First steps under way to develop supply chains for international hydrogen trade

With the transition to sustainable energy systems boosting demand for hydrogen and hydrogen-based fuels, international trade in hydrogen will be an important part of the hydrogen supply chain. Countries that have limited domestic capabilities to produce low-carbon hydrogen from renewables, nuclear energy or fossil fuels with CCUS – or that find these processes too expensive – can benefit from importing more affordable low-carbon hydrogen.

For countries with excellent renewable resources, international trade in hydrogen can provide an opportunity to export renewable resources that otherwise may not be exploited. Similarly, gas- or coal-producing countries could join the market by exporting hydrogen produced from fossil fuels with CCUS. In the Net zero Emissions Scenario, international trade in hydrogen and hydrogen-based fuels covers ~15% of global demand for these fuels in 2030.

Transporting energy over long distances is typically easier in the form of molecules (i.e. liquid, gaseous or synthetic fuels) than as electricity because fuels are characterised by high (volumetric) energy densities and lower transport losses. Most natural gas is moved worldwide in large-scale pipelines or as LNG via ships, and similar methods could be employed for hydrogen and hydrogen carriers. Hydrogen can also be transported in storage tanks by trucks, which is currently the main option to distribute it at the local level, but it is generally very expensive. For longer distances, pipelines and seaborne transportation are more economical, with the best option dependent on distance and volume (among other factors).

At present, hydrogen is generally stored as a compressed gas or in liquefied form in tanks for small-scale local use. However, a much wider variety of storage operations will be required to achieve uninterrupted international hydrogen trading. At import terminals, hydrogen storage is likely necessary as a contingency measure in case of supply disruptions, similar to the approach for LNG.

Various solutions are being explored for long- or short-distance seaborne hydrogen transport. One option is to transport it in liquefied form, which is drastically more dense than the gaseous state. However, as hydrogen liquefaction requires a temperature of -253°C (i.e. 90°C lower than for LNG), it is energy-intensive. Plus, current liquefaction processes have a relatively low efficiency and consume about one-third of the energy contained in the hydrogen. Some reports indicate that scaling up liquefier capacity could cut energy requirements to around one-fifth.

Another option for high-density transport is to convert hydrogen into another molecule such as ammonia or LOHC. Ammonia is already traded internationally as a chemical product, but as it is toxic, increased transport and use may raise safety and public acceptance issues, restricting its handling to professionally trained operators.

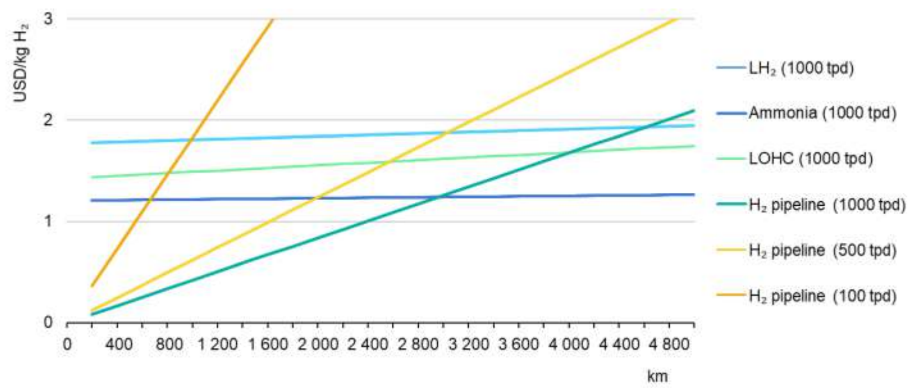
Converting hydrogen into ammonia and reconverting it back to hydrogen after transport is possible, but additional energy and purification steps will be required for some end uses. Still, the advantage of ammonia is that it liquefies at -33°C (at ambient pressure), a much higher temperature than hydrogen, resulting in a lower energy needs.

LOHCs have properties similar to crude oil and oil products, and their key advantage is that they can be transported without liquefaction. As with ammonia, conversion/reconversion and purification processes are costly, and depending on an LOHC's basic molecular makeup, toxicity issues could be a consideration. Furthermore, an LOHC's carrier molecules are often expensive and, after being used to transport hydrogen to its destination, need to be shipped back to their place of origin.

The high cost of hydrogen transmission and distribution for many trade routes means it may cost less to produce low-carbon hydrogen domestically than to import it – i.e. the higher cost of clean hydrogen production could still be less than the supply costs incurred for imports. This depends heavily on local conditions. Countries with constrained CO_2 storage or limited renewable resources will be more dependent on imports to meet hydrogen demand.

In 2020, significant progress was made in demonstrating international hydrogen trade. The Advanced Hydrogen Energy Chain Association for Technology Development successfully produced and traded hydrogen by LOHC technology from Brunei to Japan using container shipping, for use as a gas turbine fuel. Meanwhile, Saudi Aramco and the Institute of Energy and Economic of Japan collaborated to import 40 t of ammonia produced in Saudi Arabia from natural gas with CCUS to Japan for direct use as an electricity generation fuel. For liquid hydrogen (LH_2), the first planned shipment from Australia to Japan in the Hydrogen Energy Supply Chain (HESC) pilot project was postponed to the first quarter of 2022 due to the Covid-19 pandemic. Still, the import terminal and hydrogen production plant were commissioned, and the hydrogen was successfully produced and liquefied in Australia.

Costs of delivering GH2 by pipeline and LH2, LOHC and ammonia by ship, 2030



Notes: GH_2 = gaseous hydrogen. LH_2 = liquid hydrogen. LOHC = liquid organic hydrogen carrier. tpd = tonnes per day. Includes conversion, export terminal, shipping, import terminal and reconversion costs for each carrier system. Storage costs are included in import and export terminal expenses. The pipeline cost assumes construction of a new pipeline.

Sources: Based on IAE (2016); Baufumé (2013).

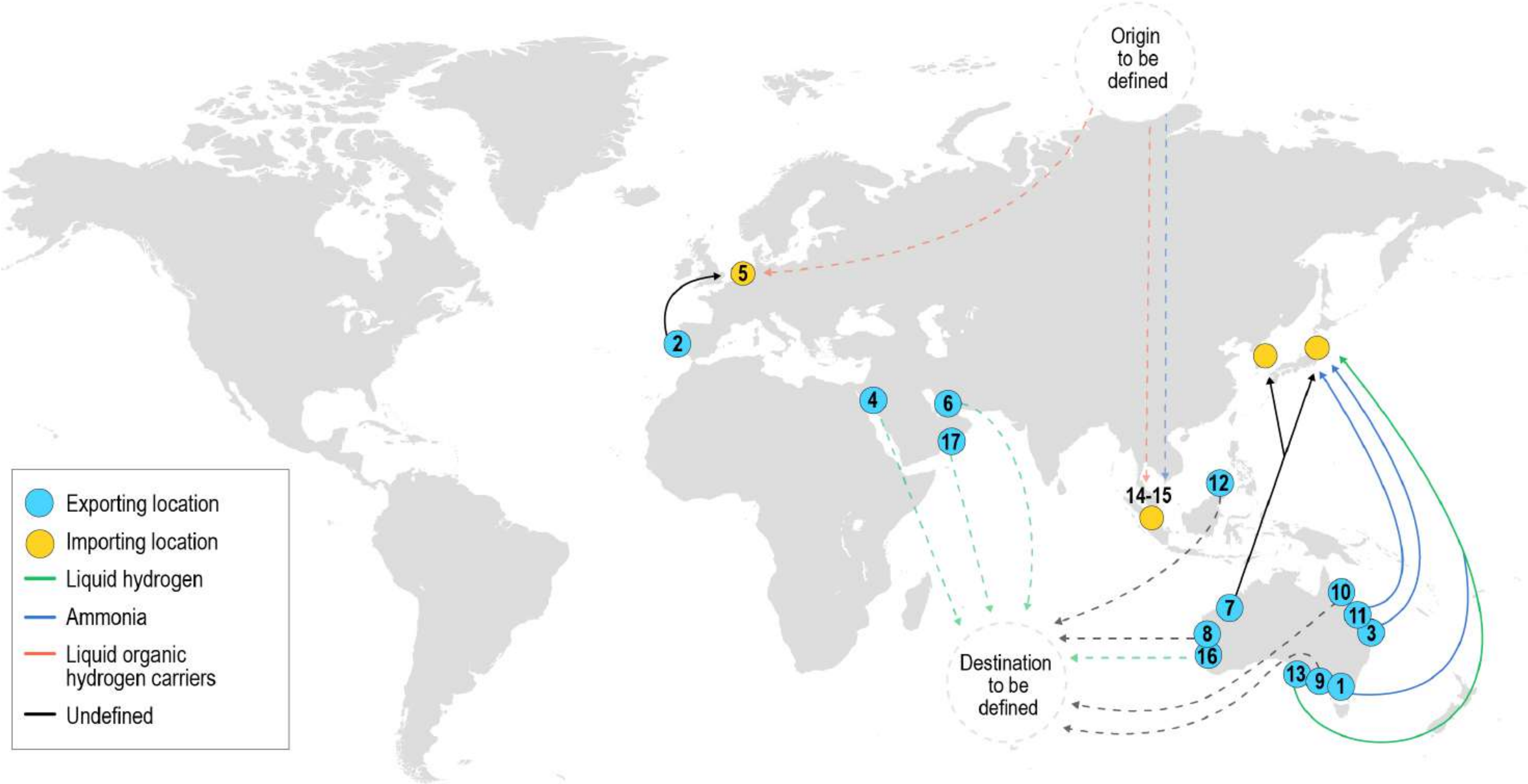
Governments and private companies have also announced several other international collaborations and projects for hydrogen trade. Germany, which stated the importance of importing hydrogen in its national strategy, signed an agreement for a joint feasibility study with Australia and Chile. Meanwhile, the Netherlands signed an MOU with Portugal, the Port of Rotterdam signed one with Chile, and Japan signed a memorandum of collaboration (MOC) with the United Arab Emirates. Around 60 international hydrogen trade projects have been announced and feasibility studies are under way for half of them. The total reported volume of these projects is 2.7 Mt H_2/yr.

Selected international hydrogen trade projects

Project	Export country	Import country	Volume	Carrier	Expected first shipping year	Map Reference
Hydrogen Energy Supply Chain	Australia	Japan	225 540 tpa	LH_2	2030	1
H2 Sines	Portugal	Netherlands	TBD	TBD	TBD	2
Stanwell - Iwatani Gladstone project	Australia	Japan	280 000 tpa	LH_2	2026	3
Helios Green Fuels	Saudi Arabia	TBD	650 tpd	Ammonia	2025	4
H2Gate	TBD	Netherlands	1 000 000 tpa	LOHC	TBD	5
ADNOC - TA'ZIZ industrial hub	United Arab Emirates	TBD	175 000 tpa	Ammonia	2025	6
Asian Renewable Energy Hub	Australia	Japan or Korea	TBD	LH_2 or ammonia	2028	7
Murchison	Australia	TBD	TBD	TBD	TBD	8
Crystal Brook Energy Park	Australia	TBD	25 tpd	TBD	TBD	9
Pacific Solar Hydrogen	Australia	TBD	200 000 tpa	TBD	TBD	10
Origin Energy - Kawasaki Heavy Industries Townsville project	Australia	Japan	36 000 tpa	LH_2	2025	11
KBR SE Asia feasibility study	Southeast Asia	TBD	TBD	TBD	TBD	12
Eyre Gateway	Australia	Japan or Asia	7 000 tpa	Ammonia	TBD	13
Unnamed	TBD	Singapore	TBD	LH_2	TBD	14
Unnamed	TBD	Singapore	TBD	LOHC	TBD	15
Project Geri	Australia	TBD	175 000 tpa	Ammonia	TBD	16
Green Mega Fuels Project	Oman	TBD	175 000 tpa	Ammonia	2032	17
Western Green Energy Hub	Australia	TBD	34 000tpa	Ammonia	TBC	18

Notes: LH_2 = liquid hydrogen. LOHC = liquid organic hydrogen carrier. SE Asia = Southeast Asia. TBD = to be determined. tpa = tonnes per annum. tpd = tonnes per day. TBD = to be determined.

Most hydrogen trade projects under development are in Asia-Pacific



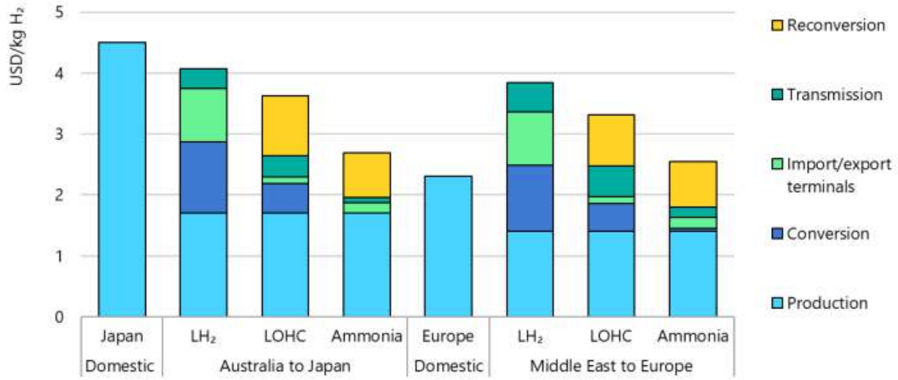
Notes: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area. LH_2 = liquid hydrogen. NH_3 = ammonia. LOHC = liquid organic hydrogen carrier. TBD = to be determined.

As part of its JPY 2-trillion (about USD 18.7-billion) Green Innovation Fund, the Japanese government has allocated JPY 255 billion (about USD 2.4 billion) to establish the first commercial international hydrogen trade. Its intent is to support LH_2 and LOHC supply chain development to reduce costs and improve the maturity of the technologies involved.

Any country deciding whether to produce hydrogen domestically or import must consider all delivery costs across the entire supply chain, from production and transport to end-use application. The IEA estimates that by 2030, importing hydrogen produced from solar PV in Australia into Japan (<USD 4.20/kg H_2) will cost slightly less than producing it domestically from renewables (USD 4.50/kg H_2). While producing natural gas-derived hydrogen with CCUS in Japan could cost even less (USD 1.85/kg H_2), access to CO_2 storage may be a limiting factor.

In the case of exporting hydrogen from the Middle East to Europe, imported hydrogen (USD 2.60-3.80/kg H_2) is unlikely to be competitive with domestic production (USD 2.30/kg H_2) in 2030. However, if ammonia can be used directly (e.g. in the chemical industry or as a shipping or power sector fuel), reconversion losses can be avoided and the supply cost could be reduced to USD 1.80/kg H_2 for these trade links, which would be competitive. In the long term, further efficiency improvements and process optimisation could reduce transport and thus total supply costs for all carriers. In some regions, this could eventually make imports more attractive than domestic production, potentially boosting international trade after 2030.

Projected costs of delivering LH_2, LOHC and ammonia in selected regions, 2030



Notes: LH_2 = liquid hydrogen. LOHC = liquid organic hydrogen carrier. Assumes distribution of 1 000 t H_2/d. Storage costs are included in import and export terminal expenses. Hydrogen is produced from electrolysis using renewable electricity.
Source: Based on IAE (2016).

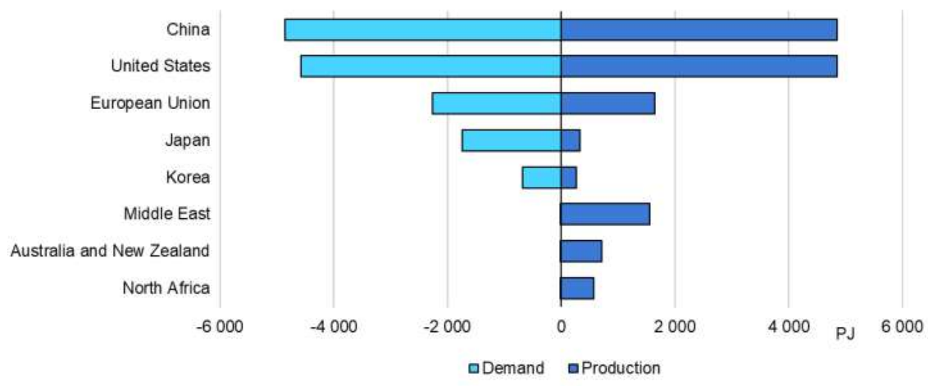
Long-term potential of international hydrogen trade

In the Announced Pledges Scenario in 2050, trade in hydrogen and hydrogen-based fuels accounts for 20% of global demand, with 8% of hydrogen demand being traded, 50% of ammonia and 40% of liquid synfuels. This reflects the comparatively lower transport costs of ammonia and synfuels. While several countries (e.g. China and the United States) manage to cover growing demand for low-carbon hydrogen and hydrogen-based fuels domestically, others (e.g. Japan, Korea and parts of Europe) rely on imports, at least in part. By 2050 in the Announced Pledges Scenario, Japan and Korea are importing each around 60% of their domestic demand for hydrogen and hydrogen-based fuels.

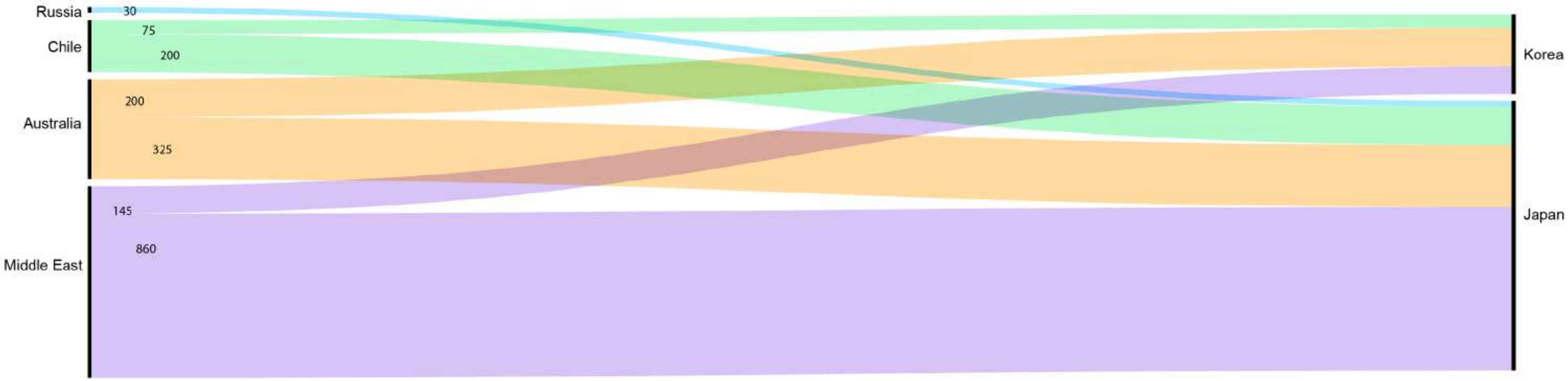
Australia, Chile, the Middle East and North Africa emerge as key exporting regions in the Announced Pledges Scenario, benefitting from the low cost of producing hydrogen from renewables or from natural gas with CCS. By 2050, North Africa, the Middle East and Chile export ~600 PJ of hydrogen and hydrogen-based fuels to Europe. For Asia, the important hydrogen suppliers are the Middle East, Australia and Chile. By 2050, these exporters meet 1 800 PJ of Asian demand for hydrogen and hydrogen-based fuels in the Announced Pledges Scenario.

However, many of these major future exporters do not yet have net zero pledges in place, so importing countries will need to engage with trading partners to encourage and guarantee relevant supply investments if they want their hydrogen imports to be low-carbon.

Announced Pledges Scenario hydrogen and hydrogen-based fuel demand and production in selected regions, 2050



Hydrogen trade flows to Japan and Korea in the Announced Pledges Scenario in 2050



Investments and innovation

Hydrogen investments rising despite Covid-19 pandemic, with unprecedented private fundraising, mostly for manufacturing and to meet project demand

Hydrogen has proven remarkably resilient during the economic slowdown induced by the global pandemic. Companies specialised in producing, distributing and using hydrogen raised almost USD 11 billion in equity between January 2019 and mid-2021 – a considerable increase from prior years – and contracts funded by government recovery packages are expected to raise project investments substantially. Nevertheless, funding is grossly insufficient to accelerate innovation to the level required to realise hydrogen's 60 Gt of CO_2 emissions reduction potential modelled in the Net zero Emissions Scenario.

Overview of recent company fundraising

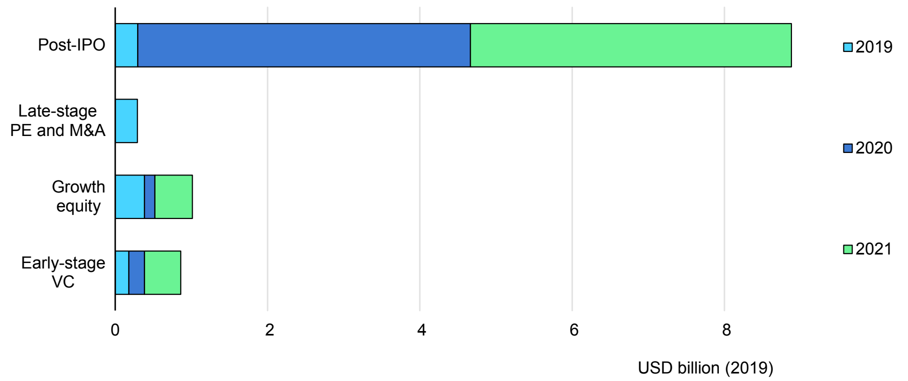
Most new funding for hydrogen in 2020 and 2021 was raised by companies already listed on a stock exchange. They issued new shares to investors, primarily to secure capital for expanding manufacturing facilities to meet expected or contracted demand for electrolysers and fuel cells. Investor confidence in hydrogen companies continued into the first half of 2021, partly in anticipation of contracts to be supported by government recovery packages.

Having sold USD 4.8 billion in new shares since 2019, the largest fundraiser was Plug Power, a US company (est. 1997) that makes electrolysers, fuel cells and refuelling equipment. Other electrolyser manufacturers – including Nel, ITM Power, McPhy Energy, Green Hydrogen Systems and Sunfire – collectively raised USD 1.5 billion. Nikola, a company developing a fuel cell truck, raised USD 250 million in 2019, then listed on the Nasdaq in 2020, raising USD 700 million. In November 2020, however, a deal to sell 11% of its shares to GM for USD 2 billion fell through. Investors have since become increasingly concerned about Nikola's ability to meet its development schedule.

Two notable acquisitions occurred in this period. US engine manufacturer Cummins bought the Canadian electrolyser company Hydrogenics for USD 290 million. In Germany, engine manufacturer Man Energy Solutions acquired the PEM electrolyser maker H-Tec for an undisclosed sum.

Several investment funds targeting hydrogen were launched in 2021. The most recent, HydrogenOne Capital Growth Fund, raised USD 150 million in an initial public offering including USD 35 million from the petrochemical company Ineos. Other funds established since 2018 include Ascent, FiveT, H-Mobility, Klima and Mirai. In China, Shanxi Hydrogen Energy Industrial Fund, a government-guided fund, was launched in 2021.

Hydrogen company fundraising by stage of funding, January 2019 to mid-July 2021



Notes: PE = private equity. M&A = mergers and acquisitions. VC = venture capital. Post-IPO includes private investment in public equity (PIPE) transactions and other new share sales. Early-stage VC includes seed, Series A and Series B. Only deals with disclosed values are included, which notably excludes certain M&A deals with undisclosed values.
Sources: Calculations based on Cleantech Group (2021) and Prequin (2021).

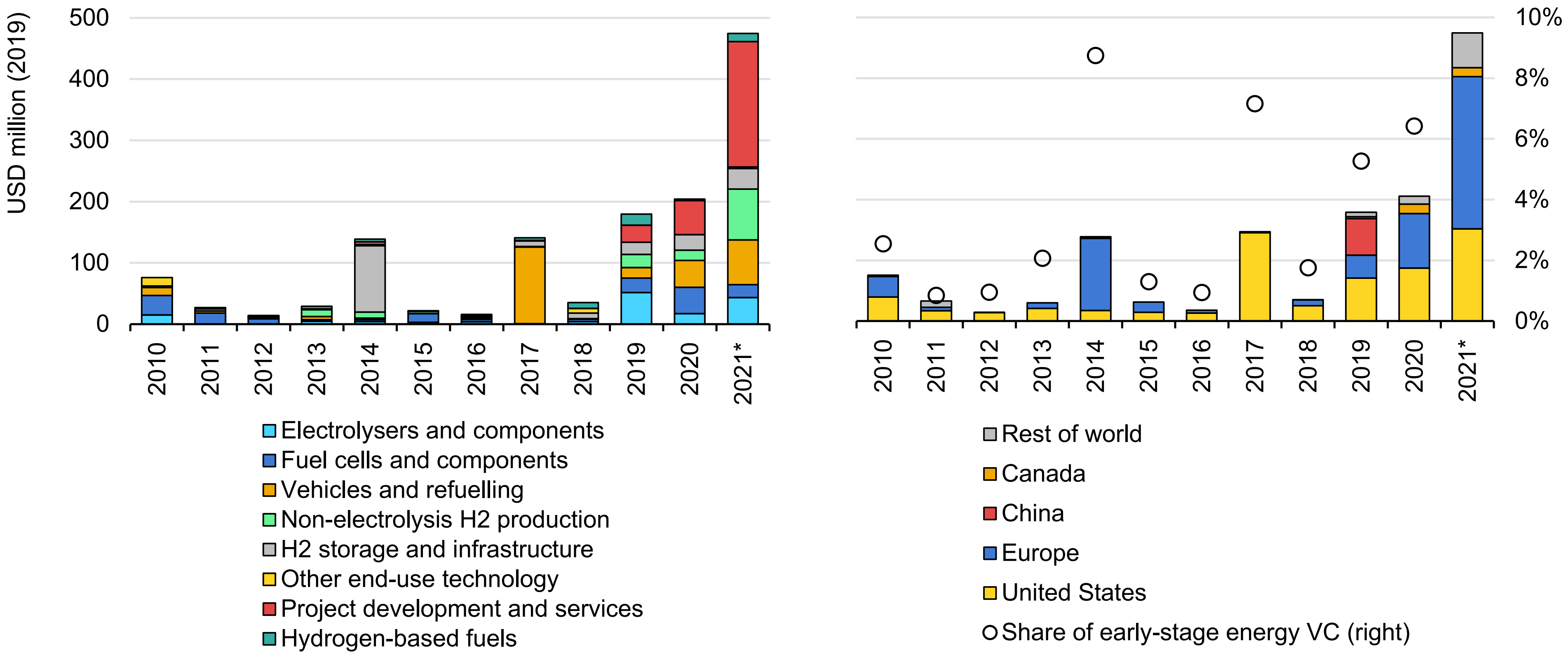
Investment in riskier early-stage hydrogen start-ups is also on the rise. In contrast to the clean energy venture capital (VC) boom around 2010, which involved few hydrogen companies, the current investment surge delivered record amounts in 2019 and 2020, with these sums surpassed in just the first six months of 2021. As electrolyser companies become more established in the market, start-up activity is shifting to focus on newer non-electrolysis routes, such as pyrolysis for extracting hydrogen from methane. Transform Materials and Syzygy Plasmonics have raised USD 50 million since 2019, while Monolith Materials raised USD 100 million in 2021 in later-stage financing.

The fact that start-ups providing project development and integration services for hydrogen projects are securing funding indicates a maturing sector. In May 2021, H2 Green Steel raised over USD 100 million, the first major deal for a project developer for hydrogen use in the steel industry. Aiming to start production by 2024, the Swedish company plans follow-up funding of USD 2.5 billion in mixed debt and equity within the next year. HTEC, an early-stage Canadian integration services firm, raised USD 170 million in September 2021.

Regionally, many start-ups in these newer areas are European. For the first time, in fact, European hydrogen start-ups are expected to raise more early-stage funds in 2020 and 2021 than their US counterparts. China has also emerged as a source of hydrogen technology start-ups and venture capital for scale-up. In 2019, Jiangsu Guofu Hydrogen Technology's fundraise of USD 60 million was the main early-stage deal in China, with the money coming from a state-backed Shanghai fund.

More early-stage capital flowing to start-ups, especially in Europe; fastest growth in companies offering project development services or non-electrolysis supply solutions

Early-stage venture capital deals for hydrogen-related start-ups by technology area and region, 2010-2021



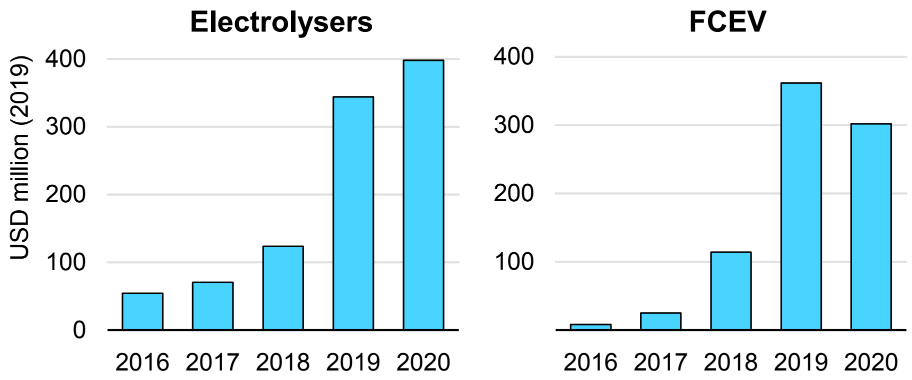
Notes: 2021* data up to mid-June. H2 = hydrogen. Early-stage VC includes seed, Series A and Series B. The share of early-stage energy VC excludes outlier deals above USD 150 million that distort trends (no such deal was recorded for hydrogen start-ups). Other end-use technology includes stationary turbines and non-transport mobile applications that do not involve proprietary fuel cell stacks.

Source: Calculations based in part on Cleantech Group (2021).

Evolution of investment in technology deployment

Investment in hydrogen technology deployment is also increasing. Despite near-term uncertainty about market-led uptake, hydrogen prospects look stronger than before the Covid-19 pandemic. Projects expected to deploy electrolysis capacity in 2021 raised more than USD 400 million in 2020, nearly four times the investments in 2018. In mobility, 2020 funding decreased slightly from 2019, likely reflecting impacts of the pandemic; investment is more than recovering in 2021, however, and deployments up to June point to a new record year.

Annual investments in electrolysers and FCEVs, 2016-2020



Note: FCEV = fuel cell electric vehicle.
Sources: Based on IEA Hydrogen Project Database and annual data submissions of the AFC TCP to the IEA Secretariat.

Clearly, government action – including funding in Covid-19 recovery plans and long-term signals embedded in national hydrogen strategies – is spurring the strong momentum behind hydrogen investment. Public investment is expected to leverage much higher private spending, which could further accelerate hydrogen technology deployment. For example, as part of its national hydrogen strategy, Germany announced a EUR 9-billion package, which the German government expects to trigger an additional EUR 33 billion of private investment. Globally, the industry sector is responding with an impressive investment appetite: according to the Hydrogen Council, the private sector has announced more than USD 300 billion of investments through 2030, although funding of only USD 80 billion has been committed.

Investment outlook for the Announced Pledges and Net zero Emissions scenarios

While recent hydrogen investments are encouraging, realising government climate ambitions will require significant ramp-ups across the entire production, end-use and infrastructure value chains. The Announced Pledges Scenario models investments totalling USD 250 billion for 2020-2030, leading to an accumulated investment of USD 3.2 trillion in 2050. This is lower than announced industry stakeholder investments to 2030, but significantly larger than those for which funding has already been committed.

Investments over the next decade could be critical in determining long-term outcomes. Every year until 2030, investments of USD 7 billion in electrolysers will be required (30 times recent record investments) and USD 4 billion in FCEV deployment will be needed (14 times record investments). To achieve net zero emissions by

2050, global cumulative investments must increase to USD 1.2 trillion by 2030 and USD 10 trillion by 2050.

Building up low-carbon hydrogen production capacity accounts for 25% of global cumulative investments to 2050 in the Announced Pledges Scenario and 27% in the Net zero Emissions. The need to deploy capacity for both new production and to decarbonise existing uses (which requires limited investments in end uses and infrastructure) means the share of investments in hydrogen production must be higher before 2030 than after. Although investment in production capacity continues to grow to 2050, its share declines as investments in new end-uses and infrastructure development increase.

End-use technologies account for about 60% of global cumulative investments to 2050 in both the Announced Pledges and Net zero Emissions scenarios, with the share increasing continuously. Investments in end-use technologies are already considerable in 2020-2030, projected at USD 8 billion/yr in the Announced Pledges Scenario and USD 30 billion in the Net zero Emissions. After 2030, several end-use technologies advance from early-stage development to commercialisation and deployment at scale, unlocking new hydrogen demand, particularly in the transport sector. Consequently, investments increase substantially to USD 90 billion/yr to 2050 in the Announced Pledges Scenario and to USD 270 billion/yr in the Net zero Emissions.

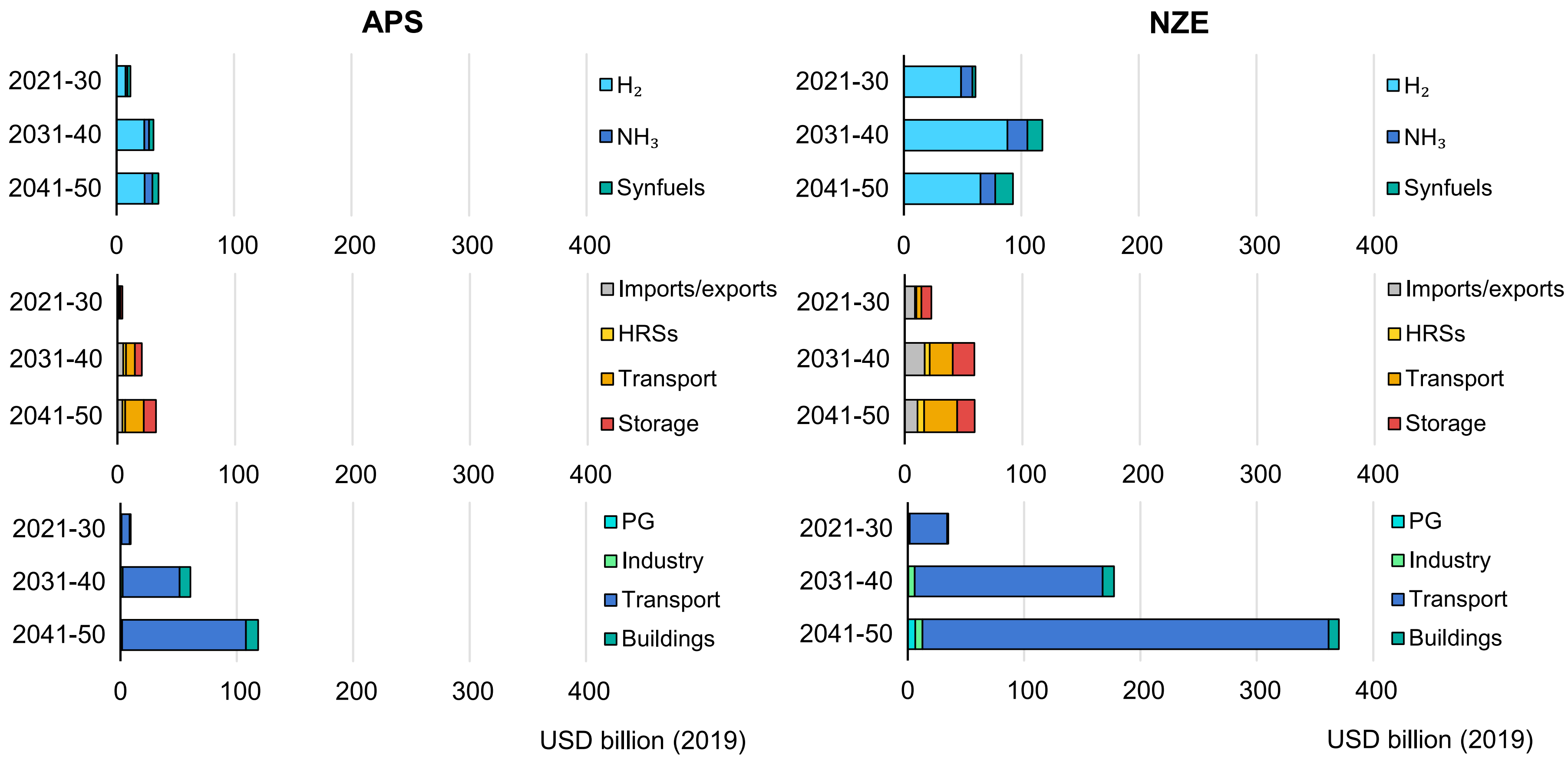
To distribute hydrogen to end users, significant investments are also required to develop infrastructure (i.e. refuelling stations, pipelines, storage and import/export terminals). In fact, infrastructure accounts for 18% of global cumulative investments to 2050 in the Announced Pledges Scenario (USD 575 billion) and 14% in the Net zero Emissions (USD 1 400billion).

Although modelling shows this share increasing nearly fivefold after 2030 in the Announced Pledges Scenario and more than twofold in the Net zero Emissions, this does not mean that infrastructure development can be delayed another decade. Rather, developing hydrogen storage capacity will be critical to ensure supply security in the short term and to provide balancing for the integration of renewable energy in the longer term. In parallel, progress can be made by blending hydrogen in the gas grid and repurposing natural gas pipelines. As hydrogen demand grows, greater investments in new pipeline infrastructure may be required, depending on regional conditions. Furthermore, the development of international hydrogen supply chains can spur investment in import/export terminals and hydrogen transport vessels.

Notable opportunities may exist to minimise expenditures by repurposing current infrastructure. With minimal modification, infrastructure for oil-derived products could be used to import/export liquid synfuels, while some parts of LNG and LPG infrastructure could be upgraded to import/export hydrogen and ammonia.

Investment on hydrogen must increase to USD 1.2 trillion by 2030 to put the world on track to meet net zero emissions by 2050

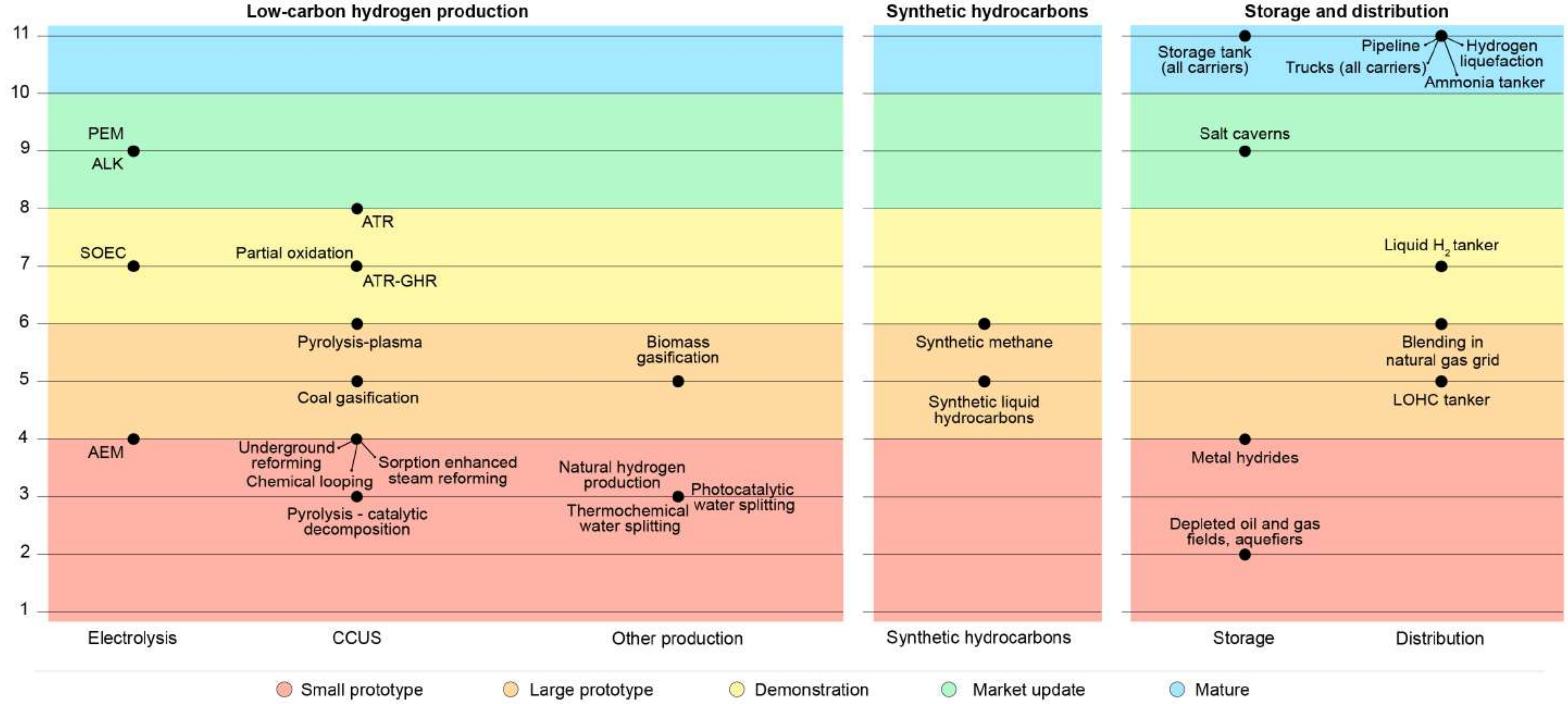
Global annual hydrogen investment needs by sector in the Announced Pledges and Net zero Emissions scenarios



Notes: APS = Announced Pledges Scenario. NZE = Net zero Emissions Scenario. HRSs = hydrogen refuelling stations. PG = power generation.

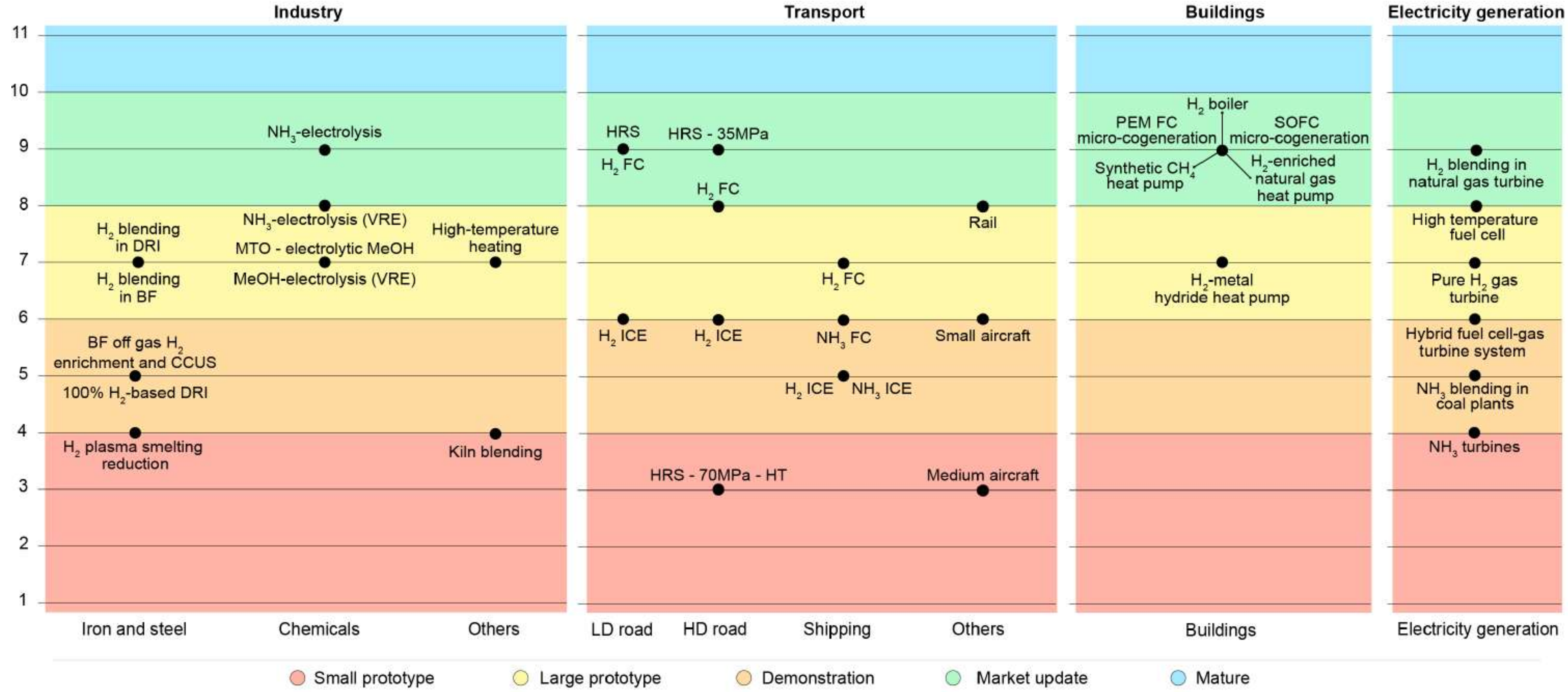
Several hydrogen technologies not yet commercially available

Technology readiness levels of key hydrogen production, storage and distribution technologies



Notes: AEM = anion exchange membrane. ALK = alkaline. ATR = autothermal reformer. CCUS = carbon capture, utilisation and storage. GHR = gas-heated reformer. LOHC = liquid organic hydrogen carrier. PEM = polymer electrolyte membrane. SOEC = solid oxide electrolyser cell. Biomass refers to both biomass and waste. For technologies in the CCUS category, the technology readiness level (TRL) refers to the overall concept of coupling these technologies with CCUS. TRL classification based on Clean Energy Innovation (2020), p. 67.
Source: IEA (2020), ETP Clean Energy Technology Guide.

Technology readiness levels of key hydrogen end-use technologies



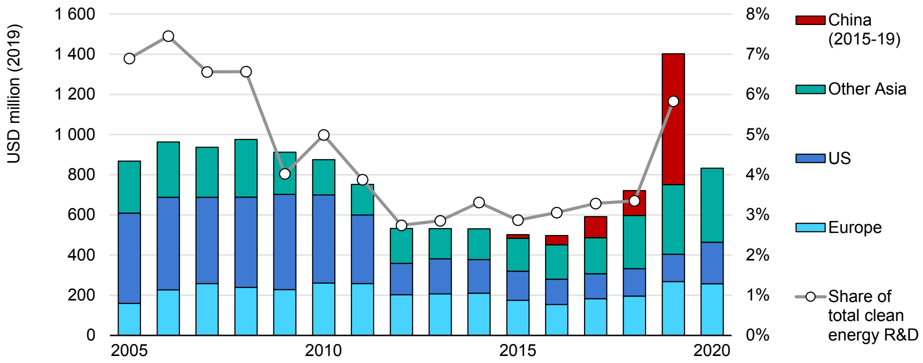
Notes: BF = blast furnace. DRI = direct iron reduction. FC = fuel cell. HRS = hydrogen refuelling station. HD = heavy-duty. HT = high throughput. ICE = internal combustion engine. LD = light-duty. MeOH = methanol. MTO = methanol to olefins. PEM FC = polymer electrolyte membrane fuel cell. SOFC = solid oxide fuel cell. VRE = variable renewable electricity. Co-generation refers to the combined production of heat and power. Technology readiness levels based on Clean Energy Innovation (2020), p. 67.

Source: IEA (2020), ETP Clean Energy Technology Guide.

Innovation in hydrogen technology is lagging

Except for well-established technologies for fossil-based production and conventional uses in industry and refining, much of the hydrogen value chain is yet to be fully developed at commercial scale. It is therefore vital that innovation efforts for all hydrogen technologies be stepped up to avoid bottlenecks in using them as a key lever for decarbonisation. In its Net zero by 2050 roadmap, the IEA estimates that USD 90 billion of public money needs to be mobilised globally as quickly as possible, with around half dedicated to hydrogen-related technologies.

R&D spending in hydrogen technologies, 2005-2020



Source: Based on IEA and Mission Innovation data. 2020 data for China not available.

Government support for hydrogen R&D was strong in the late 2000s. In fact, it accounted for 6% of all clean energy R&D, with most funding directed towards electrolyser technology and Japan being the largest funder. While a slump in R&D expenditures during 2010-2015 reflected lower overall interest in this technology family, the recent resurgence (since 2015) has focused on other hydrogen production and end-use technologies, in line with the relative maturity of fuel cell technologies. Of particular note is that the Government of China's R&D expenditures on hydrogen technologies increased sixfold in 2019.

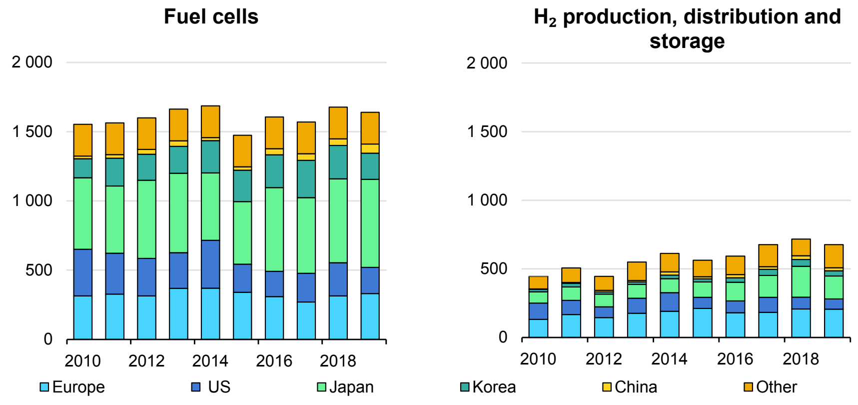
While the technology readiness levels (TRLs) of low-carbon hydrogen production technologies vary widely, analysis reveals that innovation gaps are concentrated in novel end-use industrial applications, heavy road transport, shipping and aviation. Among these technologies, the most advanced are in the early adoption stage, meaning they are ready for commercial applications but have not yet obtained significant market shares. Storage and distribution, use in buildings and light-duty road transport are all sufficiently developed for initial hydrogen use.

International patent family counts are a good proxy to measure innovation activity in any given technology. The 676 patent families registered for hydrogen production, storage and distribution technologies in 2019 reflect a 52% increase since 2010. In 2019, the highest shares of new patents were in Europe (30%) and Japan (25%).

At present, patents for fuel cell technologies outnumber those for hydrogen production, storage and distribution by a ratio of nearly 3:1, likely reflecting a higher TRL for the former as well the fact that fuel cell patent applicants include large companies (such as car manufacturers) with large R&D budgets. Japan has a clear technological lead in fuel cells, holding 39% of all patents, and the number of patent applications has been roughly constant over the past decade. Electrolyser manufacturers, in comparison, tend to be smaller companies with lower R&D budgets. Their technologies can, however, benefit from progress in fuel cells, particularly in areas such as materials or catalysts.

As public funding has been shared roughly equally between fuel cells and other applications, one can infer that the private sector has driven most of the innovation activity for fuel cells. A forthcoming study about patenting activity in hydrogen, developed jointly by the IEA and the European Patent Office, will be released in early 2022.

Patent applications by sector and region, 2010-2019



Source: Based on European Patent Office data.

Innovation and demonstration urgently needed to unlock emissions reduction potential of hydrogen technologies

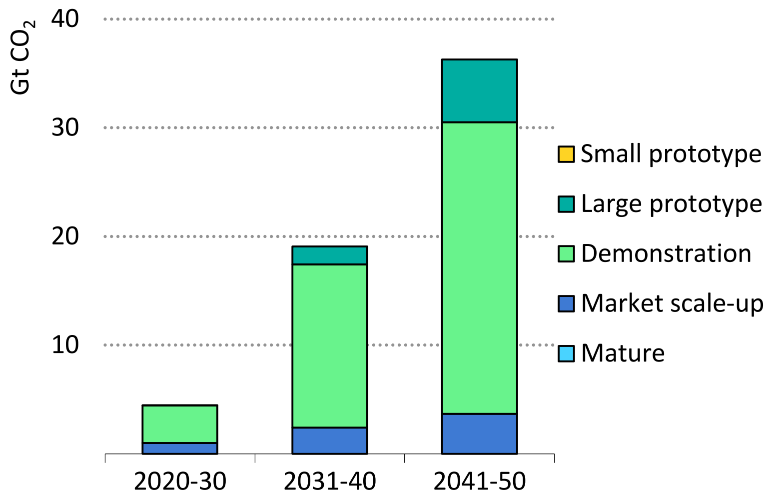
Of the 60 Gt of CO_2 emissions that hydrogen-based fuels can avoid in the Net zero Emissions Scenario, 55 Gt are achieved after 2030, reflecting that most end-use technologies for such fuels are not yet commercially available. Assessing TRLs across the entire hydrogen supply chain and in end-use sectors confirms the need to ramp up innovation to stay on track with this scenario.

Ultimately, only 12% of cumulative emissions reductions to 2050 come from technologies that are ready to enter the market and scale up production (e.g. light commercial vehicles). Most emissions reductions come from critical technologies still being developed and requiring demonstration to reach commercialisation, including co-firing ammonia and hydrogen in coal and natural gas power plants; producing chemicals using electrolytic hydrogen; using hydrogen in heavy-duty vehicles; and using hydrogen and ammonia in shipping.

In the Net zero Emissions Scenario, these technologies start delivering important CO_2 emissions reductions as early as the 2020s. While several ongoing initiatives aim to demonstrate these technologies, innovation efforts should be stepped up to ensure they reach commercialisation soon.

Other key technologies, such as using hydrogen-based DRI for steel manufacturing, are at even earlier stages of development. Their innovation cycle to reach demonstration and commercialisation should be completed as soon as possible so that they can begin effectuating CO_2 emissions reductions in the early 2030s.

Global CO_2 emissions reductions from hydrogen-based fuels by technology maturity in the Net zero Emissions Scenario, 2020-2050



Regional insights

United States: Stepping up efforts to develop hydrogen technologies

Owing to its large refining and chemical sectors, the United States is already one of the largest producers and consumers of hydrogen. With more than 11 Mt H_2/yr of consumption, the United States accounts for 13% of global demand: two-thirds is used in refining with most of the rest going into ammonia production. Around 80% of US hydrogen production is based on natural gas reforming; practically all the remainder is met with by-product hydrogen in refineries and the petrochemical industry.

The United States has been a traditional supporter of hydrogen as an energy vector and a main advocate for the adoption of hydrogen technologies in previous waves of interest. In the early 2000s, the US government strongly promoted R&D on hydrogen and fuel cells, with federal funding peaking at USD 330 million in 2007.

After a period of lower activity, the government again stepped up efforts, and in 2016 the US Department of Energy introduced its H_2@Scale initiative to enable affordable and clean hydrogen across end-use sectors (transport, metal refining, electricity generation, heating, ammonia and fertilisers, etc.) from diverse domestic resources, including renewables, nuclear energy and fossil fuels.

Instead of setting deployment targets, this programme focuses on cost and performance targets that can enable the adoption of hydrogen technologies. In 2020, the DOE Hydrogen Program Plan established a framework to encourage R&D on hydrogen-related technologies and eliminate institutional and market barriers to adoption across multiple applications and sectors.

More recently (June 2021), the DOE announced Hydrogen Energy Earthshot, an ambitious initiative to slash the cost of clean hydrogen by 80% – to USD 1.00/kg H2 – by 2030. By doing this, the US government expects to unlock a fivefold increase in demand for clean hydrogen. Previous economic analysis from the National Renewable Energy Laboratory (NREL) shows detailed scenarios for expanding the US hydrogen market size to 22-41 Mt – i.e. doubling or even more than tripling current demand – even with prices of more than USD 1.00/kg H_2.

In June 2021, 17 MW of electrolysis for dedicated hydrogen production was operative in the United States,[33] with 1.4 GW of capacity in the project pipeline (300 MW under construction or with funding committed) and another 120 MW at earlier stages of

[33] The US DOE publishes regular updates on PEM electrolysers installed and under development in the United States.