# Transport

## Greater hydrogen use is necessary to decarbonise transport

The transport sector is responsible for over 20% of global GHG emissions and one-quarter of final energy demand, with oil products supplying 90% of the energy it consumes. To date, hydrogen use in the sector has been limited, representing less than 0.01% of energy consumed. Nevertheless, hydrogen and hydrogen-based fuels can offer emissions reduction opportunities, especially in hard-to-electrify transport segments (e.g. long-haul, heavy-duty trucking, shipping and aviation).

In the Announced Pledges Scenario, hydrogen and hydrogen-based fuel consumption in transport climbs to 520 PJ or 0.4% of transport energy demand in 2030. Almost 60% of this demand is for road vehicles, as fuel cell vehicle stock expands to over 6 million. Shipping represents almost one-fifth of the demand, with hydrogen and ammonia constituting 1% of shipping fuel consumption in 2030. Similarly, hydrogen and synthetic fuels account for almost 1% of rail energy consumption. In aviation, hydrogen-based synthetic fuel use remains low, making up less than 1% of consumption. By 2050, demand for hydrogen and hydrogen-based fuels across all transport end-uses is over 15 times higher than in 2030, meeting 6% of the sector's energy demand.

In the Net zero Emissions Scenario, hydrogen and hydrogen-based fuel deployment is accelerated and demand reaches 2.7 EJ in 2030, representing 2.6% of transport energy demand. As in the Announced Pledges Scenario, the greatest share of demand (over 45%) is for road vehicles. In shipping, hydrogen accounts for almost 2% and ammonia almost 8% of fuel consumption in 2030. Synthetic fuels make up 1.6% of aviation fuel consumption in 2030 in the Net zero Emissions Scenario. By 2050, hydrogen and hydrogen-based fuels meet over one-quarter of total transport energy demand in this scenario.

# Status of hydrogen and fuel cells for transport

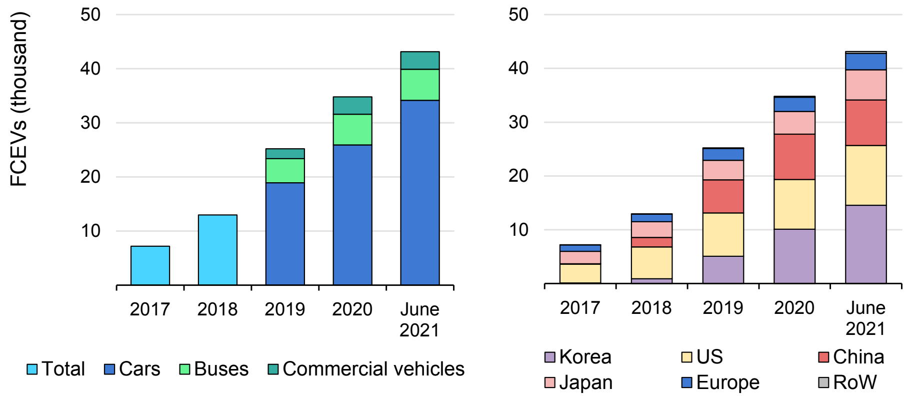
## Road transport

More than 40 000 FCEVs were on the road globally by the end of June 2021.[12] Stocks grew an average 70% annually from 2017 to 2020, but in 2020 stock growth fell to only 40% and new fuel cell car registrations decreased 15% (<10 000 new vehicles), mirroring contraction of the car market overall due to the Covid-19 pandemic. However, more than 8 000 FCEVs were sold in the first half of 2021, with record-high monthly sales recorded in California (759 in March) and Korea (1 265 in April).

Global FCEV deployment has been concentrated largely on passenger light-duty vehicles (PLDVs), constituting 74% of registered FCEVs in 2020. Three commercial fuel cell PLDV models are on the market[13] (Hyundai NEXO, Honda Clarity[14] and second-generation Toyota Mirai), with other original equipment manufacturers (OEMs) announcing plans to launch models over the next few years.

Buses, despite being deployed earlier and offering a greater number of fuel cell models (12 according to Calstart's Zero-Emission Technology Inventory tool), currently represent only 16% of total FCEV stock. Almost 95% are in China, which has also led deployment of fuel cell trucks, with >3 100 in operation in 2020.

### Fuel cell electric vehicle stock by segment and region, 2017-June 2021






Notes: FCEV = fuel cell electric vehicle. RoW = rest of world.
Sources: AFC TCP provided data on stocks from 2017-2020; 2021 new registrations are based on IPHE Country Surveys, Korea Ministry of Trade, Industry and Energy, and the California Fuel Cell Partnership.

Only 5 fuel cell truck models are currently available, but 11 are expected by 2023. Daimler Truck AG and Volvo Group announced a joint venture, cellcentric, to develop, produce and commercialise fuel

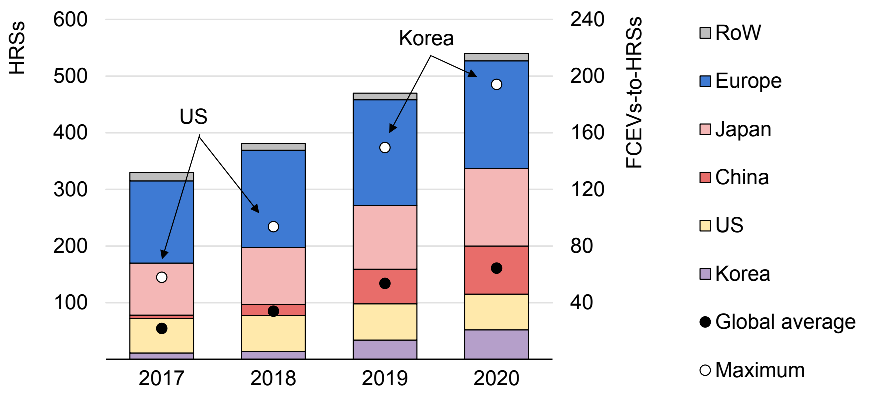
[12] For comparison, EV stock totalled 11 million at the end of 2020.
[13] 350 EV models were available in 2020.

[14] Honda announced discontinuation of the Clarity series (both plug-in hybrid and fuel cell models) as of August 2021, though the Clarity fuel cell will remain available for lease through 2022.

cell systems for long-haul trucking, among other applications. Along with IVECO, OMV and Shell, both companies also signed the H2Accelerate agreement to collaborate on large-scale hydrogen truck deployment in Europe.

Some OEMs, such as Cummins and MAN, are building and testing prototype hydrogen-fuelled internal combustion engines for commercial vehicle applications, which are at a lower technology readiness level than hydrogen fuel cells.

### Hydrogen refuelling stations by region and ratio of hydrogen refuelling stations to fuel cell electric vehicles, 2017-2020






Notes: HRS = hydrogen refuelling station. FCEV = fuel cell electric vehicle. RoW = rest of world.
Source: AFC TCP Deployment Status of Fuel Cells in Road Transport: 2021 Update.

At an average year-on-year increase of almost 20% during 2017-2020, the number of hydrogen refuelling stations (HRSs) is growing more slowly than that of FCEVs. The ratio of FCEVs to HRSs[15] is thus increasing, particularly in countries with the highest FCEV sales. In 2020, this ratio reached almost 200:1 in Korea and 150:1 in the United States, compared with just 30:1 in Japan.[16] This reflects, in part, excess HRS capacity, as stations are built anticipating FCEV growth.

Recent stations tend to have higher capacities than initial stations. In 2020, California unveiled a 1 200 kg/day station and allocated funding to construct stations of up to 1 620 kg/day; this is 2.5-3.5 times the average station size funded since 2012. In July 2021, the largest hydrogen station to date opened in Beijing, with a capacity of 4 800 kg/day.

Station refuelling pressure varies according to the vehicle market served. In most countries, the majority of stations dispense hydrogen at 700 bar to serve fuel cell cars. In China, most stations dispense at 350 bar to serve bus and truck fleets. Work is ongoing on station and component design and on fuelling protocols to enable high-throughput dispensing for trucks with 700-bar onboard storage, which will support a range of ~800 km – almost double that of current fuel cell trucks (~400 km). Some stakeholders, including Daimler, Hyzon

[15] In the absence of complete data on station capacity and dispensing, this ratio aims to provide some indication of station utilisation.

[16] For reference, the gas/diesel vehicle to station ratio in the United States is about 1 800:1.

and Chart Industries, are exploring onboard liquid hydrogen storage and refuelling to enable truck ranges of >1 000 km.

## Rail

Hydrogen and fuel cell technologies have been demonstrated in rail applications, including mining locomotives, switchers and trams, since the early 2000s. In 2018, the first commercial service of a hydrogen fuel cell passenger train (developed by Alstom) began a 100-km route in Germany. Two Alstom trains in Germany have since driven >180 000 km, and more countries have started testing and adopting fuel cell trains.

In 2020, a hydrogen train entered regular passenger service in Austria, and trials began in the United Kingdom and the Netherlands. In Europe, France, Italy and the United Kingdom have all placed orders for hydrogen fuel cell trains, while the largest fleet – 27 hydrogen trains – is slated to begin permanent, regular operations in Germany in 2022.

Countries such as China, Korea, Japan, Canada and the United States are also showing interest in hydrogen fuel cell trains. In addition to passenger trains, hydrogen trams, line-haul and switching locomotives are in various stages of development and deployment. Where direct electrification of lines is difficult or too costly, deploying fuel cell rail applications can help decarbonise the sector.

## Shipping

Hydrogen fuel cells have been demonstrated on several coastal and short-distance vessels since the early 2000s. None are yet commercially available, but the commercial operation of fuel cell ferries is expected to begin in 2021 in the United States and Norway. Most hydrogen-fuelled vessels currently under demonstration or planned for deployment in the next few years are passenger ships, ferries, roll-on/roll-off ships and tug boats, typically with fuel cell power ratings of 600 kW to 3 MW. Furthermore, a recent EU partnership aims to build a hydrogen ferry with 23 MW of fuel cell power.

Past and ongoing projects span both gaseous and liquid onboard hydrogen storage. Due to the low volumetric density of hydrogen (whether in gaseous or liquid form), direct use of hydrogen will be limited to short- and medium-range vessels, especially those with high power requirements that cannot be met through battery electrification.

Hydrogen-based fuels are also attracting attention for use as maritime fuels for large oceangoing vessels. Green ammonia in particular can be used in internal combustion engines to eliminate vessel $CO_2$ emissions. Major industry stakeholders have announced plans to make 100% ammonia-fuelled maritime engines available as early as 2023 and to offer ammonia retrofit packages for existing vessels from 2025.

**The CEM Global Ports Hydrogen Coalition**

Launched at the 12th Clean Energy Ministerial (1 June 2021), the CEM Global Ports Hydrogen Coalition aims to strengthen collaboration between government policymakers and port representatives to scale up low-carbon hydrogen use.

The IEA's The Future of Hydrogen identifies ports and coastal industrial hubs (where much of the refining and chemical production that currently uses hydrogen is concentrated) as opportune places to support the near-term scale-up of low-carbon hydrogen production and use. The shift from fossil-based to low-carbon hydrogen by industries in these clusters would boost hydrogen fuel demand by ships and trucks serving the ports as well as by nearby industrial facilities (e.g. steel plants), which would drive down costs.

To enlarge dialogue on hydrogen potential for port operations, the Coalition convenes numerous ports and stakeholders, including the International Association of Ports and Harbours and the World Ports Climate Action Program as well as regional associations (e.g. the European Sea Ports Organisation). The Hydrogen Council, the world's leading industry initiative, will also participate in Coalition activities along with other industry stakeholders.

Methanol has also been demonstrated as a fuel for the maritime sector and is relatively more mature than hydrogen and ammonia. Given its compatibility with existing maritime engines, methanol could be a near-term solution to reduce shipping emissions, but ultimately ammonia offers deeper decarbonisation potential.[17]

## Aviation

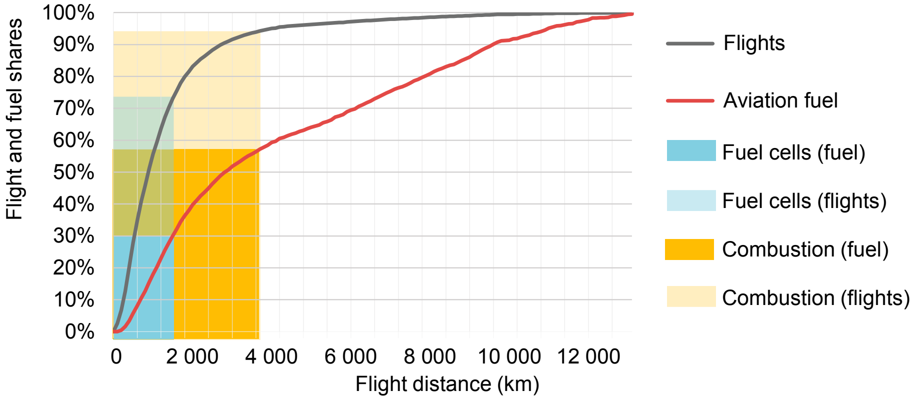
Interest in using hydrogen for aviation has also been growing. The industry group ATAG sees a role for hydrogen fuel cells for flights of up to 1 600 km, and hydrogen combustion for short flights and potentially for medium-haul ones. Assuming the technology is developed successfully, hydrogen fuel cells could be used in 75% of commercial flights but account for only ~30% of aviation fuel.

Technically, hydrogen combustion could be used for longer flights, potentially covering almost 95% of flights and 55% of fuel consumption, but equipment would be needed to mitigate NOx emissions.[18] Sustainable drop-in aviation fuels, including hydrogen-based fuels and biofuels, will be needed to decarbonise at least longer-haul flights, although means to mitigate non-$CO_2$ climate-warming effects may be required.

[17] However, ammonia combustion results in $N_2O$ and NOx emissions that may require additional equipment to mitigate climate and air pollution impacts.

[18] A recent McKinsey & Company study prepared for the Clean Sky 2 JU and FCH JU is more optimistic about hydrogen use in aviation and provides a comparison of its climate impacts with those of synthetic fuels.

## Hydrogen potential, by share of flights and fuel use in commercial passenger aviation






Note: Shading indicates shares of aviation fuel use (solid) and flights (transparent) that could theoretically be offset by hydrogen aircraft, given successful technology development to meet industry targets.
Source: IEA analysis based on OAG flight database.

Whether used with fuel cells or directly combusted, using hydrogen will require new aircraft system designs. Airbus is exploring various hydrogen aircraft concepts, focused on a capacity of up to 200 passengers and a 3 700-km range, with the goal of having a commercial aircraft available by 2035. Smaller companies working on hydrogen aircraft solutions include ZeroAvia, which targets the first commercial offering of a hydrogen plane with a 900-km range in 2024, and Universal Hydrogen, which aims to develop hydrogen storage solutions and conversion kits for commercial aircraft.

Boeing recently partnered with Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) to publish a roadmap for hydrogen in the aviation industry that considers opportunities for hydrogen use in aircrafts and airport applications (buses, stationary power, ground support equipment, taxis, trains and freight trucks). Remaining technical challenges include light-weighting cryogenic storage tanks (with minimal boil-off) and developing hydrogen infrastructure for delivery (likely pipelines with near- or on-site liquefaction) and high-flowrate liquid refuelling.

## Deployment of hydrogen in other mobile applications

**Material handling equipment**

Deploying zero-emissions material handling equipment, which includes forklifts and other machinery, is particularly important for indoor operations. Quick refuelling (~2 minutes) is cited as a benefit of fuel cells: in contrast with battery electric equipment, which forces drivers to return to a central location during a shift to swap out batteries, hydrogen refuelling can be situated more strategically throughout a warehouse. Fuel cells also perform particularly well in refrigerated environments, whereas cold temperatures degrade batteries.

Forklifts have proven to be an early commercial application for fuel cells. The United States currently has >40 000 hydrogen forklifts, with Plug Power being the major provider. Japan targets 10 000 by 2030, an ambitious scale-up from its current 330, and Belgium, Canada, France and Germany also each have fuel cell material handling equipment numbering in the hundreds. In Chile, Walmart has announced plans to convert 150 battery forklifts to fuel cell, powered by green hydrogen.

**Mining and agricultural equipment**

Hydrogen fuel cells may also be used to help decarbonise heavy off-road applications such as mining and agricultural equipment. As part of its national decarbonisation policy and Green Mining Plan, Chile supports projects to investigate and develop hydrogen-fuelled mining trucks, and the mining industry in general is investing in hydrogen technologies for mining equipment.

Anglo American expects to begin testing the first fuel cell mining truck in the second half of 2021 at a platinum group metal mine in South Africa. Komatsu, the Japanese construction equipment maker, plans to develop a fuel cell mining dump truck, aiming to commercialise it by 2030. While electric mining trucks powered by catenary lines already exist, fuel cell trucks offer decarbonisation potential for routes that power lines do not reach.

Agricultural equipment company New Holland, which showcased a fuel cell tractor in 2011, has now developed (as a transitional technology) a dual-fuel tractor that runs on a hydrogen-diesel blend. Other companies such as H2X and H2Trac are also developing fuel cell tractors.

# Insights into regional strategies for hydrogen fuels in transport

## China

China currently has the third-largest FCEV stock. Unlike other countries, it has focused on deploying fuel cell buses and trucks, and it now has the highest number in the world. Owing to a previous subsidy scheme, which set the fuel cell requirement at just 30 kW to qualify, fuel cells have been used mainly as range extenders. A new rewards-based policy framework aims to accelerate hydrogen demonstration at the regional (or city-cluster) level and focuses on the FCEV operation and supply chain, including hydrogen production and vehicle hydrogen consumption.

China has not yet approved type-IV hydrogen tanks used for 700-bar onboard storage, which partially explains its past emphasis on deploying mainly buses and trucks. While trucks and buses are expected to dominate FCEV sales in the next few years, regulatory approval and deployment of fuel cell cars will likely be needed to reach targets outlined in China's Technology Roadmap 2.0. The Society of Automotive Engineers is aiming for 50 000-100 000 FCEVs in 2025 and 1 million between 2030 and 2035.

In non-road applications, China has developed a hydrogen tram and hybrid locomotive. An ammonia fuel-ready tanker now being built could become the first maritime vessel to operate on this fuel.

## Europe

At the end of 2020, over 2 600 FCEVs were operating in Europe, with more than 1 000 in Germany. More than 90% of Europe's FCEVs are light-duty, and about 130 are fuel cell buses. Germany also leads in the number of HRSs, with 90 operating at the end of 2020 (of 190 across Europe).[19]

The Fuel Cell and Hydrogen Joint Undertaking (FCH JU) has supported a wide variety of FCEV demonstration and deployment projects, including taxis, delivery vans, buses and refuse trucks. As a result, the deployment of fuel cell taxis in Europe has been relatively high, most notably in Paris (100), the Hague (~40), Copenhagen (~10) and London (>50). Madrid has announced plans to deploy 1 000. Several European countries (the Czech Republic, France, the Netherlands, Portugal and Spain) have set FCEV targets, together aiming for ~415 000 FCEVs by 2030.

[19] The European Commission's Fit for 55 package's revisions to the Alternative Fuels Infrastructure Directive aims to ensure the HRS network is dense enough to "allow for seamless travel" of FCEVs, with an emphasis on heavy-duty vehicles.

Europe has been a leader in commercialising fuel cell trains. Additionally, the European Union has funded demonstrations of fuel cell-powered maritime vessels, including EUR 5 million (~USD 5.9 million) for the FLAGSHIPS project, which is deploying a hydrogen cargo transport vessel in France and a hydrogen passenger/car ferry in Norway, and EUR 10 million (~USD 11.8 million) for the ShipFC project, which will install a 2-MW ammonia fuel cell on an offshore vessel.

In July 2021 the European Commission presented the ReFuelEU Aviation proposal, which would require a minimum share of sustainable aviation fuel at all EU airports, including a continually increasing minimum share of synthetic aviation fuel. It aims to increase the share of synthetic aviation fuel from 0.7% in 2030 to 28% in 2050.

Additionally, the German government recently released a power-to-liquids (PtL) roadmap targeting the consumption of 200 000 tonnes of hydrogen-based sustainable aviation fuel in 2030. Meanwhile, as part of its *Plan de relance aéronautique* (a programme to help the aerospace industry recover from Covid-19 impacts), the French government has granted EUR 800 000 for development of a small (two-seat) hybrid hydrogen aircraft. The FCH JU has also funded the HEAVEN project, aimed at developing and integrating a high-power fuel cell and cryogenic hydrogen storage system into an existing small aircraft.

## Japan

At the end of 2020, Japan had 4 100 fuel cell cars and 100 fuel cell buses, and by mid-2021 the total had surpassed 5 500. With 137 HRSs at the end of 2020, Japan currently has the most in the world. Future (2030) targets include 800 000 PLDVs, 1 200 buses, 10 000 forklifts and ~1 000 HRSs (recently revised upwards from 900 as part of Japan's Green Growth Strategy).

To support targeted level of FCEV adoption, Japan aims to make them price-competitive with comparable hybrid EVs, particularly by reducing the cost of fuel cells and hydrogen storage systems. Japan is also targeting HRS cost reductions;[20] to date, prescriptive regulations have contributed to stations costing twice that in other parts of the world. Current HRS development and operations are financially supported through Japan Hydrogen Mobility (JHyM), a consortium of 26 private companies, financial institutions and the government.

[20] HRS cost reduction targets include reducing capital expenses from JPY 350 million (~USD 3.2 million) in 2016 to JPY 200 million (~USD 1.8 million) around 2025.

The East Japan Railway Company, partnering with Hitachi and Toyota, has announced plans to develop a hydrogen train, with

testing to begin in 2022. To meet International Maritime Organisation (IMO) standards on GHG emissions for international shipping, Japan is also investigating hydrogen- and ammonia-fuelled vessels. In 2020, the government published the Roadmap to Zero Emissions in International Shipping, which targets introduction of a first-generation zero emissions ship by 2028.

## Korea

Korea took the lead in FCEVs in 2020, with >10 000 cars and >50 buses on the road. Its FCEV stock doubled from 2019 to2020, and by the end of June 2021 an additional 4 400 fuel cell cars had been registered. Purchase subsidies from central and local governments cover about half of the purchase price of the popular, domestically produced Hyundai NEXO. In the Hydrogen Economy Roadmap, FCEV targets are set at 2.9 million cars, 80 000 taxis, 40 000 buses and 30 000 trucks by 2040. In the 2020 New Deal, the government set an interim target of 200 000 FCEVs in 2025.

Korea had 52 operational HRSs at the end of 2020, and the government is targeting 310 by 2022 and 1 200 by 2040. The Hydrogen Energy Network (HyNet) was therefore established in 2019 with an investment of USD 119 million to build ~100 HRSs by 2022.

According to Korea's hydrogen roadmap, the government plans to expand its focus to include hydrogen ships, trains and drones once the road vehicle market has matured. In fact, the government recently provided funding (USD 13 million) to the Korean Railroad Research Institute to develop the world's first liquefied hydrogen-based locomotive, slated for testing at the end of 2022.

## United States

The United States currently has the second-largest FCEV fleet, with >9 200 at the end of 2020. Most are in California, where the state government has supported HRS construction with funding of USD 166 million. At the end of 2020, there were 45 retail stations open in California and a total of 63 public and private HRSs across the country.

The California Energy Commission estimates the state will have 179 HRSs by 2027 with capacity to support 200 000 FCEVs, though this would miss the target of 200 HRS by 2025. Despite industry plans to expand the FCEV market to the north-eastern US states, regulatory barriers in some states are impeding deployment.

To date, the US government has not established federal targets for FCEV deployment. However, the California Fuel Cell Partnership, an industry and government collaboration, has announced its ambition to have 1 million FCEVs and 1 000 HRSs in the state by 2030.

To guide R&D efforts, the US Department of Energy has set cost and performance targets for fuel cells for light- and heavy-duty vehicles. In 2019, the DOE published heavy-duty long-haul truck targets, including reducing the cost of the fuel cell system to USD 60/kW and increasing its durability (i.e. lifetime) to 30 000 hours. To support R&D to meet these targets, the DOE established and funded the Million Mile Fuel Cell Truck Consortium.

California government agencies have also supported vehicle deployments, including the first fuel cell ferry (launch expected in 2021), development of a hydrogen fuel cell switching locomotive and the deployment of heavy-duty hydrogen trucks.

# Outlook for hydrogen in transport

## Road transport

Road vehicles account for the highest share of hydrogen and hydrogen-based fuel consumption in transport in 2030 under both the Announced Pledges (58%) and Net zero Emissions scenarios (45%). FCEV stock, across all modes, reaches >6 million in the Announced Pledges Scenario and >15 million in Net zero Emissions, with most being LDVs. The share of cars within the total FCEV stock remains at about 75% from 2020 to 2030 in the Announced Pledges Scenario, but decreases to 70% in the Net zero Emissions Scenario.

Generally, EVs are expected to be the dominant zero emissions vehicle powertrain in road transport, reflecting higher efficiency and a lower TCO in most cases. FCEV sales in 2030 reach 1% in the Announced Pledges Scenario (compared with 29% for EVs) and 3% in the Net zero Emissions Scenario (against almost 60%) owing to supportive government policies and subsidies, as well as consumer preference for non-cost factors (e.g. refuelling or charging time).

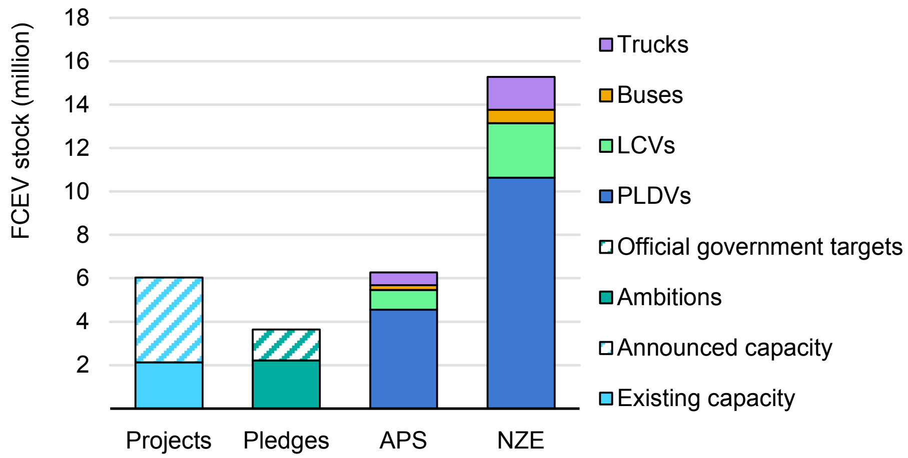
In the Announced Pledges Scenario in 2030, the sales share of fuel cell buses (3.7%) is the highest of all road transport modes, mainly because they offer advantages over battery electric technology for intercity buses. Fuel cells can also compete in the long-haul-trucking sector, as their range, refuelling time and payload capacity can enable performance and operations similar to current diesel trucks.

Similarly, fuel cell buses reach the highest sales share (6.1%) in 2030 in the Net zero Emissions Scenario. In addition, rapid technology and infrastructure development is assumed to support fuel cell truck deployment, which reaches a sales share of 4.7% in 2030. Use of synfuels for road transport is limited due to a higher TCO than for other zero- or low-emission alternatives.

In 2019, the Hydrogen Energy Ministerial published the Global Action Agenda targeting 10 million fuel cell-powered systems (including road vehicles, trains, ships and forklifts) by 2030. Annual fuel cell production capacity doubled from 2019 to 2020, but FCEV deployment in 2020 was ~20% lower than in 2019 – and well below the annual average needed to achieve the target. Even including the deployment of material handling equipment such as forklifts (~10 000 in 2020), accelerated scale-up is needed (likely beyond Announced Pledges projections) to achieve such an ambitious target.

Announced annual fuel cell manufacturing capacity by 2030 (~1.3 million systems/yr) could meet 75% of required fuel cell production for road vehicle sales in the Announced Pledges Scenario but would satisfy only less than one-third of Net zero Emissions sales. Notably, announced capacity exceeds the FCEV stock targets and ambitions stated by governments and other groups (e.g. the China Society of Automotive Engineers and the California Fuel Cell Partnership).

FCEV stock in the Announced Pledges and Net zero Emissions scenarios in 2030 vs current and announced cumulative fuel cell manufacturing capacity and FCEV deployment targets






Notes: FCEV = fuel cell electric vehicle. LCV = light commercial vehicle. PLDV = passenger light-duty vehicle. APS = Announced Pledges Scenario. NZE = Net zero Emissions Scenario. FCEV ambitions include non-government targets such as from the China Society of Automotive Engineers and the California Fuel Cell Partnership.
Sources: IEA Mobility Model (projections); E4tech (fuel cell projects).

To support FCEV deployment in 2030, an estimated 27 000 HRSs would be needed in the Announced Pledges Scenario and 18 000 in the Net zero Emissions. These estimates are highly sensitive to station capacity and utilisation assumptions. As station size and utilisation are expected to grow more slowly in the Announced Pledges than in the Net zero Emissions Scenario, the former requires a higher number of HRSs despite a lower number of vehicles.

In the Net zero Emissions Scenario, installed station capacity reaches >50 kt/day in 2030, compared with <20 kt/day in the Announced Pledges Scenario.

## Non-road transport

Shipping becomes the second-largest consumer of hydrogen and hydrogen-based fuels among transport modes in 2030 in both the Announced Pledges and Net zero Emissions scenarios. Demand for hydrogen and ammonia in shipping remains limited in the Announced Pledges Scenario, together meeting about 1% of fuel demand. In the Net zero Emissions Scenario, ammonia meets 8% of total shipping fuel demand and hydrogen meets 2%.

To enable hydrogen and ammonia fuel use in shipping, ports will need to build corresponding bunkering infrastructure. It is expected that ports with hydrogen bunkering infrastructure will remain fairly limited until 2030, with most being “first movers” such as the signatories of the Global Ports Hydrogen Coalition and others that have already begun investigating and testing hydrogen solutions (e.g. the Port of Valencia, Port of Honolulu, Ports of Auckland, Port of Los Angeles and Port of Antwerp).

As hydrogen continues to displace fossil fuels in relatively short-range vessels (especially when battery electrification is difficult), in the long term every port serving ferries, cruise ships and inland and coastal vessels will likely need hydrogen infrastructure. In the Net zero Emissions Scenario, about ten ports are projected to be first movers in providing ammonia bunkering services (fewer in the Announced Pledges Scenario), all having high maritime cargo throughput and either existing ammonia bunkering or plans to integrate new fuels. Included in the first movers are the ports of Rotterdam and Singapore (both ranking in the top ten by container throughput), as well as the Keihin ports along Japan's Tokyo Bay.

In rail, hydrogen is expected to mainly replace current diesel lines that are expensive to electrify due to relatively low utilisation.[21] Hydrogen constitutes 0.7% of rail energy consumption in 2030 in the Announced Pledges Scenario and 2% in the Net zero Emissions.

Passenger aircraft, for commercial aviation, designed to use hydrogen directly are not expected to be commercially available until the mid-2030s or later. Use of hydrogen-based synfuels (or power-to-liquids [PtL]), which can be dropped into an existing aircraft, could make inroads by 2030. In the Announced Pledges Scenario, PtL meets <0.6% of aviation fuel demand in 2030, but this share almost triples to >1.6% in the Net zero Emissions Scenario.

Given the limited availability of sustainably sourced carbon, the bulk of synfuels are consumed in the aviation sector where battery electrification and direct use of hydrogen are restricted to relatively short flights, especially in the near to medium term.

[21] See The Future of Rail for further analysis.

# Transport industry announcements for FCEVs

| Company | Target | Target year | Vehicle category |
|---|---|---|---|
| BMW | Limited-series fuel cell SUV release | 2022 | PLDV |
| Jaguar Land Rover | Prototype testing of fuel cell SUV | End of 2021 | PLDV |
| Great Wall Motor | Fuel cell SUV release | 2021 | PLDV |
| Toyota Motor Corp. | Deployment of 600 FCEV taxis in greater Paris region | End of 2024 | PLDV |
| Riversimple | Production target of 5 000 fuel cell coupes/yr | 2023 | PLDV |
| Riversimple | Light goods vehicle model release | 2023 | LCV |
| Stellantis | Fuel cell van models release | 2021 | LCV |
| Renault and Plug Power | Light commercial vehicle models release | 2021 | LCV |
| Symbio and Safra | Availability of 1 500 buses | 2021 | Bus |
| Symbio and Safra | Construction of largest EU fuel cell plant (60 000 units/yr) | Unspecified* | Bus |
| H2Bus Consortium | Deployment of 600 fuel cell buses | 2023 | Bus |
| Daimler | Testing of GenH2 truck with liquid hydrogen onboard storage | 2021 | Truck |
| Air Products and Cummins | Conversion of ~2 000-truck fleet to hydrogen fuel cells | 2022+ | Truck |
| Nikola | Purchase order of up to 800 fuel cell trucks to US Anheauser-Busch | 2023+ | Truck |
| MAN | Deployment of hydrogen fuel cell demonstration fleet | 2024 | Truck |
| Hyzon | Purchase orders for 1 500 fuel cell trucks to Hiringa Energy in New Zealand; 20 to Jan Baaker and Millenaar & van Schaik in the Netherlands; and 70 to JuVE/MPREIS in Austria | 2024 | Truck |
| Hyundai | Purchase order of 1 600 fuel cell trucks to Switzerland | By 2025 | Truck |
| Daimler and Volvo | Large-scale series production of fuel cell trucks | 2025+ | Truck |
| Industry Coalition | Deployment of 100 000 heavy-duty fuel cell trucks in Europe | From 2030 | Truck |

* Although plant construction has already begun, the target date for operations is unspecified.

Notes: PLDV = passenger light-duty vehicle. LCV = light commercial vehicle.

# Cost and supply chain analysis

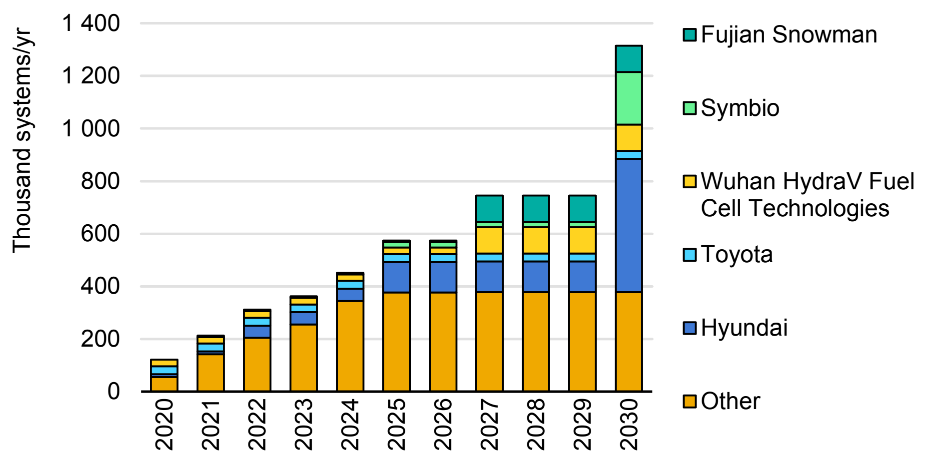
## Fuel cells

The cost of automotive fuels cells has fallen ~70% since 2008. Depending on the vehicle segment, current system costs are USD 250-400/kW, but further reductions are needed to make FCEVs cost-competitive with internal combustion engine vehicles and other low- or zero emission vehicles. Analysis suggests that scaling up manufacturing capacity from 1 000 to 100 000 systems/yr would slash costs by >70%, but significant investment is needed to boost manufacturing throughput and capacity.

To this end, new and incumbent fuel cell manufacturers have announced expansion plans. Global fuel cell manufacturing capacity is expected to reach >200 000 systems/yr by the end of 2021, with supply spread among over 40 manufacturers. Toyota can currently produce 30 000 systems/yr, and Hyundai is building a second plant to bring capacity to >40 000 systems/yr in 2022 and aims reach 500 000 systems/yr by 2030. Manufacturing capacity announcements for 2030 total 1.3 million systems/yr, with an estimated annual production potential of 90 GW.

Technological advances are needed to improve fuel cell durability (which is particularly vital for heavy-duty transport applications) and reduce costs while maintaining or improving efficiency. Key areas for R&D include the fuel cell catalyst, currently based on platinum group metals; membranes and electrolytes; and bipolar plates.

### Announced annual automotive fuel cell manufacturing capacity, 2020-2030






Source: E4tech.

Since 2008, average platinum loading in fuel cells has decreased 30%. Toyota reports reducing platinum loading in the Mirai fuel cell by about one-third from first- to second-generation models.

In addition to lowering costs, reducing platinum loading mitigates potential supply chain risks associated with highly geographically concentrated supplies, as more than 70% of platinum group metals are sourced from South Africa.

According to the IEA's critical minerals report, global demand for platinum group metals is expected to fall as FCEVs displace conventional vehicles that have a high palladium content in their catalytic converters. Overall platinum demand is, however, expected to increase despite further reductions in the platinum loading of automotive fuel cells.

## Hydrogen refuelling stations

While economies of scale in station component manufacturing are expected to reduce the delivered cost of hydrogen for vehicles, HRSs with higher capacities will also have a lower levelised cost of dispensed hydrogen. Increasing station size from 350 kg/d to 1 000 kg/d could cut the cost of dispensed hydrogen by over 30%, according to US DOE analysis. As both station capacity and vehicle demand increase, pipeline delivery will become more profitable and could further reduce the overall cost of dispensed hydrogen.

Station utilisation is another important factor. While utilisation tends to align with vehicle deployment, early FCEV fleet deployment can help ensure a certain level of utilisation, lowering hydrogen prices. Stations designed to serve both LDVs and HDVs may be able to increase utilisation and reduce overall capital expenditures, though serving both vehicle types will require more equipment to fuel at different pressures or flowrates.

The number of suppliers for key HRS components is currently limited, which can restrict station roll-out and prevent the cost reductions that come with market competition. For example, just two companies (WEH and Walther) dominate the HRS nozzle market.

Novel component designs (including for high-throughput compressors, cryogenic hydrogen pumps, hoses and nozzles) and refuelling protocols are needed for fast fuelling of heavy-duty trucks, marine vessels and aircraft.

## Total cost of ownership

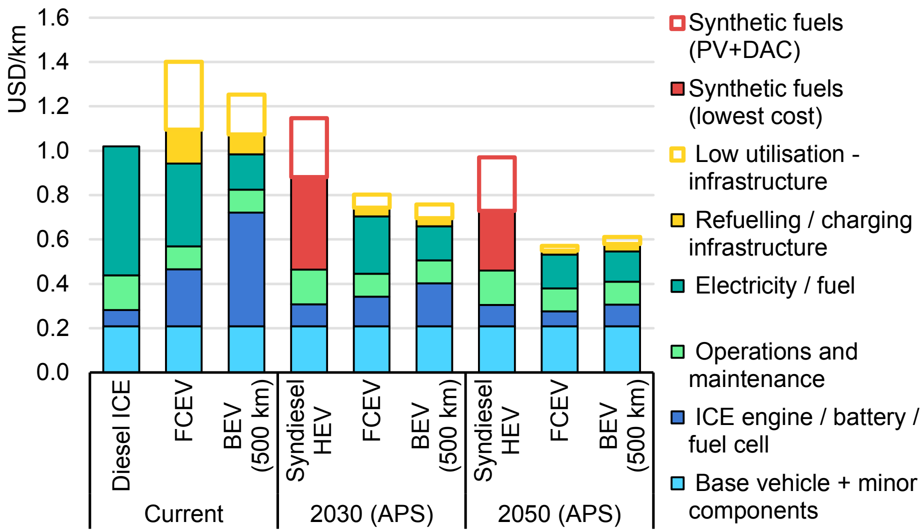
Adoption of FCEVs, especially buses and commercial vehicles, will be determined by how their TCO compares with other vehicle and fuel technologies. The main TCO factors for FCEVs are the delivered hydrogen and fuel cells costs, and station utilisation. In comparison with BEVs, daily range is another key consideration.

For long-haul HDVs, enabling a sufficient driving range may require additional battery capacity; however, the associated weight could limit payload and add to BEV cost. Fuel cell trucks begin to have a TCO advantage over battery electric at a range of 400-500 km, as shown in the IEA's Energy Technology Perspectives 2020.

The TCO for fuel cell heavy-duty trucks is currently 10-45% higher than for internal combustion diesel trucks. In the Announced Pledges Scenario, as the manufacturing of fuel cells, station components and hydrogen production technologies scales up – while station utilisation also increases – the TCO of fuel cell heavy-duty trucks drops 30-40% by 2030 and 50-60% by 2050.

Comparing decarbonisation options for this sector, the TCOs of both battery electric and fuel cell trucks are expected to be lower than for hybrid electric trucks running on synthetic diesel. In the medium term, fuel cell and battery electric trucks have comparable TCOs at a 500-km driving range, depending on refuelling or charging infrastructure utilisation. By 2050 in the Announced Pledges Scenario, fuel cell electric trucks are expected to be the lower-cost option at that range.

**Current and future total cost of ownership of fuel/powertrain alternatives for heavy-duty trucks.**






Notes: APS = Announced Pledges Scenario. ICE = internal combustion engine. FCEV = fuel cell electric vehicle. BEV = battery electric vehicle. HEV = hybrid electric vehicle. PV = photovoltaic (solar electricity for synthetic fuel production). DAC = direct air capture. Techno-economic assumptions available in the Annex.

Source: Based on input from the Hydrogen Council.

# Buildings

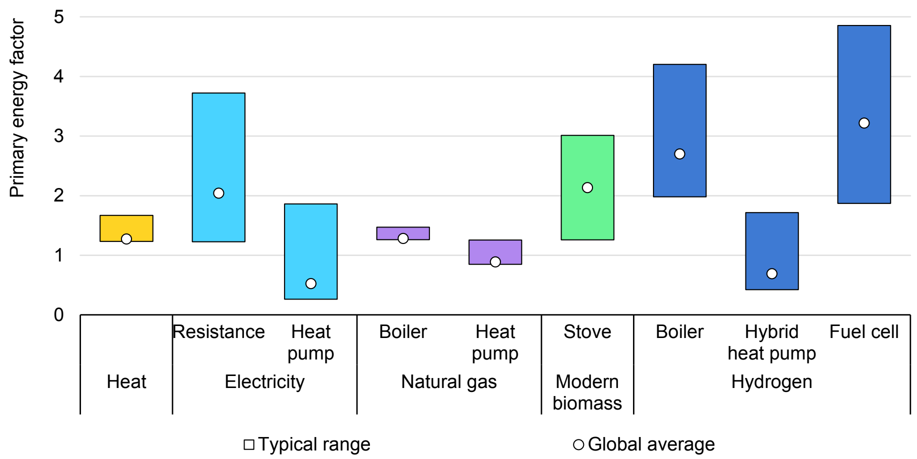
# Hydrogen and fuel cell opportunities are limited in buildings but worth exploring

With consumption of almost 70 EJ, space and water heating in buildings accounts for nearly 55% of energy use in buildings globally and 4.3 Gt $CO_2$ of emissions. In very cold areas such as in Russia, the Caspian region and Iceland, heating can make up >80% of total energy demand in buildings. Improving the thermal performance of building envelopes and integrating clean, efficient low-temperature equipment are priorities to decarbonise heating in buildings. Several options for efficient heating are currently available, including heat pumps and clean district energy.

Prospects for deploying hydrogen in this sector remain limited, reflecting the high efficiency of electricity-based solutions and the energy losses that result from converting and transporting hydrogen. For instance, PV-powered heat pumps require 5-6 times less electricity than a boiler running on electrolytic hydrogen to provide the same amount of heating. Furthermore, ensuring safe operations and converting gas infrastructure are both capital-intensive and socially challenging.

The heating sector is difficult to decarbonise, with existing (old) multi-family buildings and very cold climates being particularly challenging because integrating efficient low-temperature solutions depends on space availability, energy system layout and overall building performance, in addition to logistical and economic costs for building occupants.

### Primary energy factors of heat production by equipment and fuel, 2020






Notes: Hybrid heat pumps are assumed to use 25% hydrogen. Heat refers to district heating. Assumptions available in the Annex

Nevertheless, since hydrogen equipment can be compatible with existing buildings' energy systems,[22] localised hydrogen applications

[22] In terms of deliverable temperature range and operational schedules, but pipework, metering and verification interventions are required.

could support decarbonisation in very specific contexts where gas infrastructure already exists. Co-existence of hydrogen and other heat production technologies can also add flexibility to the electricity grid to facilitate demand-side response, particularly in very cold regions where BEVs and other storage devices would likely fall short.

Hydrogen can be blended with or replace a portion of natural gas, which currently meets 35% of global energy demand for heating. Depending on the region, such blending (at volumes of 5-20%) can leverage current natural gas infrastructure without requiring major network modifications.

Blending hydrogen at 20% would reduce carbon intensity by 7% at most – well short of the level needed for long-term buildings sector decarbonisation. It would also affect gas prices for end users. While decarbonising established hydrogen use remains a priority, blending options could help guarantee demand for low-carbon hydrogen.

In the longer term, hydrogen-specific infrastructure could be expanded (by building up dedicated networks or retrofitting existing ones) to further displace natural gas. Space and water heating equipment will also need to be upgraded or replaced, then verified as operational.

Deployment of hydrogen equipment needs to be specifically targeted to applications where it is cost-effective compared with switching to other options, and it takes roughly five days to adapt a building's energy system.

Four main groups of technologies can operate on hydrogen at the building level:

- **Hydrogen boilers** can be practical where gas networks exist because consumers will be familiar with the basic technology and its upfront capital costs. From a lifecycle perspective, however, higher fuel consumption than more efficient technologies makes this option less attractive overall for most buildings.
- **Fuel cells that co-generate**[23] **heat and electricity** include solid oxide fuel cells (SOFCs) and polymer electrolyte membrane fuel cells (PEMFCs). SOFCs require a high temperature but also provide high electrical efficiency and a more stable load compared with PEM cells, which work at a lower temperature (60-80°C) on intermittent load schedules but offer lower electrical efficiency. As SOFC efficiency typically declines when operated with pure hydrogen, optimising the system layout to address this issue is a key research focus. Natural gas field testing in Europe shows micro-cogeneration unit electrical efficiencies of 35-60% for SOFCs and 35-38% for PEMFCs, with corresponding cogeneration system efficiencies of 80-95% (SOFCs) and 85-90% (PEMFCs).

[23] Co-generation refers to the combined production of heat and power, also known as CHP.