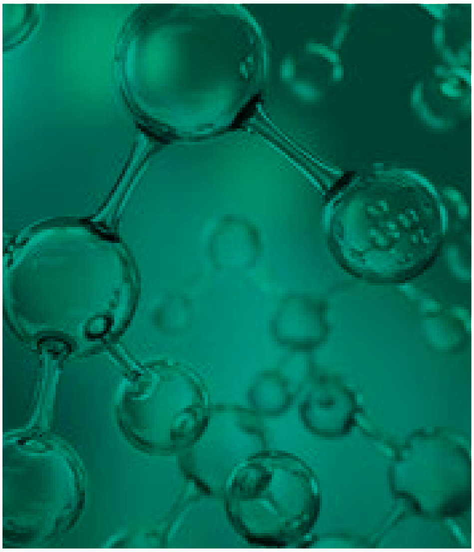
It should be noted that CCfDs would not be expected to have a large impact on government budgets. This is because CCfDs with high strike prices would only be available to kickstart commercial projects, followed by lower strike prices as the processes mature, to be eventually phased out when the technology becomes widespread and the market for green products established. Moreover, the government would not pay the full strike price of the CCfD. Rather, it would pay only the difference between the strike price and the actual observed ETS allowance price. Thus, if the carbon price steadily rises over time, the net annual cost would fall and eventually become negative. Estimates indicate that CCfD prices in Europe may be in the order of a few million euros per country to decarbonise 10% of the hard-to-abate sectors (Sartor and Bataille, 2019; Agora Energiewende, 2020).

Even more ambitious plans would not be too expensive: to convert 33% of German and 50% of EU primary steel production to green hydrogen processes, estimates foresee the annual funding requirements in the range of USD 1.2-3.1 billion for Germany and USD 4.7-11.8 billion for the European Union with the current free allocation regime. (Agora Energiewende, 2021c). Funds for the CCfD programme may come from the carbon pricing mechanism or from product-related economic instruments (see Sections 2.2 and 2.4)

When preparing CCfDs, policy makers will have to consider a variety of design elements, in part similar to those typical of renewable energy auctions (IRENA, 2019), in part novel. Important design elements will be the treatment of negative prices, the length of the contracts, the price setting and the eligible technologies

If the average ETS price is above the strike price, then the difference would be negative (as in Figure 2.7): in these cases the government could receive the difference in return for the CO_2 price risk. Another option would be to require no payment in the case of negative difference; this could support initial projects, increasing their total returns from the measure (McWilliams and Zachmann, 2021).

The length of a CCfD contract is another important feature. In any case, CCfDs will need to cover sufficiently long periods to compensate for upfront capital investment. For example, the German environment ministry plans to sign CCfDs with a ten-year period (BMU, 2021). Adjustment could be made to extend the contract in cases of financial crises or any other event that may disrupt or halt production for a period of time.



CCfD strike prices could be administratively or competitively set. In other words, the level could be set in advance to attract investment with a secure income per unit of production on a first-come, first-served basis, or it could be decided via an auction to select the most competitive price (and be less burdensome on government budgets). If administratively set, it could decrease over time to promote incentives for technological improvement and to follow technological development. If competitively set, participants could bid their proposed strike prices for a total amount of avoided emissions, and the auctioneer (a public body) could select the projects that would achieve the largest emission cuts with the least budget burden for the government.

It should be noted that a CCfD scheme may also support partial decarbonisation solutions based on the avoided emissions. Governments supporting total decarbonisation of the industry will then have to consider what projects to actually fund to avoid the “gradual shift” risk mentioned in Section 1.2.4. The same CCfD scheme could support, for example, one green hydrogen project or two blue hydrogen projects with 50% CCS rates. A whitelist of eligible technologies, including direct electrification and green hydrogen, could be a solution to guarantee long-lasting and effective decarbonisation and reduced total costs.

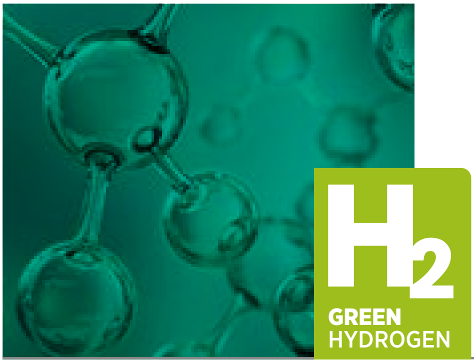
2.5.4 Procurement of green hydrogen via bilateral auctions

Without sufficient demand for green hydrogen, producers lack the incentive to deploy it at a large enough scale to reduce the cost, leaving green hydrogen at a cost that cannot generate demand, creating the chicken and egg problem (see Section 1.2.3).

A centralised auction scheme to ensure hydrogen offtake and consumption, with the cost differential paid by a public body, can help solve this issue. A public body would act as central auctioneer and would sign long-term purchase agreements with electrolysers and sale agreements with industrial players.

Through such a mechanism, green hydrogen and its derivative products could be purchased using a double auction scheme. The lowest purchase agreements and the highest sale agreements resulting from the auctions would be awarded the contract, while too high purchase offers and too low sale offers will be rejected (Figure 2.8). The public body would then cover the price difference. Moreover, it can determine a floor price below which the green hydrogen sale is not considered, and a ceiling price above which purchase is not considered.

The physical trade may be arranged by the parties or remain virtual, with the industrial players winning the auction buying only certificates and being able to claim the green nature of their production. Depending on auction design, a captive green hydrogen producer may sign both contracts, basically receiving a premium for their green hydrogen self-production.



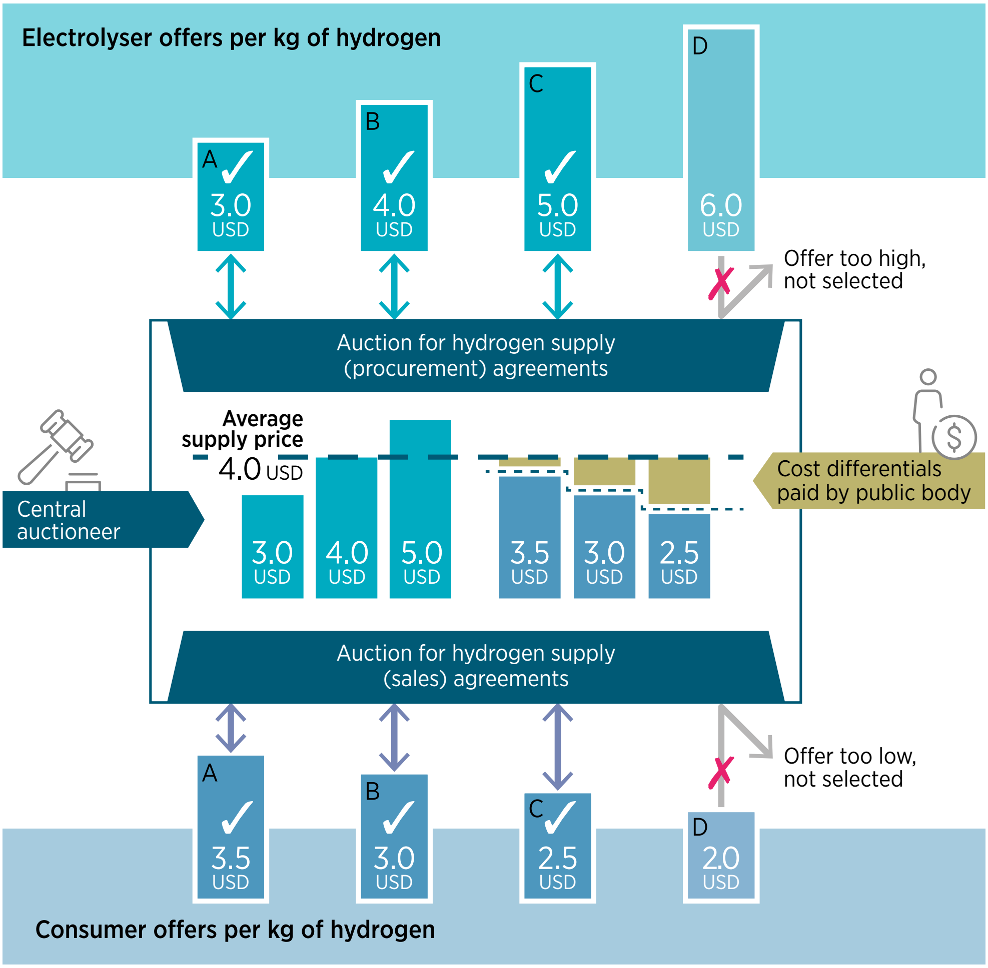
A competition-based mechanism such as an auction could prove instrumental in kick-starting the use of green hydrogen in industry. If auctions are successful in reducing the cost of green hydrogen, as has been done for solar PV and wind energy (IRENA, 2019), this would significantly improve green hydrogen's business case in various industries. Indeed, achieving cost parity with carbon-intensive forms of hydrogen is pivotal for the future prospects of green hydrogen in industry.

This kind of scheme is currently being designed in Germany under the H2Global funding programme. H2Global is an auction scheme to procure green hydrogen for German industry; it aims to procure green hydrogen from all across the globe. Germany has already signed many memorandums of understanding with other countries to plan future imports of hydrogen (IRENA, 2021a; 2022).

The H2Global programme established an intermediary body called the Hydrogen Intermediary Network Company (HINT.CO) to sign long-term agreements. HINT.CO is supported with EUR 900 million of funding to temporarily compensate the difference between the hydrogen purchase agreements and sale agreements.

The programme expects that future adjustments to the regulatory framework will increase industrial off-takers' willingness to pay for green hydrogen and the sale agreement price will rise over time. This will gradually reduce the need for HINT.CO to compensate for the price differential until a point is reached where the demand and supply prices are in line with each other. At that point, the role of the intermediary would end.

Figure 2.8 Bilateral auction system schematic



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2.6. CREATING THE MARKET FOR GREEN PRODUCTS

Although there is a growing interest in the production of green hydrogen, the demand for goods manufactured using green materials is lagging, as they are more expensive than their grey counterparts., Governments have a variety of actions that they can take to generate sufficient demand and create a market for green products, such as sustainable public procurement and quotas. These measures will require ecolabelling, meaning a scheme to measure, validate and trace the carbon content of the green materials or goods.

2.6.1 Quotas of green products

In order to create a minimum anchor demand for green materials, governments can introduce increasing demand quotas for green materials. This quota would create the basis of a market that does not currently exist.

Large consumers of basic materials (*e.g.* carmakers) would be requested to prove the purchase of a minimum amount of green materials, or pay a fine. Those producers who exceed their quota may sell their excess to non-compliant producers in the form of certificates, similarly to green certificate schemes in the power system. It is essential to remember that allowing the quota to be met through certificates might not align with a long-term net zero emissions system, *i.e.* the real consumption of green materials is the ultimate guarantee and economic signal to ensure that the system efficiently progresses towards net zero (as it also is for determining the scale of production capacity, logistics, infrastructure etc.). In this sense, the certificates and their corresponding surrendering rules could be designed to fulfil such goal, thus cancelling the risk of locking in emissions and future stranded assets.

From experience with green certificate schemes, it is possible to identify two main policy design elements that may allow the policy to succeed:

- The level of ambition for the target. If the target is set too high or the increase too steep, national supply might be below the quota requirement, resulting in high compliance costs and a detrimental effect on profitability. If the target is too lenient, it might not spur the necessary demand to kickstart the growth in production that would result in large cost decreases. Quotas should follow and anticipate green hydrogen production capacity, taking into consideration other concurrent hydrogen uses.
- The level of the fine. The fine itself sets the cap on the cost of the low-carbon material. A low fine may encourage the obliged party not to comply. An excessively high fine may conversely result in a detrimental effect on profitability, with carbon leakage risks.

An example of this policy measure is envisaged in the German Hydrogen Strategy, including definitions and criteria, and will be subject to further evaluation (BMWi, 2020b). The German strategy recognises the necessity of a verification and labelling system able to guarantee the sustainability of the goods (see Section 2.4.4).


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2.6.2 Sustainable public procurement

Public procurement refers to the process by which public authorities, such as government departments or local authorities, procure, purchase and acquire work, goods or services from companies.

UNEP's definition of sustainable public procurement (SPP) is:

> ***"A process whereby public organisations meet their needs for goods, services, works and utilities in a way that achieves value for money on a whole life-cycle basis in terms of generating benefits not only to the organisation, but also to society and the economy, whilst significantly reducing negative impacts on the environment."***

Public procurement accounted for 12% of GDP in OECD countries and up to 30% in developing economies in 2017. Over 250 000 public authorities in the European Union spend around USD 2.4 trillion per year (around 14% of EU GDP) on the purchase of services, works and supplies (European Commission, 2021b; UNEP, 2017).

National laws regulate public authorities' and utility operators' procurement activities, which are usually based on tenders. While regulations are mostly designed to avoid corruption, they can be redesigned to include elements of social and environmental sustainability.

UN Sustainable Development Goal 12.7 calls for national SPP plans, promoting public procurement practices that are sustainable, in accordance with national policies and priorities.

SPP can represent an initial and stable demand driver for green goods and materials, as governments often have high purchasing power and capital available to promote the uptake of green products. SPP may have a larger impact on the creation of a green steel market than for other materials like ammonia, as steel is used in buildings, bridges, railways and transport fleets (*e.g.* buses) (worldsteel, 2021).

Direct and indirect government purchases of steel may be small. AISI (the American Iron and Steel Institute) estimates that government purchases account for 3.3% of total steel use in the United States (Krupnick, 2020). Notwithstanding the small size of the market, through the incentives provided, the examples set and the learning by doing, such programmes might move the industry. A specific procurement of green steel could, for instance, be incorporate in auctions for wind farms (see Box 2.3).

Examples of SPP adoption are already widespread, with at least 41 countries implementing it (UNEP, 2017). The Buy Clean California Act is a recent example. It imposes a maximum acceptable global warming potential (GWP) limit on selected construction materials. It targets, among other materials, carbon emissions associated with the production of structural steel and concrete reinforcing steel, with a maximum GWP between 1.49 and 0.89 Mt CO_2-eq/ Mt_{steel}. From 2024, and every three years thereafter, the maximum acceptable GWP will be reviewed for each material, and the limit may be adjusted downward to reflect industry improvements. The GWP of a material is stated on an environmental product declaration, an independently verified and registered ecolabel that reports a product's environmental impact over its life cycle.

During COP26, the governments of Canada, Germany, India and the United Kingdom, some of the world's largest steel and concrete buyers, pledged to buy low-carbon construction material when available. The objective of the initiative is to make investors confident in the existence of a market for their products. The countries will also aim to track and report on the carbon content of public construction by 2025. The countries aim to achieve net zero public-sector buildings by 2050, with interim targets to be defined at the time of the writing (UNIDO, 2021).

In December 2021 an executive order was signed in the United States that directs the federal government to use its scale and procurement power to support the growth of clean technology industries, with the aim of achieving net zero emissions from federal procurement by 2050. The federal government aims to launch a "buy clean" initiative for low-carbon materials and prioritise the purchase of sustainable products (White House, 2021b).

Box 2.3 Procurement of green steel through auctions for renewable energy

Iron and steel are essential materials for the manufacture of important components used in the development of all renewable energy plants (Figure 2.9). According to IRENA's latest projections in the World Energy Transitions Outlook: 1.5°C Pathway report, to limit global warming to 1.5°C by 2050, renewable power capacity will have to increase over tenfold from around 2800 GW in 2020 to more than 27700 GW in 2050. The lion's share of this increase will be provided by variable renewable technologies, namely solar PV, and onshore and offshore wind. Based on IRENA's scenario, solar PV capacity will reach over 14000 GW and wind capacity (both onshore and offshore) will reach over 8100 GW.

Renewable energy auctions will be instrumental in reaching these ambitious targets. Auctions have become an increasingly popular way of procuring renewable electricity, with over 100 countries having conducted at least one auction. The ability of auctions to determine the lowest market prices has been a major motivation for their adoption worldwide. However, price discovery is not the only benefit of conducting renewable energy auctions; the flexibility in their design allows them to be tailored to country-specific conditions and to achieve objectives such as timely project completion, system integration and socio-economic development.

One of the main objectives that countries seek to address during the design of their auctions is that of fostering local development through, for example, winner selection criteria or local content requirements. Such requirements can be featured as part of qualification requirements, restricting participation to developers who comply with a minimum threshold of local content. This is typically represented as a minimum percentage of the total project costs to be spent on domestic products and services. By incentivising or mandating developers to source a proportion of their materials and equipment locally, auctions can help develop local industries and supply chains in the renewable energy sector and beyond. Such auction design elements have already been introduced in auctions conducted in Brazil (whereby wind project developers can benefit from concessional financing from the local development bank only if a certain percentage of local content is met), Morocco and South Africa where local content was introduced both as qualification requirement and as winner selection criteria. Although such design elements can increase the energy price, at least in the short term, they create local value for the economy, support innovation and further enhance energy autonomy and security.

To ensure that renewable energy projects are developed in the most sustainable manner possible, policy makers may consider the introduction of auction design elements, either in the form of incentives (*e.g.* through winner selection) or requirements on "green content" that support the use of green practices and materials, such as green steel. Although such design elements may result in higher prices, they can help achieve the objective of greening the renewable energy sector, and contribute to developing the sector for green materials and processes. More precisely, if auctions include a criterion incentivising or requiring a certain amount of the steel procured for a plant to be manufactured using net zero processes, either locally or internationally, this could substantially increase the market for green hydrogen-based materials and accelerate the proliferation of green hydrogen.

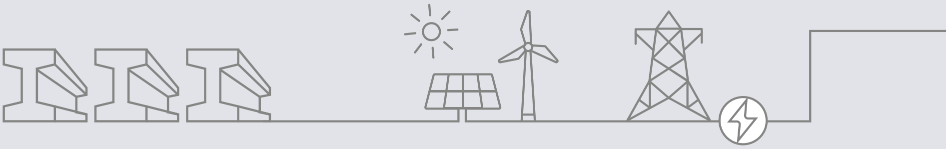
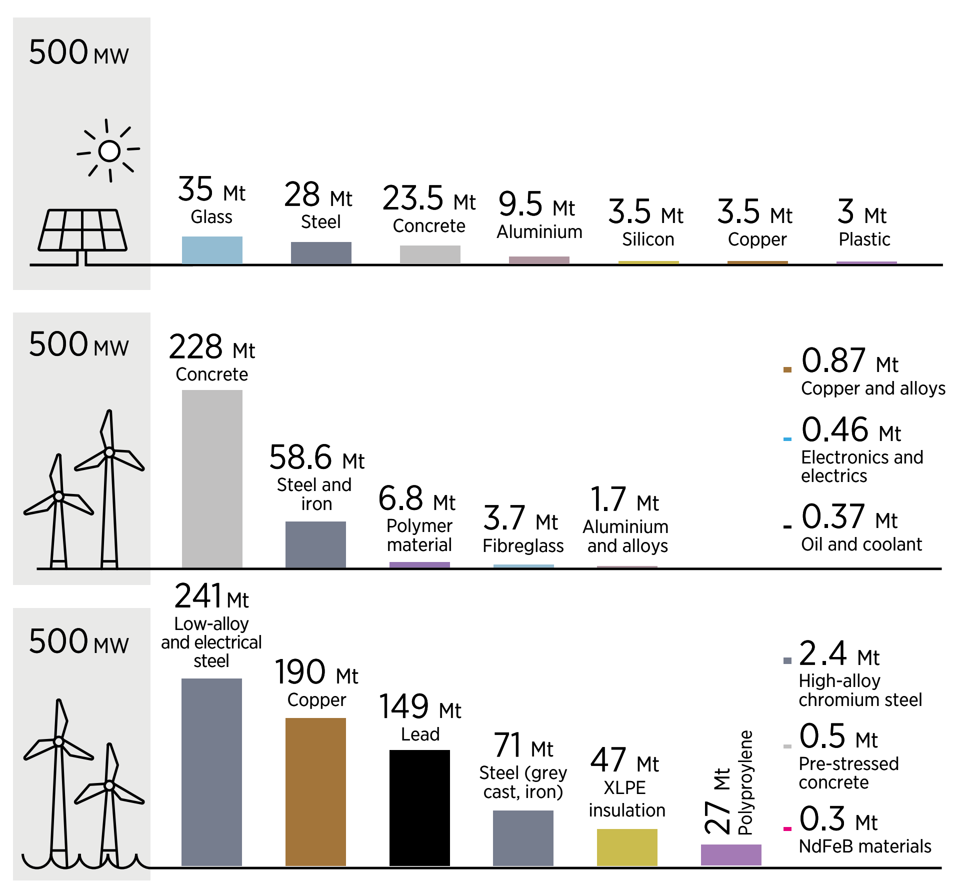


Figure 2.9 Material required to build a 500 MW solar plant, onshore wind plant or offshore wind plant



Note: values are intended for 500 solar PV systems of 1 MW size, ten onshore wind farms of 50 MW and an offshore wind farm of 500 MW

Note: XLPE = cross-linked polyethylene.

Sources: IRENA (2017a, 2017b, 2018, 2019, 2021b).

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2.6.3 Product-related economic instruments

Product-related economic instruments, such as tax differentiation and capital allowances, are measures that governments can adopt to nudge consumers and businesses toward less damaging forms of consumption.

Tax differentiation is a type of tax design in which the rates on goods are adjusted to reflect a government goal. If producers do not pass the tax on to customers in the form of increased pricing, the tax's impact will be seen in lower profitability, which will push enterprises to move toward producing less taxed alternatives.

Consumers will be incentivised to switch to alternatives if the tax is passed onto them in the form of increased product costs. Taxes affecting less than 10% of the selling price of items are unlikely to cause major behavioural changes in consumer purchasing or company production choices (OECD, 2014).

Tax differentiation should be designed to ensure that the difference in taxation is proportionate to the scale of climate impact involved, and in order to have this kind of data, an ecolabel may be necessary.

Tax differentiation can have a particular impact on recurrent purchases (*e.g.* cleaning products), as opposed to one-off purchases where many factors impact the final decision. For non-recurrent purchases, such as cars and new buildings, tax relief can be adopted to encourage consumers to invest in more expensive green goods. Under such a scheme, the expense incurred in buying a green product can be partially or totally deducted from corporate or income taxes.

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Currently, no scheme specifically targets green materials or goods (as intended in this report), focusing more on the energy efficiency of appliances and cars. Policy makers could consider them once the green products are commercially viable to facilitate their market entrance.

All UK businesses that pay corporation or income taxes can benefit from an enhanced capital allowance, which provides 100% tax relief on any investment in new or unused energy-saving equipment in the same tax year as the purchase is made. Therefore, a business paying corporation tax at 30% will receive GBP 0.30 tax relief for every GBP 1 invested in energy-saving equipment.

2.6.4 Ecolabelling

Materials and goods produced in a sustainable manner are typically indistinguishable from their counterparts. For this reason, many different systems collect data and track products to inform the public of the quality and sustainability of production in a process known as ecolabelling.

Many ecolabels exist for various goods (paper, food, etc.). Ecolabelling is intended to provide a mechanism for conveying information to consumers on products that meet environmental standards, and to manufacturers or retailers on targets for reducing environmental impact. Ecolabels are instrumental in creating a market that values sustainability, with this value translating into justifiable higher prices and improved economics for sustainable producers. However, voluntary ecolabels may have a limited impact on the market, struggling to be noticed by environmentally conscious and environmentally unaware consumers alike (Song *et al.*, 2019).

In order to identify the environmental impacts, a system of traceability is needed, *i.e.* a system to follow each part of the supply chain and quantify the impact of each process. Traceability systems vary widely and are designed to be fit for purpose. They could be paper-based with a limited level of detail, or could adopt more advanced solutions to have more granular visibility over all the materials and processes. Recently, the use of the Internet of things and blockchain has been proposed to assist data gathering (ISEAL, 2016; Balzarova and Cohen, 2020).

As many of the best GHG abatement opportunities are in materials such as steel, which are rarely purchased by consumers directly, ecolabels would be primarily aimed at public bodies that purchase these materials in large quantities or that support them. The presence of ecolabels is a necessary condition to either impose the use of green materials or simply to guarantee their provenance for SPP (Agora Energiewende, 2021c; Rissman *et al.*, 2020).

Ecolabelling can be a private sector-led initiative or a public-sector initiative, such as the Ecoleaf programme in Japan (see Box 2.4)

Ecolabelling chemicals may be more difficult because the supply chain is more complicated, with more intermediary steps, but digitisation is changing industrial production processes and producing data that allow plant management to determine energy use, emissions and abatement opportunities (Rissman *et al.*, 2020).

Box 2.4 Ecoleaf

The Ecoleaf environmental label is an ecolabel supported by the Japanese government. The programme was fully implemented in 2002 as a way of promoting an eco-conscious lifestyle among the Japanese populace through the proliferation of environmentally friendly goods and services.

Ecoleaf quantitatively shows environmental information for a wide range of products, including food, clothing and office supplies, but also construction products and steel.

The system follows all the stages of the products life cycle, from the extraction of resources to discarding or recycling. It aims to facilitate the comparison of products' environmental impacts and promotes transparent communication between a business and its stakeholders. Each product category under the Ecoleaf label contains a set of unified criteria known as the product category rules, which determine data acquisition methods, life-cycle assessment calculation methods and label content.

As an example, an environmental declaration for a steel plant under the Ecoleaf certification provides information on its global warming impact, resource consumption, environmental effects (acidification, land use, etc.) and the amount of recycled materials and renewable energy used by the process.

Source: Ecoleaf (2021).

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2.7. RESEARCH AND DEVELOPMENT

While governments can incentivise or mandate industry to decarbonise their processes, continued Research and Development (R&D) to make green hydrogen products competitive with incumbent technologies will increase the effectiveness of the supporting policies and, ultimately, make them less necessary.

R&D programmes, sponsored by government, can accelerate innovation. Governments have traditionally had a central role in setting the research agenda through dedicated funds, grants, tax incentives for private industry, concessional loans and equity in start-ups. Moreover, patents in green hydrogen technology can increase the competitiveness of local industry and allow it to become a leader in the nascent sector.

Policy makers can set R&D goals in their hydrogen strategies: while most refer to the reduction of green hydrogen costs, they can also introduce goals to measure the impact of R&D for manufacturers. These can include CO_2 emission reductions from new processes or the number of key technologies ready for large-scale use.

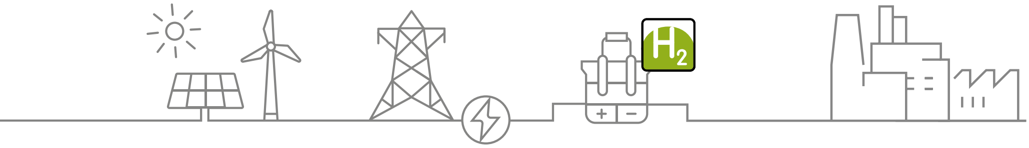
Hydrogen serving industrial users must be produced on a large scale and delivered with a certain regularity. Industrial processes need stability of supply, so storage (batteries or hydrogen storage) becomes necessary to cope with the variability of wind and solar PV generation, increasing costs. For the adoption of green hydrogen in the steel industry, it will be necessary to replace BF-BOF with DRI-EAF fuelled by hydrogen. While a prototype is already in place (see Box 1.3), replicability of the process in different contexts is still to be assessed. The physical aspects of the hydrogen-driven reduction process vary depending on parameters such as the operating temperature, type of metal oxide and grain size. These aspects still have to be deeply researched for the several metal oxides used in the production of steel.

Research into decarbonising ammonia production is focused on increasing the operational flexibility of the synthesis unit to cope with the variability of supply and on new processes that could succeed the Haber Bosch process. These include the electrochemical, plasma-chemical, thermochemical and photochemical generation of ammonia. All these routes, however, are still at their inception, with very low technology readiness levels.

Methanol production needs to identify a sustainable and low-cost carbon source. Further research is needed on various integrated pathways. This issue is shared with other synthetic fuels. Possible solutions include DAC or the use of waste biomass (*e.g.* sewage gas), unrecyclable waste (*e.g.* plastics), or by-products of cement production (CO_2 production is unavoidable when calcinating limestone). Another research pathway includes the co-electrolysis of CO_2 and water, which could lead to higher process efficiencies

Governments around the world are already supporting the use of green hydrogen for industry through R&D programmes:

- A variety of funding programmes are being launched in Germany. These include the Use of Hydrogen in Industrial Production programme, amounting to EUR 15 million in 2020 and with a commitment amounting to EUR 430 million by 2024 (BMWI, 2020b).
- The US Department of Energy awarded around USD 8 million for HySteel, a programme to improve hydrogen-based steelmaking (Fuel Cells Bulletin, 2020).
- Australia is looking forward to becoming a major exporter of green hydrogen and green ammonia. The Australian Renewable Energy Agency has allocated USD 40 million (AUD 55 million) for R&D and demonstration of green hydrogen and ammonia projects and has supported various feasibility studies for ammonia (ARENA, 2020).



3 THE WAY FORWARD

As seen in the previous chapter, policy makers have various options to support green hydrogen for the decarbonisation of hard-to-abate sectors. They can push for a change with strategies and specific bans and mandates or incentivise the industry to decarbonise by making it pay for its emissions. In these cases, carbon leakage policies may be needed to avoid a situation where businesses transfer production to other countries with more lenient emission constraints. Alternatively, policy makers can support industry with direct support schemes or indirectly by creating a market for green materials and goods.

It is likely that a mix of these policies will be needed to both support and push the necessary change. Certain policies are suitable for kick-starting the change, informing developers of what is expected to happen and supporting R&D, while others will be needed later as the system makes progress. The "policy stage" concept, introduced in IRENA (2020a) has been created to help policy makers understand when a policy could be introduced, according to the status of the country's hydrogen sector.

For the industrial sector, the stages are described as:

STAGE ONE

DEMONSTRATION AND GOVERNANCE. At this stage the profitability gap is the widest, requiring the largest economic incentives. Compensation for the higher investment can be directed through grants or loans that attract private capital. Strategies and targets are set to inform stakeholders about the decarbonisation of the industrial sector. Green steel, ammonia and methanol are not yet valued for their lower GHG emissions, so a system is needed to track the upstream emissions and create a differentiated market that values these properties. Carbon pricing policies are introduced. Given the international market for materials from energy-intensive industries, global co ordination and co operation are even more critical than for other hydrogen applications. CCfDs can be introduced to support the uptake of green materials. Ecolabels should be defined to allow SPP and other policies in the later stages. SPP rules can be put in place to create demand promptly once green materials and goods are available.

STAGE TWO

ACHIEVING COMMERCIAL SCALE.

At this stage the first green products are being produced. Green hydrogen progressively replaces grey hydrogen, in particular if green gas targets are in place. Policies in place need to create a market for green product, such as SPP and quotas. Green products can be supported with specific product-related economic instruments.

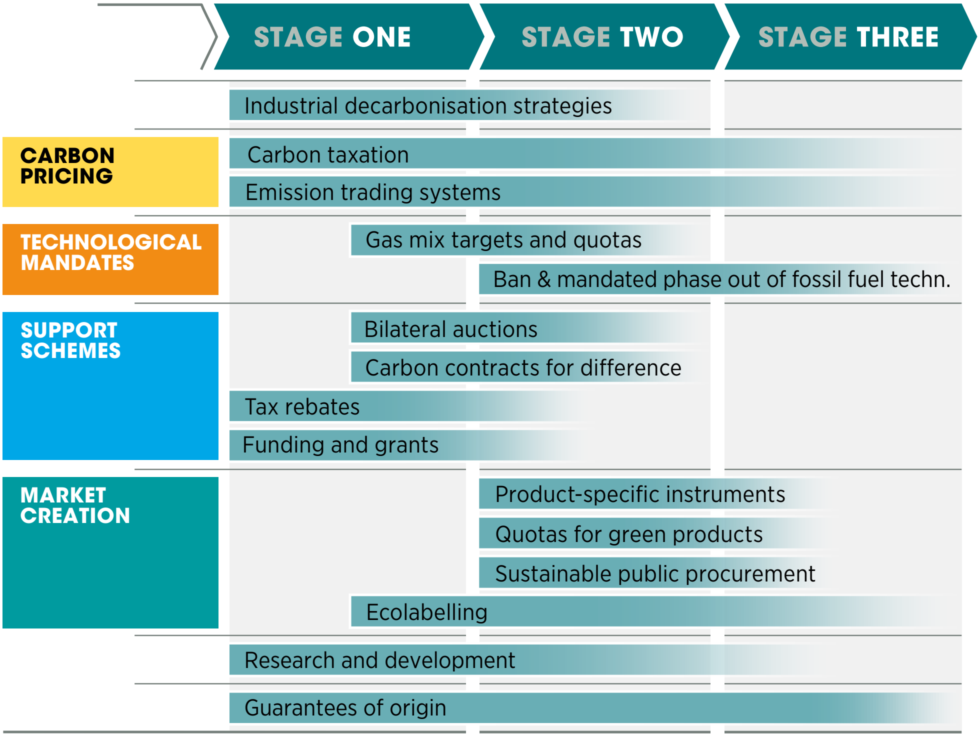
STAGE THREE

ON THE PATH TO FULL DECARBONISATION.

Green hydrogen has become widespread across the energy system and costs have greatly reduced. Policies supporting green hydrogen or green products are no longer necessary, as the economic gap has been closed. The role of policy makers is to ensure the progressive phase-out of the final fossil fuel technologies while maintaining all the instruments that allow clear and comparable information on both the materials and the goods, and to prevent carbon leakage vis-à-vis regions not making comparable decarbonisation efforts.

Figure 3.1 shows the range of policies explored in this report across the three stages, proving a roadmap for said policies. The bars indicate when a policy should be in place; in order to be ready, however, actions for its implementation will have to be enacted beforehand.

Figure 3.1 Roadmap of policies to promote hydrogen use in industry across three stages of deployment



CONCLUSIONS

There is growing global awareness of the effects of climate change. As a result, many governments have adopted suites of policies to start decarbonising the energy sector, the main source of GHG emissions. Policies have been so far mostly focused on the power sector.

The next challenge for policy makers will be to focus on the whole energy system, which includes the manufacturing facilities producing basic materials such as steel, chemicals and refined fossil fuels. Global emissions from these industries have been increasing, notwithstanding the ever-decreasing costs for renewable energy, in contrast to the commitments made in Paris to limit global warming and the IPCC recommendations.

One challenge in these industries is the fossil fuel dependency of their processes, causing them to fall under the umbrella of hard-to-abate sectors. As renewable energy technology has evolved, however, solutions for these industries have emerged; among them, green hydrogen is one of the more prominent, and is shared between industries.

Moving toward green hydrogen-based heavy industries would require a major technological shift in their core industrial processes. Historically, such shifts have occurred because of major economic gains enabled by technological innovation. There is no time to wait for green hydrogen technology to become cost-competitive with current technologies, due to the urgency of taking climate action and the fact that hard-to-abate sectors are only one investment cycle away from 2050. The change must be led by policy makers who, through policies and regulation, can accelerate the change and drive investments in this direction.

While the challenge is daunting and pressing, there are signs that this transition is achievable. Technological solutions exist, several initiatives are currently ongoing with pilot trials, and growing numbers of countries are planning policies to support the adoption of green hydrogen by industry.

Industrial policy will be needed to overcome the barriers presented in this report, to support early movers and to make sure that the innovation brought by green hydrogen will become the default option to decarbonise material manufacturing.

This report has laid out a list of proposals for policies that would support in different ways the uptake of green hydrogen in the industrial sector. Some of these policies are already in place in parts of the world, while others are being considered and suggested. Not all these policies will be needed in all jurisdictions at the same time, but it is likely that a combination of policies – both mandating or pushing for change and supporting the same – will be necessary across the globe. Only mandating change, without support, may meet organised resistance from industry, and carbon pricing may not achieve the level and stability needed to push for decarbonisation. At the same time, only supporting green basic materials and goods – without an overall decarbonisation roadmap – risks being ineffective in the long term.

The policies presented, along with the roadmap in Figure 3.1, are not meant to be a to-do list. Rather, this guide aims to provide a comprehensive overview of the options for policy makers, to present the tools already available to facilitate the discourse around these options and accelerate their adoption.

Industrial assets have a long lifetime and industries are deeply interlinked with society, creating jobs and wealth for the hosting countries. As the 2050 deadline approaches, any further delay will complicate their transition. These factors, together with the urgency dictated by the climate change crisis, call for immediate appropriate action by policy makers, who are urged to act now to secure the industrial energy transition.

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