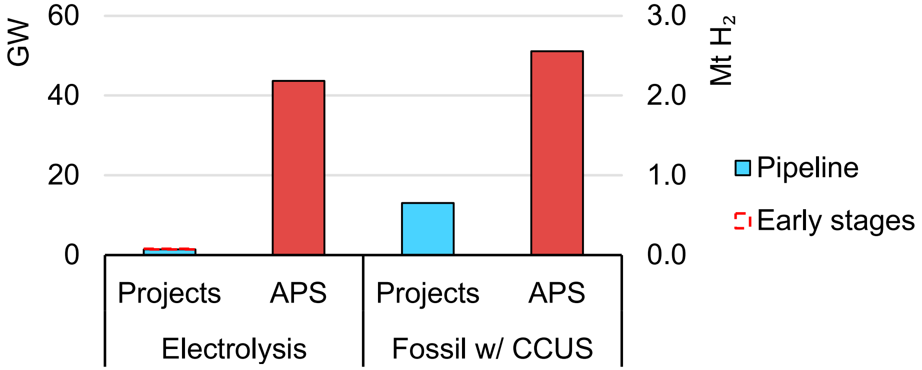
development with could become online by 2030.[34] The US DOE estimates a potential deployment up to 13.5 GW based on company proposals and projections. These numbers fall short of what is needed to meet net zero goals.

US electrolysis capacity and hydrogen production from fossil fuels with CCUS in the Projects case and the Announced Pledges Scenario, 2030



Note: APS = Announced Pledges Scenario.
Source: IEA (2021), Hydrogen Projects Database.

In the Announced Pledges Scenario, 44 GW of electrolysis capacity is deployed by 2030. US progress on deploying capacity to produce hydrogen from fossil fuels with CCUS is accelerating in response to the 45Q tax credit, which rewards CCUS projects at rates of USD 50/t CO_2 for geological storage of CO_2 or USD 35/t CO_2 if used for enhanced oil recovery. In 2021, annual US production from fossil fuels with CCUS was 0.23 Mt H_2, around one-third of global production capacity.

The largest project currently under construction in the world (Wabash Valley Resources) is in the United States and expected to become operational in 2022, which could push production capacity to over 0.3 Mt. To align with the Announced Pledges Scenario, however, capacity should expand to more than 2.5 Mt by 2030.

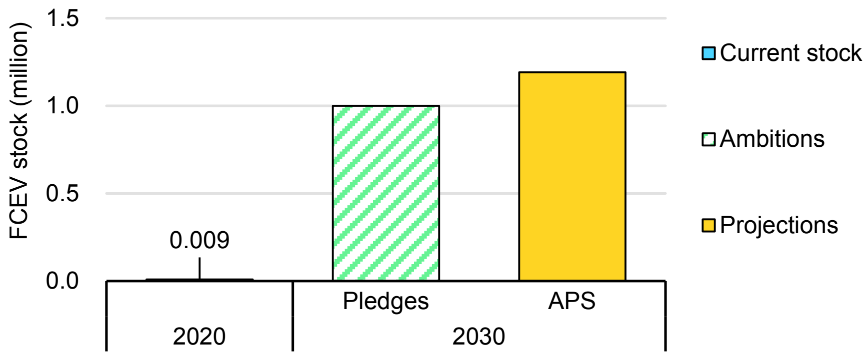
The United States led global deployment of FCEVs until 2020, when Korea pulled ahead. At the end of 2020, of the 9 200 FCEVs in the country, most were in California, which has been supporting deployment for almost a decade through the Clean Vehicle Rebate Project and by funding construction of hydrogen refuelling stations (HRSs).

In 2013, Assembly Bill 8 (AB8) required establishment of at least 100 HRSs; this target was doubled in 2018 to 200 HRSs by 2025. The main support mechanisms are grants (up to USD 115.7 million offered in GFO-19-602) and credits under the Low Carbon Fuel Standard Hydrogen Refuelling Infrastructure, which incentivise both

[34] Projects in the pipeline includes, in addition to projects already operational, projects currently under construction, that have reached final investment decision (FID) or that are undergoing feasibility studies. Projects for which there has just been an announcement or a cooperation agreement signed among stakeholders are considered projects at early stages of development.

renewable hydrogen (33-40%) and high-capacity HRSs. To support FCEV deployment, Air Liquide is building a 30-tpd renewable liquid hydrogen plant to supply HRS infrastructure in California.

FCEV deployment in the United States in the Announced Pledges Scenario, 2020-2030

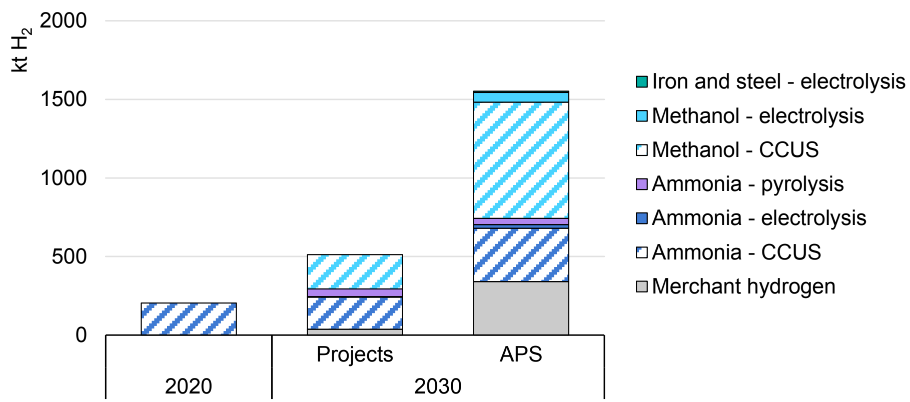


Notes: FCEV = fuel cell electric vehicle. APS = Announced Pledges Scenario. "Ambitions" refers to the California Fuel Cell Partnership target.
Source: AFC TCP.

In addition to FCEVs, a successful DOE programme has triggered commercialisation of hydrogen fuel cells for material handling equipment: in 2021, roughly 115 HRSs served over 40 000 fuel cell material handling vehicles. While the US government has not set an official federal target for FCEV deployment, the California Fuel Cell Partnership aims for 1 million FCEVs in the state by 2030. In the APS, national FCEV deployment slightly exceeds this target, reaching 1.1 million in 2030.

Opportunities to use low-carbon hydrogen in industry in the United States are mainly in the chemical sector. Low-carbon hydrogen is already produced in facilities incorporating CCUS, particularly for ammonia production. Since 2013, 1.7 Mt CO_2 have been captured every year at two fertiliser plants (Coffeyville and PCS Nitrogen), where captured CO_2 is used for EOR.

Low-carbon hydrogen demand in the US industry sector in the Announced Pledges Scenario, 2020-2030



Notes: APS = Announced Pledges Scenario. CCUS = carbon capture, utilisation and storage.
Source: IEA (2021), Hydrogen Projects Database.

A small number of projects for the production of hydrogen from fossil fuels with CCUS are currently in the pipeline in the United States. If all these projects become fully operational, the production capacity will meet 40% of the Announced Pledges requirement of 1.1 Mt H_2

produced from fossil fuels with CCUS in 2030. For electrolytic hydrogen use, current announced projects fall far short of the 2030 Announced Pledges level of around 85 kt H_2 for ammonia and methanol production – i.e. 25 times the capacity of the single ammonia project currently under development.

Interest is growing in the ways hydrogen can provide energy storage and be used as a means of generating on-demand electricity to balance the power grid as variable renewable generation increases. The Advanced Clean Energy Storage Project (ACES), under development in Utah by Mitsubishi Power Americas and Magnum Development, aims to pair 1 GW of electrolysers with large salt caverns to store 150 GWh of dispatchable energy. The hydrogen will be used in an 840-MW plant currently running on coal, which will initially be converted to run on natural gas and hydrogen blends, then eventually modified to operate on 100% hydrogen. While this is one of the largest project of its kind in the world, it would meet less than 12% of the nearly 1.4 Mt H_2 needed for electricity generation by 2030 (according to the Announced Pledges Scenario) to keep the United States on track with its net zero target for 2050.

The significant hydrogen uptake projected in the Announced Pledges Scenario, especially for new applications such as electricity generation and transport, would require rapid deployment of hydrogen infrastructure to facilitate delivery to end users. With more than 2 600 km of hydrogen pipelines currently in commercial operation, the United States accounts for over half of global hydrogen pipelines. Most are owned by merchant hydrogen producers and are located mainly in the Gulf Coast region where US refining capacity is concentrated.

The Hydrogen Strategy, published by the DOE in July 2020, considers blending an option to deliver pure hydrogen to downstream markets, using separation and purification technologies near the point of end-use. To help determine acceptable blending limits and material compatibility, in 2020 the DOE, together with industry and national laboratories, launched the HyBlend initiative.

In California, a first demonstration project using polymer-based distribution pipelines is expected to launch in 2021, with an initial hydrogen blend level of 1 vol% H_2, potentially rising to 20 vol% H_2. Meanwhile, Dominion Energy started a pilot project (spring 2021) to blend 5% hydrogen into a test gas distribution system. Kinder Morgan, one of North America's largest gas pipeline operators, estimates that hydrogen in 5-10% blends could be transported through natural gas transmission pipelines with little to no modification.

At present, three of the four hydrogen salt caverns storage sites operating globally are in the United States (all in Texas), including the world's largest facility in Spindletop (commissioned in 2016).

Japan: Announcement of a 2050 net zero target triggers new push for hydrogen technologies

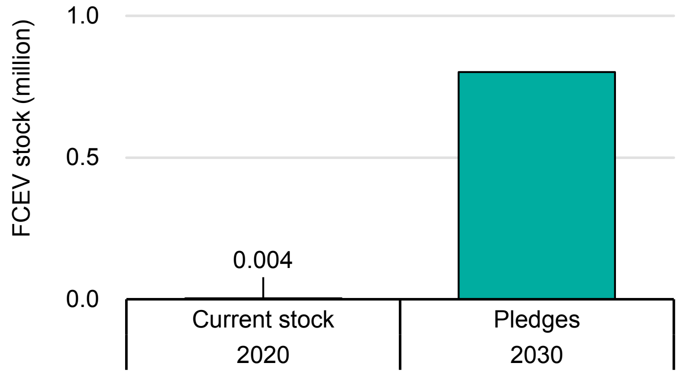
Hydrogen demand in Japan was close to 2 Mt H_2 in 2020. Refining is responsible for close to 90% of demand, with a small amount of domestic ammonia production making up the rest. Natural gas-based production accounts for more than 50% of the country's hydrogen supply, and another 45% is by-product hydrogen from refineries and the petrochemical industry and a small coal-based production meeting the remainder.

Japan has been spearheading efforts to adopt hydrogen technologies. It was the first country to release a hydrogen strategy (December 2017) and has been leading international co-operation since 2018 through its annual Hydrogen Energy Ministerial meetings. The country considers hydrogen technologies as practical options to decarbonise significant parts of its energy and industry sectors and to boost energy security.

Therefore, although Japan has yet to publish details on its plans to achieve the 2050 climate pledge announced by Prime Minister Suga (October 2020), hydrogen is likely to be an important part of its programme. The government's Green Growth Strategy (announced in June 2021) includes a target to expand hydrogen use to 3 Mt in 2030. To support this goal, the government announced a public investment plan of JPY 700 billion (~USD 6.6 billion) to develop hydrogen supply chains in Japan.

The plan includes up to JPY 70 billion (~USD 0.7 billion) for domestic hydrogen production capacity based on dedicated renewables and up to JPY 300 billion (~USD 2.8 billion) to develop international supply chains (using liquid hydrogen and liquid organic hydrogen carriers) and to demonstrate co-firing or pure combustion of hydrogen in fossil-based electricity generation plants. In addition, JPY 330 billion (~USD 3.1 billion) have been allocated to innovation projects for hydrogen applications in aviation, shipping, steelmaking, ammonia production and CO_2 utilisation.

Current stock and 2030 target for FCEV deployment in Japan



Note: FCEV = fuel cell electric vehicle.
Source: AFC TCP, Strategic Roadmap for Hydrogen and Fuel Cells.

Japan has been a first mover in the use of hydrogen in transport, with Honda offering the first commercial FCEV in 2008. With around 5 600 FCEVs (including cars and buses) on the road in April 2021, Japan is the fourth-largest market in the world and has ambitious targets for FCEV deployment – 200 000 by 2025 and 800 000 by 2030. Toyota recently expanded fuel cell manufacturing capacity to 30 000 units/yr, though capacity will need to expand further if domestic original equipment manufacturers are to be relied upon to achieve government targets.

Japan has shown interest in using hydrogen to decarbonise energy demand in buildings. The ENE-FARM programme has subsidised installation of more than 350 000 micro-cogeneration[35] fuel cells, most fuelled by natural gas. Although ENE-FARM subsidies stopped in FY2019 for PEM fuel cells, more than 40 000 micro-cogeneration units were installed in 2020, similar to the number deployed annually while the programme was active. Subsidies remain in place for SOFCs until FY2020.

On the supply side, in 2020 a 10-MW solar-powered electrolysis project was inaugurated in Fukushima, the world's largest at the time. To date, Japanese stakeholders have not announced plans to deploy significant electrolysis capacity for dedicated hydrogen production; only some small projects (<5 MW) have been announced for upcoming years. This outlook may change following the government announcement of a budget of JPY 70 billion 70 (~USD 0.7 billion) to scale up and modularise electrolysers with the aim of decreasing manufacturing costs.

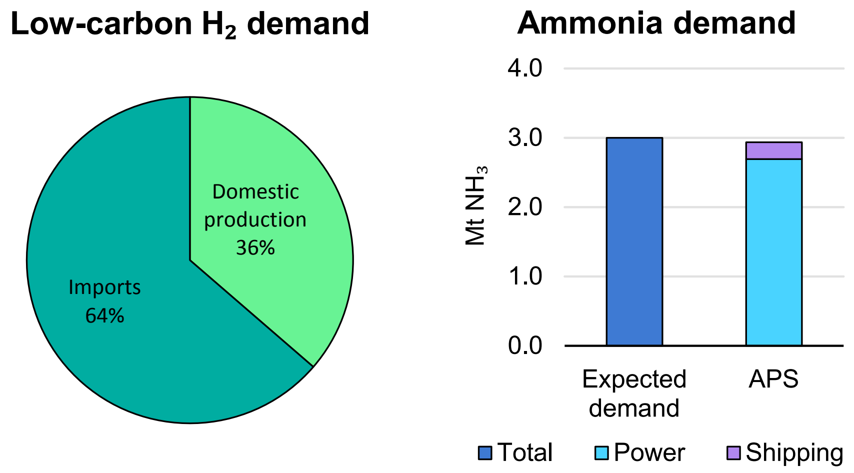
Regarding hydrogen production from fossil fuels with CCUS, the Tomakomai demonstration project was operational until 2019, and no projects for the near future have been announced. Low-carbon hydrogen production needs to be accelerated and international hydrogen supply chains must be developed to meet Japan's strategy target of 420 kt of low-carbon hydrogen by 2030. Japan is currently updating its strategy to align with its revised climate target, but it is likely that achieving the new targets will require substantial volumes of low-carbon hydrogen, with a significant portion having to be imported.

Japan has also targeted the use of ammonia as a fuel. In February 2021, the government released an Interim Report of the Public-Private Council on Fuel Ammonia Introduction highlighting its potential use in shipping and for co-firing in coal power plants to reduce their carbon intensity and avoid decommissioning them, as they are critical to Japan's electricity supply security. The concept was demonstrated at small scale by Chugoku Electric Power Corporation, and now JERA is scaling up the concept to demonstrate a 20% co-firing share of ammonia at a 1-GW coal-fired unit by 2024.

Using 100% ammonia in electricity generation is also gaining traction: Mitsubishi Power announced it is developing a 40-MW gas turbine able to run on ammonia, aiming to commercialise it in 2025. By 2030 in the Announced Pledges Scenario, Japan consumes close to 3 Mt NH_3 as fuel, mostly for co-firing in coal plants but also 0.25 Mt as fuel for maritime transport and. In addition, 0.7 Mt is used as feedstock in the chemical industry.

[35] Co-generation refers to the combined production of heat and power

Low-carbon hydrogen and fuel ammonia demand in Japan in the Announced Pledges Scenario, 2030



Notes: APS = Announced Pledges Scenario. "Expected demand" represents the proposal of the Interim Report of Public-Private Council on Fuel Ammonia Introduction.

Japan has been very active in developing international hydrogen trade: various projects are ongoing with Australia, Brunei, Indonesia, Saudi Arabia and the United Arab Emirates. Most noteworthy is the Hydrogen Energy Supply Chain (HESC) project, led by the Hydrogen Energy Supply-chain Technology Research Association (HySTRA), which aims to establish a hydrogen supply chain between Australia and Japan. As part of this project, in 2020 Kawasaki Heavy Industries presented its Suiso Frontier, the world's first liquefied hydrogen carrier; the first demonstration shipments will take place will take place during the first quarter of 2022. The Suiso Frontier has one tank with a capacity of 1 250 m^3, which can store 75 t H_2. A future commercial supply chain between Australia and Japan would require ships with much larger capacity, estimated by HESC project developers at four tanks, each with 40 000 m^3 of capacity. Ships of similar size to Suiso Frontier could be used for shorter distances.

Japan has also spearheaded development of international fuel ammonia trade. In September 2020, the world's first shipment of ammonia produced from fossil fuels with CCUS (40 t NH_3) took place between Saudi Arabia and Japan. Plus, the Japan Oil, Gas and Metals National Corporation (JOGMEC) recently launched several initiatives with partners in Japan and around the world. With the aim of supplying low-carbon ammonia to Japan, JOGMEC, Mitsubishi Corporation, the Bandung Institute of Technology and PT Panca Amara Utama (PAU) agreed (March 2021) to conduct a joint study on producing ammonia from natural gas with CCUS in a PAU plant in Central Sulawesi (Indonesia).

Additionally, in July 2021 JOGMEC, INPEX Corporation and JERA announced a joint study agreement with the Abu Dhabi National Oil Company (ADNOC) to explore the commercial potential of low-carbon ammonia production in the United Arab Emirates and to provide a platform for ADNOC and its partners to explore supplying Japanese utility companies. Also in July 2021, JOGMEC signed a joint research agreement with Woodside Energy, Marubeni Corporation, Hokuriku Electric Power Company and Kansai Electric Power to develop a supply chain from Australia to Japan for fuel ammonia produced from natural gas with CCUS.

European Union: EU Hydrogen Strategy set the foundation in 2020, but meeting net zero targets will require ambitious action in next decade

Close to 7 Mt H_2 were produced and used in the European Union in 2020. Refining (3.7 Mt H_2) and the chemicals sector (3.0 Mt H_2) were the main consumers of hydrogen, which was produced mainly from unabated natural gas (two-thirds of total production) and as a by-product in refineries and the petrochemical sector (30%).

In November 2018, the European Commission set out its vision for reaching net zero emissions by 2050, followed in March 2020 by the proposal for the first European Climate Law, which was adopted by the European Council in June 2021. To date, most decarbonisation efforts have focused on electricity generation, but adoption of the net zero target widened the scope beyond the power sector to include industry, transport, agriculture and heating in the built environment.

In turn, interest in hydrogen has grown exponentially, with launch of the EU Hydrogen Strategy (July 2020) and the European Clean Hydrogen Alliance (November 2020) being major milestones. The strategy emphasises use of hydrogen in industry and heavy transport as well as its balancing role in the integration of variable renewables (particularly offshore wind in the northwest region and solar PV in the south). The Alliance brings together industry, national and local public authorities, civil society and other stakeholders to implement the strategy.

On the supply side, electrolytic hydrogen from renewable sources is considered the main route for hydrogen production, although the role of other low-carbon technologies in the near term is recognised as the hydrogen market develops and scales up and the cost of electrolytic hydrogen decreases. Beyond decarbonising hydrogen production, the European Union sees electrolysis as a strategic opportunity to export technology: EU countries currently hold more than 60% of global electrolysis manufacturing capacity. With the aim of creating market rules for hydrogen deployment, the Hydrogen Strategy also announced a review of the legislative framework for gases.

The strategy envisages three phases for hydrogen adoption. The first phase (until 2024) focuses on scale-up, with an interim target of 6 GW of renewable energy-powered electrolysis to decarbonise current production capacities and trigger uptake in some new uses (e.g. heavy-duty transport). In the second phase (2025-2030), hydrogen should become an intrinsic part of an integrated energy system while renewable hydrogen becomes cost-competitive and reaches new applications (steelmaking or shipping). By 2030, 40 GW of renewable energy-powered electrolysis should be installed. In the third phase (post-2030), renewable hydrogen technologies should reach maturity and be deployed at large scale to reach all hard-to-decarbonise sectors.

In December 2020, the European Commission adopted a proposal to revise the EU rules on Trans-European Networks for Energy (the TEN-E Regulation) to end support for natural gas pipelines, instead including cross-border hydrogen networks as infrastructure eligible for EU support as Projects of Common Interest. The proposal covers both new and repurposed assets for dedicated hydrogen transport and large-scale electrolyser projects linked to cross-border energy networks.

A significant step taken by the European Commission in adopting low-carbon hydrogen technologies came from proposals to modify directives and regulations announced in July 2021 as part of the Fit for 55 package. If approved by the EU Council and the EU Parliament, these proposals will incorporate into EU legislation several targets for using hydrogen and hydrogen-based fuels in industry and transport, and for developing required infrastructure.

Some EU countries have also released national hydrogen strategies (the Czech Republic, France, Germany, Hungary, the Netherlands, Portugal, and Spain); others are under public consultation (Italy and Poland) or expected to be released soon (Austria). While focusing on each country's strengths, these strategies are very aligned with each other and with the EU Hydrogen Strategy in terms of sectors and technologies to prioritise. Practically all have deployment targets for electrolysis by 2030, amounting more than 20 GW by 2030 (with another 7 GW in the planned strategies of Italy and Poland).

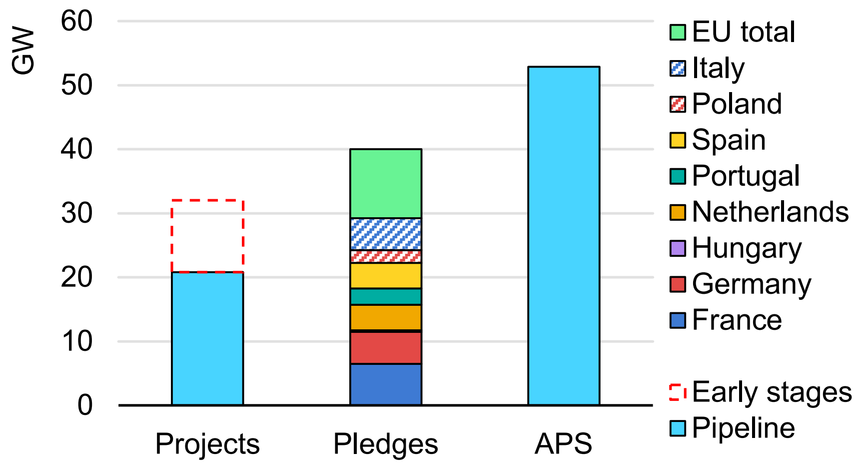
Hydrogen-related targets proposed by the European Commission in the Fit for 55 package

Proposal	Target
Renewable Energy Directive modification	50% renewable hydrogen consumption in industry by 2030
Renewable Energy Directive modification	At least 2.6% share of renewable fuels of non-biological origin in 2030[1]
ReFuelEU Aviation	0.7% share of synfuels in aviation by 2030 5% by 2035 8% by 2040 11% by 2045 28% by 2050
Regulation on deployment of alternative fuels infrastructure	1 HRS (>2 t H_2/day of capacity and 700-bar dispenser) every 150 km along major routes 1 HRS with liquid hydrogen every 450 km

[1] Renewable fuels of non-biological origin include hydrogen and hydrogen-based fuels produced from renewable electricity.

The European Union has registered progress in adopting hydrogen technologies. The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) has played a fundamental role with its programmes to support research, innovation and demonstration. More than 140 MW of electrolysis for dedicated hydrogen production have been installed, accounting for more than 40% of global capacity. The strong signals sent by government strategies have created momentum for additional deployment, with the pipeline of projects currently under development accounting for more than 20 GW by 2030 (11 GW more from projects at very early stages of development), although initial assessment by the Clean Hydrogen Alliance suggests that total electrolysis capacity at different stages of development could be larger.

Electrolysis capacity deployment in the EU in 2030 in the Projects case and the Announced Pledges Scenario compared with national and EU targets



Note: APS = Announced Pledges Scenario.
Sources: IEA (2021), Hydrogen Projects Database; National Strategies, CEM H2I consultation.

Of the more than 20 GW in the pipeline, more than 1 GW is already under construction or has funding committed. While the current project slate may not meet the EU target, the number of projects is growing quickly and the gap is shrinking. However, both the current project pipeline and the EU target may fall short of the electrolysis capacity deployment needed to meet the EU pledge of net zero emissions by 2050. The Announced Pledges Scenario shows more than 50 GW of electrolysis deployed in EU countries by 2030.

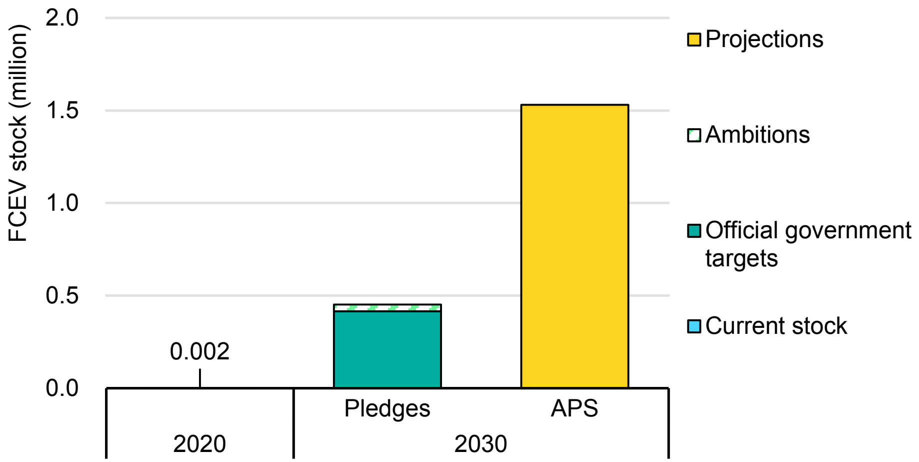
Progress in deploying hydrogen production from fossil fuels with CCUS has been slower, despite its envisaged near-term importance. Two projects are already operational in the European Union, although in both cases for hydrogen production from fossil fuels and CCU: the Shell gasification project at the Pernis refinery (the Netherlands) and Air Liquide's Port Jerome project (France).

The Netherlands is the most active country in developing hydrogen production from fossil fuels with CCUS. Through its SDE++ scheme, the Dutch government recently committed EUR 2 billion to fund Porthos, a project to develop CO_2 transport and storage infrastructure in the Port of Rotterdam, which will store 2.5 Mt CO_2 annually, with a significant share coming from hydrogen production.

The current pipeline of projects for producing hydrogen from fossil fuels with CCUS will more than meet EU net zero ambitions. While in the Announced Pledges Scenario 3 Mt CO_2 are captured from hydrogen production in the European Union by 2030, currently the project pipeline amounts to more than 7 Mt CO_2 captured (plus close to 3 Mt CO_2 more from projects at early stages of development), although this figure could be significantly lower. Several projects are large CCUS hubs that will involve activities beyond hydrogen production and, as such, it is difficult to estimate how much of the projected capture capacity would be linked to hydrogen production.

In transport, some 2 200 FCEVs were on the road in EU countries by the end of 2020 (mostly passenger cars) and around 165 HRSs were in operation. Germany has the largest number of both, but the Czech Republic, France, the Netherlands, Portugal and Spain have FCEV targets that, if achieved, would result in about 415 000 FCEVs by 2030. In the Announced Pledges Scenario, FCEV deployment reaches 1.5 million by this date.

FCEV deployment the European Union in the Announced Pledges Scenario, 2020-2030



Notes: FCEV = fuel cell electric vehicle. APS = Announced Pledges Scenario. FCEV ambitions include unpublished government targets from Italy and Slovakia.
Sources: AFC TCP; National Strategies; CEM H2I consultation.

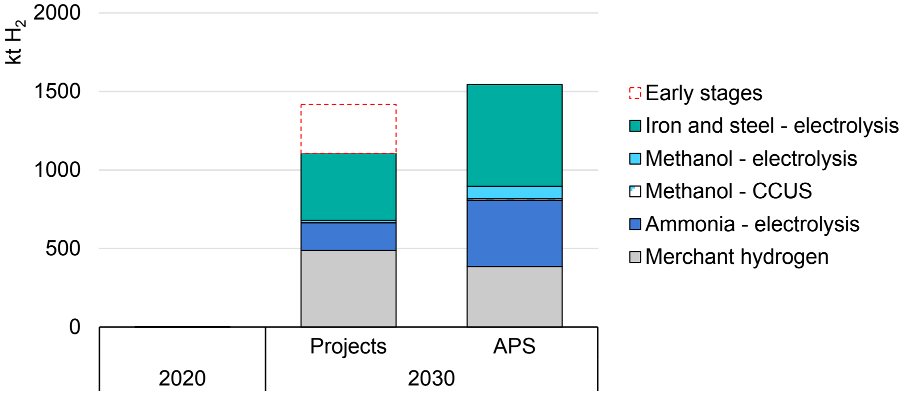
In the industry sector, EU stakeholders have been active in recent years and some significant developments are taking place. As part of the REFHYNE project, in July 2021 ITM and Shell put a 10- MW PEM electrolyser in the Rhineland Refinery (Germany) into operation. In steel manufacturing, Thyssenkrup has demonstrated using hydrogen to partially replace pulverised coal in one of the tuyeres of a blast furnace – and is working to extend this practice to other blast furnaces.

Since 2019, the H2FUTURE project has been feeding hydrogen produced in a 6 MW PEM electrolyser via the coke gas pipeline to a blast furnace of the steel works (Linz, Austria). Meanwhile, the HYBRIT project – the first attempt to produce steel from DRI using pure hydrogen – is currently at the pilot stage (4.5 MW of electrolysis capacity) but is expected to advance to a demonstration facility by 2025. Also in steel manufacturing, the largest SOEC electrolyser in the world (0.72 MW, manufactured by Sunfire) became operational in the GrinHy2.0 project.

In the chemical sector, Fertiberia and Iberdrola in Spain are building the world's largest demo project (20 MW) to produce electrolytic ammonia, expected to become operational at the end of 2021. The GreenLab Skive (Denmark) is building a 12 MW demonstrator for methanol production, to start operations in 2022. These proposed projects will not meet Announced Pledges goals for 2030, however.

Projects currently under development account for 1.1 Mt of low-carbon hydrogen use by 2030 (0.3 Mt more if early-stage projects are realised), whereas required Announced Pledges consumption is 10% higher.

Low-carbon hydrogen demand in EU industry in the Announced Pledges Scenario, 2020-2030



Notes: APS = Announced Pledges Scenario. CCUS = carbon capture, utilisation and storage.
Source: IEA (2021), Hydrogen Projects Database.

The first steps to develop hydrogen-specific infrastructure for delivery to end users have already been taken. Europe has more than 1 600 km of hydrogen pipelines, mostly owned and operated by industrial producers and users, but large-scale deployment of low-carbon hydrogen will require additional transmission and distribution systems.

A consortium of gas grid operators therefore presented a European Hydrogen Backbone (EHB) initiative proposal in 2020 (updated in 2021). Across 21 countries (including non-EU countries such as Switzerland and the United Kingdom), the EHB envisions 39 700 km of pipelines by 2040 – with 69% being repurposed natural gas networks and 31% newly built hydrogen pipelines. The first natural gas pipeline, 12 km with throughput capacity of 4 kt H_2/yr, has been converted and put into commercial service (November 2018) by Gasunie in the Netherlands.

In June 2021, Gasunie also announced that it had been asked by the State Secretary for Energy and Climate to develop a national infrastructure for hydrogen transport by 2027, of which 85% will be repurposed natural gas pipelines. In September 2021, the Dutch government announced an investment of EUR 750 million (as part of a wider EUR 6.8 billion package on climate measure) to convert parts of the existing gas network into hydrogen transport infrastructure. Furthermore, based on project submissions, the latest Ten-Year Network Development Plan of the European Network of Transmission System Operators for Gas assessed that roughly 1 100 km of gas pipelines could be converted to hydrogen by 2030, but FIDs have not yet been secured for these projects.

Several EU countries are also undertaking pilot blending projects, including France, Germany, the Netherlands and Portugal. In May 2021, the Government of Germany announced that 62 large-scale hydrogen projects, including pipeline transport, have been selected for further assessment for funding of up to EUR 8 billion under the Important Projects of Common European Interest (IPCEI) scheme.

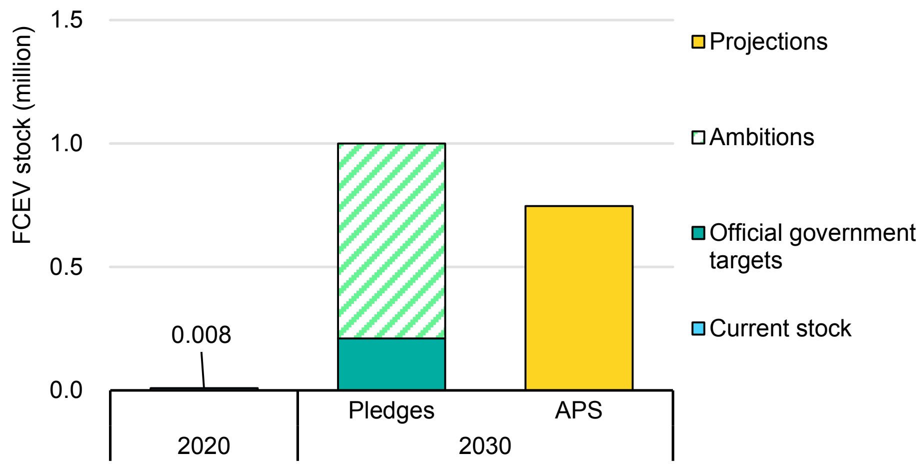
China: Hydrogen development focused on transport, but carbon-neutrality pledge will offer opportunities for other applications, particularly in industry

With annual consumption of more than 25 Mt, China is the world's largest hydrogen user, mainly in refining (9 Mt H_2) and the chemical sector (16.5 Mt H_2). This demand is met by domestic production based on fossil fuels, with coal accounting for 60% and natural gas for 25%. The remaining 15% is by-product hydrogen from refineries and the petrochemical industry.

In 2020, China announced its ambition to reach carbon neutrality by 2060. Hydrogen use will be important, especially in the country's vast industry sector, which accounts for 60% of final energy demand. Using hydrogen as an alternative to fossil fuels received attention even before China's net zero pledge, as it was seen as a means to address air quality concerns in cities.

As such, practically all developments around hydrogen adoption for new uses have focused on transport. Initial projects were based on using by-product hydrogen from coke ovens and petrochemical processes, which facilitated access to low-cost hydrogen in industrial hubs, and deploying fuel cell truck fleets by maximising utilisation rates of HRSs. Thanks to these strategies and government support schemes, China has now the world's third-largest FCEV stock and leads in fuel cell truck and bus deployments. At the end of 2020, 8 400 FCEVs had been deployed, of which two-thirds were buses and one-third trucks.

FCEV deployment in China in the Announced Pledges Scenario, 2020-2030



Notes: FCEV = fuel cell electric vehicle. APS = Announced Pledges Scenario. Official government targets include city and provincial targets; ambitions refer to additional FCEV deployment needed to achieve the China Society of Automotive Engineers target.
Source: AFC TCP.

Although the government does not have an official target for FCEV adoption, the China Society of Automotive Engineers targets 1 million FCEVs by 2030. In response to China's recent pilot cities programme, which rewards city clusters for FCEV deployment and supply chain development, several city- and province-level targets have been set. Beijing and Shanghai each aim for 10 000 FCEVs by

2025, and Guangzhou envisions 100 000 by 2030. In the Announced Pledges Scenario, China's FCEV stock reaches 750 000 in 2030.

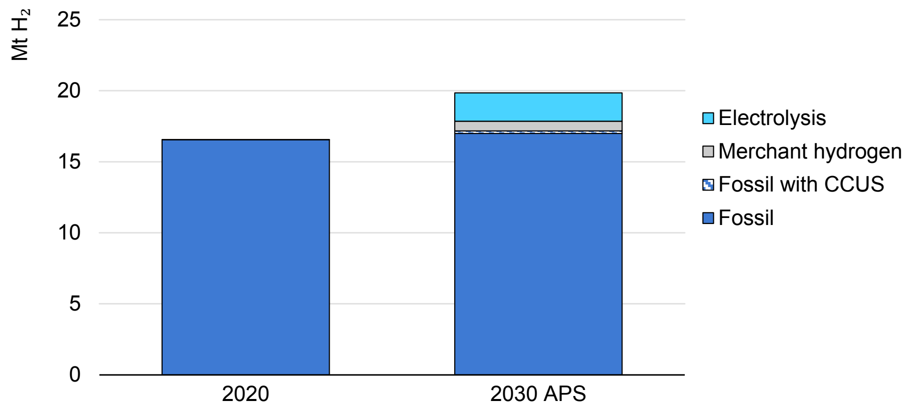
More recently, China has recognised how important hydrogen can be in transforming the energy system, and interest is growing beyond transport, particularly in industrial applications. China is the largest producer of methanol, ammonia and steel, three subsectors in which low-carbon hydrogen use could play a significant in the future. Beyond its traditional production and use in industry, low-carbon hydrogen adoption is in the early stages in China, with first steps for demonstrating new applications forthcoming.

In the chemical sector, Ningxia Baofeng Energy Group is building the world's largest electrolysis plant for dedicated production of hydrogen to provide some of the feedstock for making the methanol used in its coal-to-olefins project in Ningxia Province. The company has already installed a 30-MW electrolyser and intends to add 70 MW of electrolysis capacity by the end of 2021.

Baosteel, the country's largest steel producer, has pledged to reach net zero emissions by 2050, relying in part on developing hydrogen-based DRI production at scale by 2035. Meanwhile, Hebei Iron and Steel Group (HBIS), the second-largest producer, has taken the first step towards hydrogen steelmaking, developing a small but commercial-scale DRI project to blend 70% hydrogen (with 30% coke oven gas) for ironmaking.

These demonstration projects could lay the groundwork for low-carbon hydrogen adoption in China's industry sector. Although projects currently under development could result in 45 kt of low-carbon hydrogen production and use in industry by 2030, this is well short of the Announced Pledges projection of 2.2 Mt, produced mostly through electrolysis.

Industry hydrogen demand in China in the Announced Pledges Scenario, 2020-2030



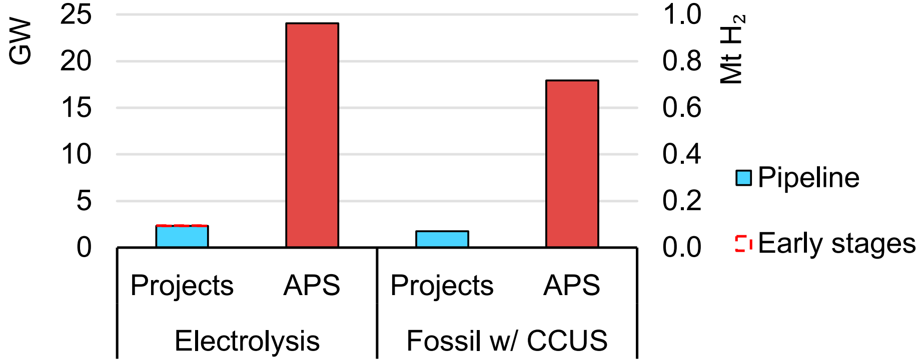
Notes: APS = Announced Pledges Scenario. CCUS = carbon capture, utilisation and storage.

China's greatest challenge is to decarbonise existing hydrogen production while deploying new production capacity to meet demand from new applications. At present, hydrogen production creates direct emissions of 360 Mt CO_2/yr.[36] Therefore, to stay on track with long-term climate ambitions, low-carbon hydrogen production technology deployment needs to accelerate in the next decade. By 2030 in the Announced Pledges Scenario, more than 20 GW of electrolysis is deployed in China, most of it in industrial facilities for producing methanol and ammonia. Plus, the first plant for manufacturing steel through DRI using hydrogen sequestered from coke oven gas should start operating by the end of 2021, and second-phase expansion and conversion towards electrolytic hydrogen should then begin.

Compared with other regions, China was slow to deploy electrolysis for dedicated hydrogen production; as a result, projects under development are insufficient to reach China's goals for 2030. However, several factors have triggered significant acceleration in the last two years:

- The cost of alkaline electrolysers in China is low – USD 750-1 300/kW including electrical equipment, gas treatment, plant balancing, and engineering, procurement and construction (EPC), with some sources reporting as low as USD 500/kW[37] – compared with the average of USD 1 400/kW in the rest of the world. Other factors, such as electrolyser reliability and durability, differ among regions and could strongly affect hydrogen production costs over a plant's lifetime.
- China has also deployed a huge amount of renewable energy generation capacity in recent years, especially in regions where potential is considerable but energy demand is fairly low. The resulting electricity grid congestion has forced some regional governments to limit the amount of power that can be loaded into transmission grids. Electrolysis can minimise curtailment and store energy for local use or for transport to regions with lower renewable energy potential and large energy needs.
- China accounts for one-third of global electrolyser manufacturing capacity. In response to anticipated domestic market growth, all major manufacturers have announced plans to expand their manufacturing capacity.

Electrolysis capacity and hydrogen production from fossil fuels with CCUS in China in the Projects case and the Announced Pledges Scenario, 2030



Notes: APS = Announced Pledges Scenario. CCUS = carbon capture, utilisation and storage.
Source: IEA (2021), Hydrogen Projects Database.

[36] An additional 115 Mt CO_2 is emitted through the use of hydrogen-derived products (e.g. urea and methanol) that capture carbon only temporarily.

[37] Based on CAPEX for the electrolyser system itself of USD 200/kW (China EV100, 2020; MOST, 2021). Including electrical equipment, gas treatment as well as EPC increases the overall CAPEX to USD 500/kW

The use of carbon capture to decarbonise current fossil fuel-based hydrogen production will also need to ramp up. This could be particularly beneficial for the chemical industry in China's north-western regions, where a very young fleet of plants currently uses coal to produce hydrogen-based ammonia and methanol. In the Announced Pledges Scenario, production capacity of 0.7 Mt H_2 in the chemical industry is retrofitted with CCUS by 2030.

Canada: Hydrogen to play a critical role in net zero ambitions and economic growth through exports

In 2020, Canada produced and used around 3 Mt H_2, almost equally split between refining and the industry sector. Around 80% of production is based on natural gas, and the remainder is by-product gas from refineries.

In December 2020, Canada released its strengthened climate plan, which lays the foundation to reach net zero emissions by 2050. Hydrogen and other clean fuels feature prominently in this plan. Also at the end of 2020, Canada released its Hydrogen Strategy with a call for action to promote investments and partnerships among national stakeholders, sub-national governments and indigenous organisations, as well as at the international level, to seize the economic and environmental opportunities that hydrogen can offer. The strategy shows that, in a net zero future, Canada's economy will be mobilised by two equally important pathways: clean power and clean fuels, with hydrogen making up to 30% of the energy mix.

The Canadian strategy addresses the role of hydrogen across a very wide range of end-use sectors, including industry, refining, transport, power and buildings. It also sees the variety of domestic energy resources available as a great opportunity to diversify the mix of technologies to produce hydrogen. This mix includes oil and gas reserves (coupled with CCUS) in Alberta, Saskatchewan, British Columbia and the East Coast, an 80% non-emitting power grid, nuclear capacity, and large renewable capacity. Based on these vast resources, Canada has an ambitious goal to become a major exporter of hydrogen-based fuels. As it is home to some of the sector's major technology developers (e.g. Ballard and Hydrogenics, recently acquired by Cummins), the potential to export hydrogen technologies is also high.

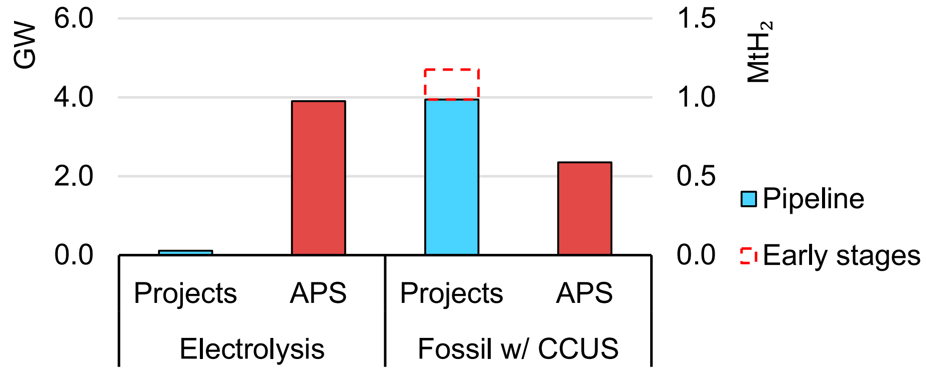
The Canadian government has already established a series of clean energy support programmes to enable the development of business cases for hydrogen technologies. In June 2021, Natural Resources Canada announced the Clean Fuels Fund, providing CAD 1.5 billion (~USD 1.1 billion) to help private investors with upfront capital costs to construct new clean fuel production capacity, including support for developing at least ten hydrogen projects. In addition, the Net zero Accelerator initiative will provide up to CAD 8 billion (~USD 6.0 billion) for projects that reduce domestic GHG emissions, including decarbonisation of large industrial emitters, fuel switching to hydrogen in industrial processes, and development of CCUS capacities for hydrogen production in heavy industries already using hydrogen.

Even before the national hydrogen strategy and related programmes were launched, Canadian stakeholders had been very active. With four operative projects capturing and storing around 3 Mt CO_2/yr, Canada is the second-largest producer of hydrogen from fossil fuels with CCUS. Another four projects are under development, aiming to capture an additional 5.0 Mt CO_2/yr (1.8 Mt CO_2/yr if early-stage projects are included). If all are realised, total hydrogen production from fossil fuels with CCUS could reach close to 1 Mt H_2/yr in 2030 (0.2 Mt H_2/yr with early-development projects) – around 70% higher than in the Announced Pledges Scenario.

However, projects under development aim to produce merchant hydrogen for diverse applications rather than decarbonise existing hydrogen production capacity in the chemical sector. Consequently, almost 200 kt H_2 (0.5 Mt H_2/yr with early-development projects) in fossil fuel with CCUS production capacity for industrial applications could be reached by 2030 – almost reaching the capacity in the Announced Pledges. Initiatives such as the Net zero Accelerator can speed deployment of low-carbon hydrogen capacity in industrial processes to better align with the Announced Pledges Scenario.

Concerning electrolysis, in January 2021 Air Liquide put into operation the world's largest PEM electrolysis plant at Bécancour. The project, which includes a 20 MW electrolyser running on hydropower, doubled the site's hydrogen production capacity. Currently, close to 100 MW of electrolysis projects are at different stages of development; if all are realised, total installed electrolysis capacity for dedicated hydrogen production could reach around 120 MW. In the Announced Pledges Scenario, electrolysis capacity in Canada reaches more than close to 4 GW by 2030, 40 times more than the capacity currently under development.

Electrolysis capacity and hydrogen production from fossil fuels with CCUS in Canada in the Projects case and the Announced Pledges Scenario, 2030



Notes: APS = Announced Pledges Scenario. CCUS = carbon capture, utilisation and storage.
Source: IEA (2021), Hydrogen Projects Database.

In the transport sector, Canada had a stock of around 130 FCEVs at the end of 2020. In the Announced Pledges Scenario, FCEV stock reaches close to 50 000 in 2030. Recent measures can facilitate this deployment: for instance, in December 2020 the government announced a new Clean Fuel Standard that will require liquid fuel suppliers to gradually reduce the carbon intensity of the fuels they produce and sell for use in Canada (final regulations will be published at the end of 2021). In June 2021, the government committed to a mandatory 100% ZEV sales target by 2035, followed by the announcement in August 2021 of a CAD 2.75 billion (~USD 2.1 billion) Zero Emission Transit Fund to support the purchase of zero emission public transit and school buses and associated infrastructure.

Other regions: Hydrogen momentum is building as more countries get on board

Africa

Of Africa's annual close to 3 Mt H_2 consumption, 70% is used in the chemical sector, mainly to produce nitrogen fertilisers that boost crop yields and replenish soil nutrients and are thus a critical component of food security across the continent. Without synthetic nitrogen fertilisers (together with other macro-nutrients), soil fertility would be significantly lower and land required for farming significantly higher.

Africa is one of the few places in the world where fertiliser use is projected to grow strongly in upcoming years, even as care is taken to apply it efficiently and judiciously, identifying the right fertiliser source, applying it at the right rate, at the right time and in the right place (CITE). In turn, ammonia production (the starting point of all synthetic nitrogen fertilisers) for existing agricultural and industrial uses increases 40% by 2030 in the Announced Pledges Scenario (see the IEA's forthcoming Ammonia Technology Roadmap).

Virtually all hydrogen production in Africa is currently based on fossil fuels, including the portion used to produce nitrogen fertilisers. The ability to produce hydrogen from renewables is therefore a great opportunity for African countries to replace fossil fuel-based production, which in many cases depends on imports. This is particularly important for landlocked countries that face additional challenges in distributing fertiliser and/or securing the natural gas needed to produce it.

Africa's potential to generate low-cost renewable electricity to produce low-carbon hydrogen is considerable. As electrolyser and renewable electricity generation costs continue to decline, cost parity with fossil fuel-based generation is a genuine prospect in the medium to long term in locations with the best renewable resources. In areas where the necessary transport and storage infrastructure is practical and scalable, low-cost natural gas equipped with CCUS is another option to produce low-carbon hydrogen for ammonia synthesis. Having an indigenous supply of nitrogen fertilisers made using low-carbon hydrogen would reduce CO_2 emissions from this energy-intensive industry while also boosting food security by reducing dependence on food imports.

Developing projects to produce renewable hydrogen for fertiliser manufacturing can also create high-quality jobs and spur economic growth, although project realisation will hinge on innovation and scale-up to close the cost gap with conventional production methods. Due to unfavourable economics, two large electrolysers (of 100 MW in Zimbabwe and 165 MW in Egypt) producing ammonia using renewable electricity from hydropower installations closed or switched to natural gas in the last decade, highlighting the challenges facing this technology option.

Similarly, ultra-low-cost electricity at a high capacity factor, or variable renewable electricity combined with hydrogen storage, is required for electrolysis-based ammonia production to become competitive with natural gas, even when equipped with CCUS. Given the practical ease and relatively low cost of shipping nitrogen fertiliser products (e.g. urea produced in the Middle East), cost reductions in the production process are required to make electrolysis a viable option for a price-sensitive market segment and region.

On-site production, storage and use of renewable hydrogen in mini-grids to generate electricity in remote areas is another hydrogen application attracting great interest. In fact, this concept has already been demonstrated. Hydrogen South Africa (HySA) has been operating a hydrogen-based mini-grid installed at a high school in Goedgevonden since April 2018, and Tiger Power is developing a project to power 3 000 rural households and businesses in Kyenjojo (Uganda). This application is cost-competitive with the traditional use of diesel for remote power generation, thus facilitating electricity access while decreasing CO_2 emissions.

Some countries in the region have taken the first steps to seize the opportunities hydrogen can offer. Morocco is leading the way with its Green Hydrogen Cluster, established by the government to promote collaboration among private and academic stakeholders to support the emerging renewable hydrogen sector. With the dual objectives of collaborating in technology development and positioning Morocco as a potential exporting hub, the government has been building international partnerships with countries such as Germany and Portugal.

Some activity is also well under way in South Africa, led predominantly by the private sector. Anglo American is building a 3.5-MW electrolyser at its mine in Mogalakwena to produce hydrogen on site to fuel a hydrogen-powered fuel cell electric haul truck. Expected to become operational in 2021, the project will be a first demonstrator to gain operational knowledge and experience, and thus support replication at other mines around the world.

Australia

In November 2019, Australia launched its National Hydrogen Strategy. It explores potential for clean hydrogen production, outlines a plan for quick scale-up and details the necessary co-ordinated actions for governments, industry and communities. As part of this plan, the government has invested over AUD 1.3 billion (~USD 1.0 billion) to accelerate domestic hydrogen industry growth. The strategy also highlights the significant opportunity offered by hydrogen exports, which the government is fostering by developing international partnerships with Singapore, Germany, Japan, Korea and, more recently, the United Kingdom.

Current hydrogen demand in Australia is very small, practically all used in refining and ammonia production; moreover, growth in domestic demand is generally seen as limited. However, the country has tremendous potential to affordably produce low-carbon hydrogen, which can decarbonise production for both domestic use and export. Recognising this opportunity, the government has invested in seven hydrogen hubs that centralise users geographically, thereby minimising infrastructure costs.

Australia's potential to produce hydrogen from renewables is considerable. Currently, nine projects with a capacity >1 GW are under development or at early stages. These include some of the world's largest projects: the Western Green Energy Hub (20 Mt NH_3/yr, equivalent to >20 GW of electrolysis capacity); the Asian Renewable Energy Hub (14 GW); HyEnergy Zero Carbon Hydrogen (8 GW); and the Murchison Project (5 GW). If all projects under development are deployed, electrolysis capacity in Australia will reach nearly 20 GW by 2030 (33 GW including early-stage ones), the vast majority aiming to export hydrogen and ammonia. However, the Asian Renewable Energy Hub recently encountered government pushback; in June 2021 its application was rejected due to potential adverse impacts on habitats and native species.

Australia has also significant fossil fuel resources, particularly Victoria's brown coal reserves. Combined with CCUS, they could be another energy source for low-carbon hydrogen production. The first facility for producing hydrogen from coal started operation (in the Latrobe Valley) in March 2021 as part of the HESC project lead by HySTRA. The facility is not incorporating CCUS in its first phase, but it will be retrofitted with CCUS capabilities by 2030, subject to successful demonstration of the economic viability of transporting liquid hydrogen from Australia to Kobe in Japan.

India

More than 7 Mt H_2 was used in India in 2020, with 45% used for refining, 35% for chemicals and almost 20% for iron and steel. India is the world's largest producer of steel using the DRI route, consuming one-quarter of global hydrogen demand for this end use. Practically all hydrogen demand is met through domestic production based on fossil fuels, with natural gas accounting for three-quarters, coal for more than 15% and by-product from refineries making up the rest.

Irrespective of the scenario context, hydrogen use in India is expected to rise substantially in the next decade as population growth and greater prosperity necessitate increased food production (requiring ammonia) and new infrastructure (requiring steel). In the Announced Pledges Scenario, hydrogen demand grows to close to 11 Mt H_2 by 2030, with DRI-based steelmaking accounting for around 30% of this increase.

India's enormous potential to expand hydrogen demand and its considerable renewable energy possibilities offer an extraordinary opportunity to decarbonise the industry sector while also reducing fossil fuel import dependency. If electrolysis were deployed at scale and the potential for cost reductions materialised, India could be one of the regions with the lowest costs for producing hydrogen from renewables.

As early as 2030, hydrogen production from renewables could cost just USD 1.4-3.7/kg H_2, competitive with production through unabated fossil fuel methods. Low production costs for renewable hydrogen could enable the export of low-carbon hydrogen and hydrogen-based fuels, particularly to other Asia-Pacific economies that are likely to require imports to meet national hydrogen demand (e.g. Japan and Korea).

The Indian government has taken the first steps to seize the energy sector decarbonisation opportunities hydrogen can offer. Early in 2021, it launched the National Hydrogen Mission (NHM) to articulate the government's vision, intent and direction for hydrogen and to outline a strategy. The NHM will also explore policy action to support the use of hydrogen as an energy vector and develop India into a global hub for hydrogen and fuel cell technology manufacturing.

The first policy actions are under way, with the government having announced the adoption of auctions (in 2021) for producing hydrogen from renewables and mandatory quotas for using renewable hydrogen in refining and ammonia production. According to the proposal, starting in 2023/24 refineries will have to meet 10% of their hydrogen demand with renewable hydrogen, increasing to 25% in the following five years. Fertiliser producers will need to meet 5% of demand with renewable hydrogen in 2023/24, increasing to 20%. This proposal is expected to be extended to the steel industry in the near future.

The Indian government also announced plans for new developments in gas grid infrastructure, connecting major demand centres with ports to help the latter become major import/export hubs. The industry sector has also become involved, with some major companies (e.g. Adani, Arcelor Mittal, the Indian Oil Corporation, NTPC, Reliance Industries and the Solar Energy Corporation of India) announcing ambitious plans to develop projects for low-carbon hydrogen production.

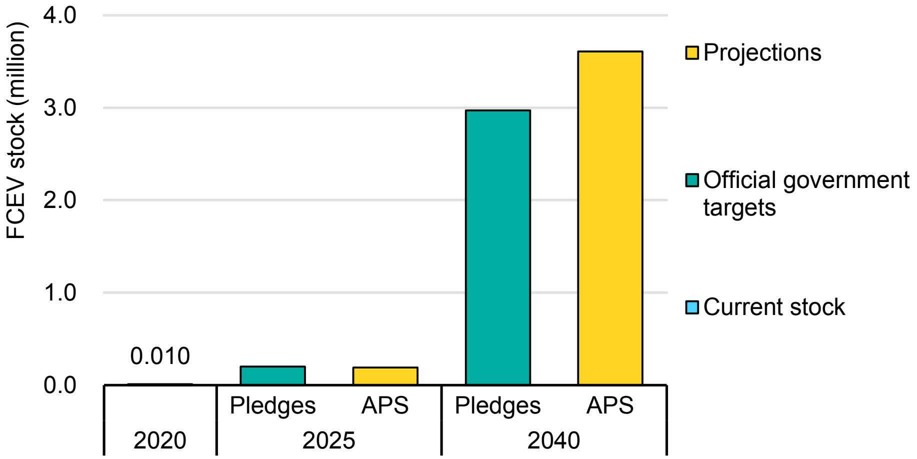
Korea

More than 1.8 Mt H_2 were produced and used in Korea in 2020, with practically all demand coming from refining and petrochemical processes. Around 60% of the hydrogen used is obtained as by-product from various sources, with the remaining 40% produced from natural gas. Korea is among the most active countries in adopting hydrogen technologies. In 2019 the government launched its Hydrogen Economy Roadmap, which outlines a vision for the role of hydrogen in the energy sector. The roadmap highlights two priorities: creation of a hydrogen market; and the development of hydrogen-utilising industries to create the world's largest market for fuel cells for transport and electricity generation.

In transport, Korea became the leader in FCEV deployment in 2020, with over 10 000 FCEVs on the road. In its 2020 New Deal, the government increased the 2025 FCEV target from 100 000 (set in the 2019 hydrogen roadmap) to 200 000, and for 2040 it is targeting close to 3 million FCEVs, including 2.9 million domestically manufactured fuel cell cars, 30 000 fuel cell trucks and 40 000 fuel cell buses.

Furthermore, interest in using hydrogen in transport extends beyond decarbonising domestic transport. As fuel cell development is also considered an important technology export opportunity, the roadmap established targets for exporting 3.3 million FCEVs by 2040. Hyundai's announced fuel cell manufacturing capacity of 500 000 units/yr in 2030 largely aligns with the production target of 6.2 million fuel cell cars by 2040.

FCEV deployment in Korea in the Announced Pledges Scenario, 2020-2040



Notes: FCEV = fuel cell electric vehicle. APS = Announced Pledges Scenario. Source: AFC TCP; Korea 2020 New Deal; Hydrogen Economy Roadmap.

Regarding stationary fuel cells, Korea currently has 620 MW of installed capacity – almost double what it had at the end of 2018, according to its Hydrogen Economy Roadmap. Most of this capacity is used for electricity generation (605 MW), but a small fraction (15 MW) is used in buildings. Practically all this capacity is fuelled by natural gas, but stakeholders are taking steps to operate fuel cells with 100% hydrogen.

By 2040 in the Announced Pledges Scenario, Korea consumes 1.9 Mt H_2 to generate 33 TWh of power. This will require an installed capacity of 18 GW – far more than the Korean government's target of 8 GW. This 18 GW also includes other hydrogen technologies for electricity generation, such as co-firing hydrogen with natural gas in gas turbines. The Korean government also considers stationary fuel cells a technology export opportunity, so the Hydrogen Economy Roadmap targets 7 GW of stationary fuel cell exports by 2040.

Korea is also giving considerable attention to producing low-carbon hydrogen and developing hydrogen infrastructure. So far, hydrogen demand for fuel cell applications has been met with by-product hydrogen or unabated natural gas-based production. In the transition to 2040, the Hydrogen Economy Roadmap prescribes greater hydrogen production from water electrolysis and from natural gas with CCUS, and more hydrogen imports.

The first projects to develop low-carbon hydrogen production are already under way: in 2021, SK E&S and Hyundai Oilbank