



E4tech

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The Fuel Cell Industry Review 2021



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NOTE ON CURRENCIES

The following exchange rates can be used as guidance to convert currencies mentioned in this report. These are the average mid-point exchange rates from 30th November 2020 to 30th November 2021.

US\$1 = € 0.8407	€1 = US\$ 1.1899	1£ = US\$ 1.3723	1¥ = US\$ 0.0092
US\$1 = £ 0.7289	€1 = £ 0.8673	1£ = € 1.1536	1¥ = € 0.0077
US\$1 = ¥ 108.60	€1 = ¥ 129.17	1£ = ¥ 149.04	1¥ = £ 0.0067

LIST OF ABBREVIATIONS

ABS – American Bureau of Shipping	JV – Joint Venture
AC Transit – Alameda-Contra Costa Transit District	KEPRI – Korea Electric Power Research Institute
ADL – Alexander Dennis Limited	KEPCO – Korea Electric Power Corp.
AFC – Alkaline Fuel Cell	kFW 433 – Förderung für das Heizen mit Brennstoffzelle
AFO – Alternate Fuel Organisation of Indian Railways	German national mCHP programme)
AI – Artificial Intelligence	KIK – Keskkonnainvesteeringute Keskus
AIP – Air Independent Propulsion	(Estonia's Environmental Investment Center)
APU – Auxiliary Power Unit	KOGAS – Korea Gas
ARRA – American Recovery and Reinvestment Act	KRRI – Korean Railroad Research Institute
ASL – ASL Aviation Holdings	KSOE – Korea Shipbuilding & Offshore Engineering Co.
ATI – Aerospace Technology Institute	kW – Kilowatt
BC – British Columbia (Canada)	LCV – Light commercial vehicle
BOC – British Oxygen Company (Linde subsidiary)	LH2 – Liquid Hydrogen
BOP – Balance-Of-Plant	LIDAR – Light Detection and Ranging Technology
BMW – Bayerische Motoren Werke AG	LNG – Liquefied Natural Gas
BMWi – German Federal Ministry for Economic Affairs and Energy	LNVG – Landes Niedersachsen ein bedarfsgerechtes öffentliches
(since 2021 renamed the BMWK)	Verkehrsangebot (regional transport authority for Lower Saxony)
BVLOS – Beyond Visual Line Of Sight	LOHC – Liquid Organic Hydrogen Carrier technology
BWT – Blue World Technologies	LPG – Liquefied Petroleum Gas
Capex – Capital Expenditure	LRV – Light Rail Vehicle
CARB – California Air Resources Board	LT-PEM – Low-temperature PEM
CCI – California Climate Investments	MCFC – Molten Carbonate Fuel Cell
CCS – China Classification Society	MEA – Membrane Electrode Assembly
CCS – Carbon Capture & Storage	MES-M – Mitsui E&S Machinery
CCUS – Carbon Capture, Utilisation & Storage technologies	METIP – Maritime Emerging Technologies Innovation Park
CEC – California Energy Commission	MIIT – Ministry of Industry and Information Technology
CEOG – Centrale Electrique de l'Ouest Guyanais	MIL-STD – United States Military Standard
CHEM – Chung-Hsin Electric and Machinery Mfg Corp	MMC – Shenzhen MicroMultiCopter
CHP – Combined Heat and Power	MOF – Ministry of Finance (China)
CH2 – Compressed hydrogen	MOST – Ministry of Science and Technology
COP – United Nations Climate Change Conference	MOU – Memorandum of Understanding
COVID/COVID-19 – Coronavirus 2019 (SARS-CoV-2)	MTU – MTU Friedrichshafen (now Rolls Royce Power Systems)
COMAC – Commercial Aircraft Corp of China	MW – Megawatt
CT – Connecticut (US State)	MZK – Miejski Zakład Komunikacji (Poland)
CTE – Center for Transportation and the Environment	NASA – National Aeronautics and Space Administration (US)
DAPA – Defense Acquisition Program Administration (South Korea)	NEDO – New Energy and Industrial Technology Development Organization
DC (power) – Direct Current	NEV – New Energy Vehicle (authorized battery and fuel cell vehicles in China)
DEEP – Department of Energy & Environmental Protection (US)	NHN – Development Agency Noord-Holland Noord
DG – Distributed Generation	NM – Nautical Mile
DLR – German Aerospace Centre	NREL – National Renewable Energy Laboratory
DMFC – Direct Methanol Fuel Cell	NY – New York (US State)
DMI – Doosan Mobility Innovation	NOx – Nitrogen Oxides
DOD – Department of Defense (US)	OEM – Original Equipment Manufacturer
DOE – Department of Energy (US)	OGE – Open Grid Europe
DTU – Technical University of Denmark	Opex – Operational Expenditure
EAS-HyMob – Easy Access to Hydrogen Mobility (project)	PACE – Pathway to Competitive European fuel cell micro-CHP market
EFOY – Energy For You (SFC Energy fuel cell products)	(FCH2 JU project)
EKPO – JV of ElingKlinger and Plastic Omnium	PAFC – Phosphoric Acid Fuel Cell
EMEC – European Marine Energy Centre	PBI – Polybenzimidazole Fuel Cell
EMU – Electric Multiple Unit (train)	PCBFC – Printed Circuit Board Fuel Cell
ENC – ElDorado National-California	PEM(FC) – Polymer Electrolyte Membrane (Fuel Cell)
ENOVA – Norwegian government enterprise responsible for promotion of	PGNIG – Polish Oil and Gas Company
environmentally-friendly production and consumption of energy	POSCO – (formerly Pohang Iron and Steel Company),
EPA – United States Environmental Protection Agency	a South Korean steel-making company
ERDF – European Regional Development Fund	PPA – Power Purchasing Agreement
ESA – European Space Agency	PSA – Peugeot S.A., now Stellantis
EU – European Union	PV – Photovoltaic
EUDP – Danish Energy Technology Development and Demonstration Program	R&D – Research and Development
EVLOS – Extended Visual Line Of Sight	RoW – Rest of World
EV – Electric Vehicle	RMB – Chinese Yuan
FC – Fuel Cell	RTG – Rubber-Tired-Gantry crane
FAA – Federal Aviation Administration	SAE (China) – China Society of Automotive Engineers
FCE – FuelCell Energy, Inc.	SAF – Sustainable Aviation Fuel
FCEB – Fuel Cell Electric Bus	SAIC – Shanghai Automotive Industry Corporation
FCT – Fuel Cell Today	SARTA – Stark Area Regional Transit Authority
FCV/FCEV – Fuel Cell (Electric) Vehicle	SATE – Sustainable Aviation Test Environment
FCH JU – Fuel Cells and Hydrogen Joint Undertaking	SCADA – Supervisory control and data acquisition
(replaced in 2021 by Clean Hydrogen JU)	SCAQMD – South Coast Air Quality Management District
FCH2Rail – Fuel Cell Hybrid Power Pack for Rail Applications	SFC – SFC Energy AG
FCIR – Fuel Cell Industry Review	SGN – Scottish Gas Network operator
FCTS – Toyota SinoHytec Fuel Cell (JV)	ShyFT – Scottish Hydrogen Fuel Tank, composite high-pressure vessel,
FPS – Future Proof Shipping	developed by Innovatus Technologies
FRP – FRP Advanced Technologies Aerospace & Defence S.L.	SK – Saskatchewan (Canada)
FST – Freudenberg Sealing Technologies	SK E&S – South Korea's largest private renewable energy operator
GE – General Electric	SNCF – Société Nationale des Chemins de Fer français
GM – General Motors Company	SOEC – Solid Oxide Electrolyser Cell
GW – Gigawatt	SOFC – Solid Oxide Fuel Cell
HD(V) – Heavy Duty (Vehicle): trucks, sometimes also applied to buses	SPAC – Special-Purpose Acquisition Company
HEART – Hydrogen-Electric and Automated Regional Transportation	SUV – Sports Utility Vehicle
HES – HES Energy Systems	TESS – Toshiba Energy Systems & Solutions Corp.
HEV – Hybrid Electric Vehicle	TTSI – Total Transport Services Inc.
HTWO – Hyundai Motor Group's fuel cell brand	TU (Delft) – Delft University of Technology
HMM – JV of Hyundai Motor and H2 Energy	UAE – United Arab Emirates
HIAL – Highlands and Islands Airports Limited	UAV – Unmanned Aerial Vehicle
HI ERN – Helmholtz Institute Erlangen-Nurnberg for Renewable Energy	UK – United Kingdom
HNH – Development Agency Noord-Holland Noord	UPS – Uninterruptible Power Supply
HQ – Headquarters	UPS (Company) – United Parcels Service
HRS – Hydrogen Refuelling Station	US/USA – United States of America
HT-PEM – High Temperature PEM (PBI)	UTC – United Technologies Corp.
IAA – Internationale Automobil-Ausstellung (Motor show in Germany)	VDL – VDL Bus & Coach
IAG – International Airlines Group	VTOL/eVTOL – (Electrical) Vertical Take-off and Landing (aerial vehicle)
ICE – Internal Combustion Engine	VTT – VTT Technical Research Centre of Finland
IE – Intelligent Energy	W – Watt
IMO – International Maritime Organization	WA – Washington (US State)
IPCEI – Important Projects of Common European Interest	ZAL – ZAL Centre for Applied Aviation Research GmbH
IPHE – International Partnership for Hydrogen and Fuel Cells in the Economy	ZECAP – Zero Emissions for California Ports
IPO – Initial Public Offering	ZEV – Zero Emissions Vehicle
ISS – International Space Station	
JAXA – Japan Aerospace Exploration Agency	
JIVE – Joint Initiative for Hydrogen Vehicles across Europe	
JLR – Jaguar Land Rover	

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Back on the growth curve?

Despite the late appearance of this year's Review, we have tried to focus on what 2021 told us. Events in 2022 so far have affected energy markets dramatically; we have resisted second-guessing developments for the rest of the year.

Our 2019 hope that the industry would ship 2 GW came true a year late – in fact over 2.3 GW went out in 2021. Total units were up too – by 4,000 to nearly 86,000. There is no change in the main contributors though – Hyundai and Toyota dominate the power side and Ene-Farm the units, though portable power showed an uptick. PEM fuel cells for all mobility uses are 86% of the MW – even more than 2020.

But the interesting movements are not in these headline figures – though they offer clues. The two car models being shipped are helping prove the technology for all transport, including stimulating the very encouraging uptake of heavy duty solutions. The increasingly broad PEM supply chain also plays a development role – offering options for different end-user players and gradually reducing cost.

Hyzon continues its meteoric rise in heavy duty, mainly trucks for now, announcing financing, partnerships and early shipments on a regular basis. Ever more Hyundai FC trucks run around Switzerland, quietly getting on with the job of delivering goods, and truck numbers nearly doubled in Europe overall, also increasing substantially in China. Cellcentric and Toyota continue their development pathways in the sector, and Nikola seems to have survived its near-death experience and is pushing forward with Iveco. And nearly all the major truck manufacturers in Europe have now called for the creation of a network of around 300 high-performance HRS by 2025, rising to 1,000 by 2030. A notable dissenter is Scania, which now seems to have set its path on renewable fuels and battery electric vehicles.

Global FC bus shipments dropped slightly in 2021, to around 1,100 units, with a fall in Chinese demand; Europe saw a doubling to around 220.

Rail appears set on a slow and steady growth path, with Alstom and Siemens entrenching further with Cummins and Ballard respectively, and players from India to North America exploring the option. Around 50 train units are anticipated globally by the end of 2022, and more are being ordered.

Fuel cell activity is also increasing in shipping, with Doosan (using Ceres technology), Prototech/Clara (Sunfire stacks), TECO 2030 (AVL fuel cells) and Topsøe. Larger SOFC and PEM systems are now being researched actively for propulsion, not just hotel loads.

Timelines in aviation are just as long, but announcements from Airbus with Elring Klinger, PowerCell, ZeroAvia and Universal Hydrogen (with Plug Power) are only a part of the ongoing activity, with regional flights the initial target.

And Plug is continuing its 'total system' mission – it is now the largest global supplier and user of liquid hydrogen, its aviation play is one of many it has all across transport, and it is looking to scale up the hydrogen production capability from its Giner acquisition.

That scaling is not just for Plug's own use. Hydrogen roadmaps and targets have not only continued to appear but have increased in ambition. Plug intends to be one of many suppliers of equipment into the emerging market, and likely also of the hydrogen produced. They are one of only a few players to do both fuel cells and electrolyzers, though that is changing. Cummins is a long-term player in both; Sunfire too; Bloom has partially rediscovered its roots and is making SOEC as well as SOFC, and other SOFC companies like Ceres and SOLIDpower have similar developments ongoing. Even start-ups like Bramble now target this space.

This set of multiple target markets and even business models partially reflects the earlier days of the industry, when Ballard, *inter alia*, covered everything from portable power to marine and large stationary.

It also reflects the not-yet-mature state of the sector, where the final integrator is also sometimes the system developer, and opportunities to increase sales by serving multiple end-users with essentially identical technology are valuable. Hyundai and Toyota are both increasing their flexibility to provide standard offerings across transport and into stationary settings. The other crucial driver of the broad array of different end-uses, and especially the 'systems thinking' approach taken by companies like Plug, is those hydrogen roadmaps.

Even before the devastating events of early 2022 savaged the energy markets, COP26 in Glasgow was sending the latest desperate signals of the urgency of change away from any emissions of CO₂. Fuel cells have always been an option for better end-use efficiency and lower pollution, but need clean – ideally renewable – hydrogen to complete the low emissions system. By coupling the demand signals of ever-tighter emissions regulation with the supply signals of hydrogen roadmaps, strategies and funding, the dots are starting to be joined.

Although these roadmaps and strategies inevitably have long-term horizons (2030-2040), the required policies will be supportive to the industry. Green H₂ is set to be produced in much greater volumes, with trading of H₂ as a commodity a realistic possibility. Fuel cell players are responding to deliver ever-larger plants, designed to be fuelled by H₂ rather than natural gas. The end-uses are likely to demand more hydrogen than can come from green sources for a while, however, so the window for fuel cells using natural gas could remain open for some time. Advent has even launched a fuel cell specifically to reduce wellhead methane that would otherwise be emitted.

The most developed strategies have specific targets for electrolyser capacity, ambitious power-to-H₂ and e-fuels plans, and commitments to policy level support, recognising that primary legislation will be required to reach the targets. These ambitions start to offer direction, and more importantly some certainty, for suppliers, end-users and investors.

Investment in hydrogen companies generally has been very high, and some fuel cell companies have benefited. More share offerings (valued at nearly US\$3bn) took place in 2021 than ever before, while JVs, MoUs and strategic partnerships proliferate. New entrants are faring well, as are many established companies. Many are opening regional offices, to serve new markets.

The dominance of PEM in MW terms helps with cost reduction in the technology; the need for MEAs for all of those units should help still further, as the MEA volumes scale in multiples of stack volume. Other cost reductions come with increasing standardisation and from new supply chain entrants with know-how in mature markets.

Other positive signs come in a variety of regions – the number of fuel cell forklifts going to Europe increased by 340% in 2021, to nearly 3,500 units. Ever-larger materials handling platforms are being targeted, such as those at ports. Portable power from leisure through to military uses remained strong, even growing slightly.

Micro-CHP remains a tough sell though. Unit sales to Japan (Ene-Farm) and to Germany (KfW 433) were muted in 2021, possibly related to ongoing pandemic restrictions. Though from July, German grant eligibility was extended to large companies installing fuel cells in non-residential buildings, which may have a small positive impact. Korea's programme does not seem to have got far off the ground, despite leading in several other areas. The implementation of the new Hydrogen Portfolio Standards may help.

What next? The race to decarbonise, the unvanquished virus, economic slippage and the energy market turmoil thrust upon us render our crystal ball not just opaque but full of thunderclouds. The general mood in the industry is good, however, with full order books for many and a sense that fuel cells offer a good option to address several of the issues above. The ride could be wild though – is anybody planning a fuel cell-powered rollercoaster?

About the Review

Applications

To allow year-on-year data comparisons, we base our categorisation of shipment data on that defined by FCT. For applications, these categories are Portable, Stationary and Transport, defined as follows:

Application type	Portable	Stationary	Transport
Definition	Units that are built into, or charge up, products that are designed to be moved, including small auxiliary power units (APU)	Units that provide electricity (and sometimes heat) but are not designed to be moved	Units that provide propulsive power or range extension to a vehicle
Typical power range	1 W to 20 kW	0.5 kW to 2 MW	1 kW to 300 kW
Typical technology	PEMFC DMFC SOFC	PEMFC MCFC AFC SOFC PAFC	PEMFC DMFC
Example	<ul style="list-style-type: none"> • Small 'movable' APUs (campervans, boats, lighting) • Military applications (portable soldier-borne power, skid-mounted generators) • Portable products (torches, battery chargers), small personal electronics (mp3 player, cameras) 	<ul style="list-style-type: none"> • Large stationary prime power and combined heat and power (CHP) • Small stationary micro-CHP • Uninterruptible power supplies (UPS) • Larger 'permanent' APUs (e.g. trucks and ships) 	<ul style="list-style-type: none"> • Materials handling vehicles • Fuel cell electric vehicles (FCEV) • Trucks and buses • Rail vehicles • Autonomous vehicles (air, land or water)

Portable fuel cells encompass those designed or able to be moved, including small auxiliary power units (APU); Stationary power fuel cells are units designed to provide power to a 'fixed' location, also including APUs on e.g. trucks and large vessels; Transport fuel cells provide either primary propulsion or range-extending capability for vehicles.

Fuel cell types

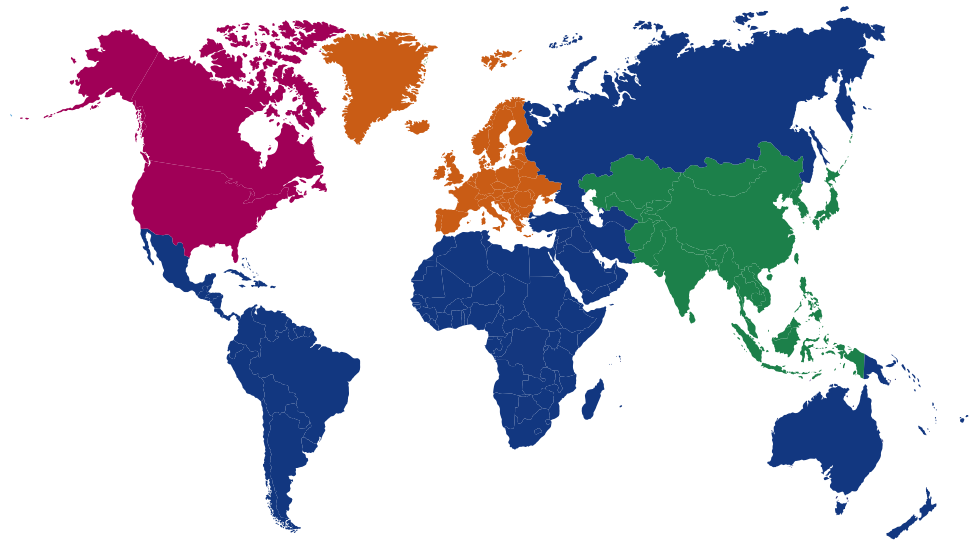
Shipments by fuel cell type refer to the six main electrolytes used in fuel cells: proton exchange membrane fuel cells (PEMFC), direct methanol fuel cells (DMFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC) and alkaline fuel cells (AFC). High temperature PEMFC and low temperature PEMFC are shown together as PEMFC.

Explanations of these six main types of fuel cells can be found on the archive of the FCT website <https://web.archive.org/web/20220119090819/http://www.fuelcelltoday.com/technologies>

Geographic regions

We maintain FCT's four main geographic regions of fuel cell adoption: Asia, Europe, North America and the Rest of the World (RoW).

- RoW
- Asia
- North America
- Europe



Reported shipment data

E4tech has been publishing this Review for eight years now. Tables of data can be found at the back of this Review going back to 2016. Editions of the review prior to 2018 included historical information from Fuel Cells Today dating back to 2012. Data are presented for each year in terms of annual system shipments and the sum total of those systems in megawatts, both divided by application, region and fuel cell type as described in the section below.

Shipment numbers are rounded to the nearest 100 units and megawatt data to the nearest 0.1 MW. Where power ratings are quoted, these refer to the electrical output unless stated otherwise. In general, we use the nominal, not peak, power of the system, with the exception of transport. Because continuous power depends heavily on system design and how it is used, we report peak power for these units.

The reported figures refer to shipments by the final manufacturer, usually the system integrator. In transport we count the vehicle when shipped from the factory. This is because the shipments of stacks or modules in a given year can be significantly different from the shipment of final units (e.g. vehicles) in the same timeframe. We use stack and module shipment data to help us sense-check numbers between years. The regional split in our data refers to the countries of adoption, or in other words, where the fuel cell products have been shipped to, not where they have been manufactured. Where possible, we do not include shipments for toys and educational kits.

Data sources and methodology

We have been in direct contact, either verbally or in writing, with over 50 companies globally for this report. Some of these are not yet shipping other than small quantities for tests but of those that are shipping very few declined to give us primary data.

For those – but also for others, as a way to sense-check our numbers – we have collected and cross-referenced data from publicly available sources such as company statements and statutory reports, press releases, and demonstration and roll-out programmes, in addition to discussions with other parties in the supply chain. We do not count replacement stacks in existing applications, and where possible we also do not count inventory, only systems that are shipped to users.

Our dataset is based on firm numbers for the period January to end of September 2021 and in most cases as late as December 2021. Where we do not have full year data, we use forecasts shared with us by individual companies or forecasts prepared by us in discussion with industry. We will revise data for 2021 in our 2022 edition as appropriate. We have revised the figures for 2020 in this report: Unit numbers were decreased by 0.8% and MW numbers increased by 1.4% compared to our published 2020 forecast. The main changes relate to fewer Ene-Farm units shipped, more buses to South Korea, and slightly fewer trucks shipped to China than initially forecast, after final data for 2020 became available, together with an uplift in the fuel cell stack power applied to commercial vehicles in China.

We thank all of the companies that have responded to our requests for data and clarification. If you ship – or plan to ship – fuel cell systems and we have not been in touch with you, please do contact us so that we can further improve our coverage for future editions.

Looking back on 2021

2020 was tough for everyone. 2021 was just as tough for some, though vaccines and supply chain reconfiguration helped a few regions to partially recover. Supply chain modifications also helped the fuel cell industry regain some of its previous trajectory and ship a record amount of power. Car sales were back up, but particularly important for the sector was the multitude of announcements in the heavy-duty realm. Increased numbers of fuel cell trucks will help to drive down costs of components, and improve investment in infrastructure. Buses will contribute some of the same support, while their use also informs the public and local authorities of the benefits fuel cells can offer.

The 'battery vs fuel cell' question remains hard to answer. We maintain that this is partly because it is the wrong question! BEV sales continue strong, despite some headwinds from supply chain development, critical materials availability and a retrenching of production to reduce geopolitical risk. But a significant number of major players (e.g. Bosch) continues to invest in hydrogen and fuel cells as part of the energy transition, even for vehicles. Nothing in the work we do suggests that fuel cells are going away – quite the opposite.

As in all industries, fuel cell actors in 2021 were partly hampered by travel restrictions. Not being able to visit suppliers, installation sites and conferences slowed development, deployment and discovery. Innovative and sometimes highly effective online solutions were implemented, but it seems most people prefer a chance to discuss face-to-face. A lot of catching up will be happening through 2022!

'Big system' strategies continued to evolve through 2021. When the industry began, many players had to do everything because the supply chain simply didn't exist. Once hardware supplies were available, it was often gaps in the business model chain that required companies not only to make stacks, but also systems, and organise fuel provision, and deal with the consumer. Now the benefit of doing all of those things is to manage the end-to-end economics. Being able to optimise the system size, the fuel delivery, the timing and other aspects can make the difference between a bankable project and a loss-making one.

And since fuel cell projects are now often part of bigger hydrogen energy projects, driven by governments increasingly demonstrating their realisation that hydrogen is an important component of a low carbon future, systems thinking will remain essential.

At the other end of the spectrum we see more standardisation. "You can have any size fuel cell as long as it's 100 kW" could be today's equivalent of the Model T Ford's original colour choices (black). While this reduces the level of optimisation possible, it means the supply chain can be more robust, and costs can come down through repeat production, which improves the economics from the other direction.

"How much does a fuel cell cost?" is still a tricky question to answer though. While increasing numbers of companies have some sort of list price, pricing remains somewhat confidential in most cases, and subject to bilateral negotiation. And of course prices vary dramatically by fuel cell type and system need. Still, the numbers we see are coming encouragingly down a conventional learning curve, and that should continue with the increasing manufacturing capacity announced by Bosch, cellcentric, Cummins, EKPO, Symbio and others. But the ongoing proliferation of joint ventures is symbolic of the need to pool talent (and risk), even as the opportunities come ever closer to market.



2021 saw just over 2.3 GW of fuel cells shipped globally, a 173% increase on 2020, particularly impressive given the COVID backdrop. And the announcements and other signs from 2021 bode well for the numbers in 2022.

Corporate developments

More money is flowing into the fuel cell sector, and more significant partnerships are developing. What we find interesting is the breadth of investments in 2021 (almost every type of fuel cell and every end-use market) as well as the increasing number devoted to raising production levels or putting units out for sale, rather than early-stage research.

Fundraising

In January, Plug Power successfully concluded a US\$1.8 bn public offering of 28m shares, one of the largest primary bought offerings in recent years and right after Plug's US\$972m public offering in November 2020. It will use the proceeds to push its transition to the broader green H₂ market, with fuel cells remaining a key component. At the end of 2021 Plug acquired Frames Group, a system integrator, mainly for electrolyser integration.

In February, Ballard's public share offer brought in US\$527m. This also followed a November offering – US\$386m. Funds will go towards growth and acquisitions, like the purchase of the UK's Arcola Energy, now Ballard Mobility Solutions, late in 2021.

Also in February, European HRS designer and manufacturer Hydrogen Refueling Solutions raised €84.6m in its IPO on Euronext Growth Paris.

March saw Ceres raise £181m (US\$248m) from existing investors Bosch and Weichai, and from a wider share issue to the public. 25% will be used to drive the SOFC activity, 55% to grow the solid oxide electrolyser offering, and 20% across the business.

After 20 years, Loop Energy is starting to commercialise its eFlow FC. An IPO on the Toronto Stock Exchange in February raised CA\$100m (US\$79m), and in March the logistics company Rheintal-Transporte ordered 20 units; significant given the slowly-building European market. Loop already had an agreement with a Slovenian actor focused on network resilience, for more than 50 eFlow modules for integration with Ecube's green H₂ thermal energy storage solution, 'Hydrogenium'.

In late 2021, SAIC Motor, China's largest home-grown carmaker, announced an intention to spin off Shanghai Hydrogen Propulsion Technology, its business unit focusing on H₂ fuel cell technologies, by listing it on the Shanghai Star Market. A major competitor, Beijing SinoHytec, is also listed on the Star Market, following its IPO in August 2020.

In July, HDF Energy raised €132m (US\$156m) in an IPO to help develop its first factory for utility-scale (1 MW+) FC systems, using PEMs from Ballard, and to invest in the equity of projects, initially in Mexico, Barbados and Chile. HDF's plants will provide continuous or on-demand electricity from wind or solar, combined with fuel cells.

Belgium-based Alkaline Fuel Cell Power joined AFC Energy and GenCell as listed companies on 16 July, on the NEO Exchange. All three share some roots in Belgium's space industry, though Fuel Cell Power's focus is on micro CHP systems based on alkaline FC technology. GenCell also raised capital, up to US\$39.5m through the private placement of shares, including participants such as the Harel Group and Migdal Insurance.

New South Wales-based H2X Global is targeting a 2022 IPO. Its Warrego Ute, an H₂ FC Ford Ranger derivative to be launched in 2023, has a claimed range of 750 km and over AU\$50m (US\$36m) in pre-orders from "enthusiastic early adopters".

Joint Ventures and Partnerships

2021 also saw an increase in partnering activity, much of which is outlined elsewhere in the Review.

In April, EKPO Fuel Cell Technologies, the 60:40 JV between ElringKlinger and Plastic Omnium was launched following antitrust approvals. The company site in Dettingen/Erms, Germany can already produce up to 10,000 stacks a year, and EKPO aims for 10-15% of the automotive fuel cell market by 2030, realising revenues up to €1bn. ElringKlinger and VDL Bus & Coach in the Netherlands have also agreed a strategic partnership to develop and industrialise fuel cell stacks and systems for mobile and stationary end uses, such as gensets.

Hyundai Heavy Industries partnered with AVL to develop fuel cells of 200 kW to 1 MW for ships by 2025. Bramble Energy and MAHLE continue collaborating on Bramble's PCBFC technology.

Acquisitions

In March, Advent Technologies purchased UltraCell, the fuel cell division of BrenTronics. Then in July Advent acquired the fuel cell businesses of Fischer Group, for €52m, including SerEnergy.

In May, Alstom bought Helion Hydrogen Power, renamed as Alstom Hydrogène SAS. It is based in Aix-en-Provence and covers the entire value chain of high-power PEM FCs: design and development to manufacturing, engineering support and customer training. Helion presently produces bespoke rather than volume product, for energy and transport markets.

And US Hybrid, making FC engines for medium- and heavy-duty commercial fleet applications, was acquired in June for US\$50m by New York's Ideanomics, with a mission to accelerate the adoption of commercial EVs.

Business Growth

In February, Danish HT-PEM Blue World Technologies took possession of its Aalborg production site and closed €6m investment. Capacity is 5,000 units (50 MW) a year, with initial pre-series production set for late 2021. BWT also acquired Danish Power Systems, bringing core components in the FC value chain in-house. Vaekstfonden and DEUTZ have each invested €7.5m in BWT.

In April, Hyzon Motors set out plans to build an MEA production line for commercial vehicles at its new Innovation Centre in Bolingbrook, Illinois. At full capacity, MEAs for up to 12,000 H₂ fuel cell trucks a year will be produced. The company also officially commenced trading on the Nasdaq Global Select market in August, following completion of a combination with SPAC vehicle DCRB.

September saw Proton Motor announce a collaboration with Aumann AG, a specialist in automated production lines, to expand series production of hydrogen fuel cells, and in September, Symbio launched Symbio North America, to target the US market.

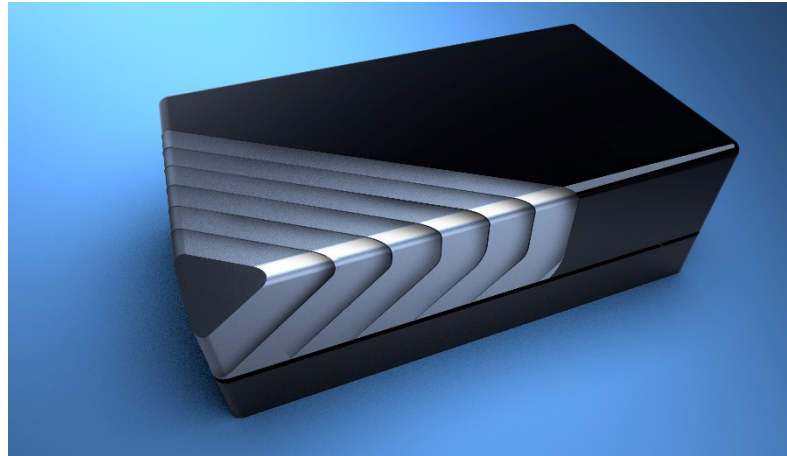
In October, Plug Power announced a new regional HQ in Germany's North Rhine-Westphalia, to drive sales across Europe. The 70,000 ft² facility will have 30 employees, house an innovation centre with engineering labs and technical support and training, and be a logistics hub. Renault's main e-mobility factory, at Flins in France, will assemble fuel cells and hydrogen refuelling stations for Renault and Plug's JV HYVIA, to offer three FC-powered Master Large Van models.

Standardising products

2021 saw more companies pushing scalable FC modules for a range of cross-cutting applications.

Hyundai's new sub-brand, HTWO, covers its H₂ modules for the NEXO and racing cars. It plans a hybrid powertrain for unmanned air cargo by 2026.

In February, Toyota announced a compact mobility module (trucks, buses, trains and ships, but also stationary power), in four variants. Type I is vertical and Type II horizontal, power is 60 or 80 kW. This responds to FC system developers looking for standard modules to adapt to their own products.



Rapid charger application

With battery vehicle uptake on the rise, the somewhat ironic use of fuel cells to deliver resilience to rapid charging networks is also rising.

January saw more details of the strategic partnership between UK-based AFC Energy and ABB. They plan to launch a bespoke high-power, ultra-rapid EV charging product for distribution through ABB's market channels, for use at logistic hubs, bus depots, and for marine markets (ferries).

AFC Energy is not alone. In November, GenCell Energy signed an agreement with EV Motors, an Israeli importer of BPEVs, chargers and energy storage systems, to create autonomous HEV charging stations, replacing fossil fuel backup generators with NH₃-fuelled AFCs. And Pure ETCR-real electric car racing has agreed with WSC Group and HTWO that the charging process for all cars competing in the world's first all-electric, multi-brand touring car series will be powered by HTWO's hydrogen twin fuel cell generator.

Cars and vans

Hyundai and Toyota: keeping the pace

2021 saw the highest number of fuel cell passenger car shipments to date, with global sales above 15,800 vehicles – almost twice 2020. Not surprisingly, most deployments came from the Hyundai NEXO and the new Mirai from Toyota. Deliveries of the former increased to over 9,300 units in 2021, mainly in South Korea, while the latter has been well-received in Japan and overseas. Both vehicles are also in the running for range records.

In April, the NEXO travelled the then longest distance, 887.5 km (551 mi) by a hydrogen powered vehicle on a single tank, but a few months later, the new Mirai set a new Guinness World Record with an unprecedented 1,360 km (845 mi) – three times or more the range of a battery-powered car. This may have put the pressure back on Hyundai, which has announced plans to increase significantly the range of its next generation NEXO, expected by 2023.

Honda is out for now

In August, Honda discontinued production of its Clarity Fuel Cell, with the remaining stock being available for lease through 2022. The less than 300 units shipped in 2021 barely figure in the overall volume of fuel cell car shipments for the year. The Japanese car maker keeps developing next generation fuel cell systems together with GM, though no news has emerged regarding their Fuel Cell System Manufacturing joint venture, initially set to start operations around 2020.

Meanwhile, GM is working actively to deploy its HYDROTEC fuel cell power cubes beyond cars, in truck, rail and aerospace. Daimler continues to keep its fuel cell focus away from cars, in April announcing the creation of the JV cellcentric with Volvo Group, focused on heavy-duty trucks.

New cars on the horizon

BMW is testing its iHydrogen NEXT concept car on European roads and presented its iX5 Hydrogen vehicle at the IAA Mobility 2021 motor show in Munich. A small series of the iX5 Hydrogen will be produced as demonstrators from late 2022, using stacks arising from BMW's product development cooperation with Toyota. In contrast, the latest news suggests Audi might no longer include fuel cells in its future product portfolio, which could terminate the development of the H-tron SUV concept.



Jaguar Land Rover has teamed up with R&D partners to develop a fuel cell prototype vehicle, based on the new Land Rover Defender. Road testing was scheduled to begin in the UK in late 2021, with a focus on validating key characteristics such as fuel consumption and off-road capabilities.

In France, in June, start-up Hopium presented the first prototype of its Mâchina, a high-end fuel cell sedan, during the Viva Technology week in Paris. The first 1,000 units have been pre-booked, though the vehicle will not be commercially available until 2025.

Danish FC start-up Blue World Technologies (BWT), is collaborating with Karma, the California-based luxury electric car company, with plans to integrate methanol HT-PEM systems in Karma GS-6 vehicles for testing and validation. This adds to BWT's partnerships with Chinese electric car maker Aiways and German engine manufacturer Deutz. BWT continues to expand its factory in Aalborg, aiming for an annual capacity of 500 MW by the end of 2023.

Europe's fuel cell car numbers are growing... slowly

Around 1,000 fuel cell passenger cars shipped to Europe in 2021, mostly Mirais, with just over 300 NEXOs. Building on demonstrators placed with influential stakeholders, the commonest real-world use case is emerging as fuel cell taxis, which are slowly building in numbers in major cities across Europe. 100+ Mirai taxis now run in Copenhagen, supporting the city's goal of zero-emission taxis by 2030. Oslo has similar plans. In Paris, H₂ mobility operator Hype (with Total as a 20% shareholder) envisages 10,000 taxis by the 2024 Olympics. Madrid wants to replace at least 1,000 internal combustion taxis with Mirais by 2026.

Little news from America

Honda shipped around 270 Clarity Fuel Cell cars to the United States, but this will now fall away. The launch of the new Mirai model boosted overall fuel cell passenger car sales to the US to over 3,300 units in 2021, mostly destined for California. This is a big jump over last year's shipments of around 940 passenger cars overall to the country.

Canada's efforts to raise fuel cell vehicle awareness appears to be paying off. Ride-sharing app Lyft Canada and Toyota Canada are partnering to make new Mirais available to Vancouver drivers and riders. Also in British Columbia, zero emissions courier Geazone announced the addition of 40 Mirais to its fleet

In August 2021, Symbio North America was formed, to focus on light-duty, commercial medium- and heavy-duty vehicle H₂ solutions for the region.

Outside the large number of fuel cell cars now accreting to the US, vans are very much secondary to heavy-duty trucks in unit numbers and in interest. In April, Linamar Corp., the automotive components multinational, began evaluation of four fuel cell delivery vans in their contract with the Center for Transportation and the Environment (CTE), the manager of the Next Generation Fuel Cell Delivery Van Deployment Project for CARB. The vans will be used by UPS in an in-revenue service trial in California. Roush CleanTech supplied the overall vehicle and system design, integration, build and commissioning for the vans, with stacks from Ballard. The UPS vans use a Ford F-59 chassis with a modest 150 mile range. Funding for the trial was first announced back in 2018.

Asia continues to lead

South Korea is now extending its lead in the manufacture and deployment of fuel cell cars, driven by supportive government policy. A record 8,500 NEXOs were shipped in the country in 2021, and this figure looks set to increase substantially in the coming years. By the end of 2023, Hyundai plans to ramp fuel cell system production up to 100,000 units a year, coinciding with the expected roll out of the next generation NEXO. The firm's unveiled fuel cell vehicles extend to the Genesis premium brand GV80 SUV concept, seemingly still under development, and the high-performance sports car Vision FK, as well as the ELEC CITY Bus. Its Hydrogen Vision 2040 says it aspires to integrate fuel cells in all commercial vehicles including LCVs by 2028.

In Japan, the highly anticipated new Mirai is selling well, with almost 2,400 deliveries the country in 2021 out of a global total of nearly 6,000 Mirais. The vehicle was showcased during the Tokyo 2020 Olympics, celebrated in 2021 due to the pandemic, where 500 Mirais transported staff and athletes among venues. Following this trend, China imported 140 new Mirais to be used in the Beijing 2022 Winter Olympics. More than 1,000 fuel cell vehicles including cars, buses and support trucks.



Momentum in China increasing slowly

The Chinese fuel cell car market is growing very slowly, with around 60 units across the year in 2021, in the context of a growing New Energy Vehicles sector at 3.3m electric vehicles, out of a total 21.5m passenger cars across the country. Even light-duty commercial shipments are small, with the emphasis mainly on buses and medium and heavy-duty trucks.

SAIC is expected soon to scale up production of its multi-purpose vehicle, the Maxus EUNIQ 7. The fuel cell system for the vehicle is produced by SAIC's H₂-focused subsidiary, Shanghai Hydrogen Propulsion Technology, which is to be spun-off, going public, to raise funds for its anticipated growth.

Great Wall Motor unveiled its H₂ energy strategy, featuring a holistic view across the H₂ value chain, planning to roll out its first fuel cell SUV in 2022 and aspiring to become a global leading maker of H₂-powered vehicles by 2025. Other Chinese OEMs released fuel cell versions of existing car models, including GAC's AION LX Fuel Cell, FAW's Hongqi H5 FCV and Changan's CS75 Hydrogen. Many of these cars participated in the first China Hydrogen Car Super League.

The Chinese capital envisions over 10,000 fuel cell vehicles on its roads by 2025, part of an ambitious plan to develop indigenous H₂-based capabilities and industries.

Is the rest of the world moving fast enough?

FCEVs became available in Australia in 2021, with tens of cars shipped largely to public entities. The governments of the Australia Capital Territory and Queensland added 20 and 5 NEXOs to their fleets, respectively. Another NEXO was delivered to the Queensland police, while the country's national science agency took delivery of a new Mirai.

Elsewhere, fuel cell cars are expected to be on New Zealand roads soon, the Mirai made its UAE debut at the Expo 2020 (postponed to 2021) and the NEXO received type-approval certification in India.

Fuel cell microcars on the go

In February, Welsh FCEV developer Riversimple and Siemens UK signed an MoU with a focus on the full-scale manufacture of the Rasa microcar. In Sweden, micro fuel cell company myFC has been selected to participate in public funded projects to develop small, clean and efficient vehicles like pod taxis. And in June, H2e Power PVT announced plans to build India's first fuel cell three-wheeler, collaborating with Canadian solid state hydrogen storage provider H2M, to serve intercity transport.

We are expecting more fuel cell racing

Fuel cell car racing keeps hitting the headlines. The China Hydrogen Car Super League kicked off at the Shanghai International Circuit in September, on the same day as the China Touring Car Championship race. Eight fuel cell cars and trucks from four OEMs took part in the event. Despite heavy rain, all the vehicles successfully completed the race, with final victory for the FAW FAW Hongqi H5 sedan.

In the Netherlands, Hyundai formed a partnership with Forze Hydrogen, a student team from Delft University of Technology specialised in H₂ electric racing (becoming something of an annual event). Students can consult with experts from the Hyundai Motor Europe Technical Centre while developing their Forze IX car, expected to be finalised in 2022 as the world's fastest fuel cell racing car.

In March 2021, the Alpine F1 Team and Plug Power announced the formation of partnership to explore mobility solutions in motorsport and road cars. The net zero carbon championship Formula E is starting to consider its Gen4 regulations, inviting views on how to shift to hydrogen technology to attract new manufacturers to the grid in five years' time. This would add to the HYRAZE League and MissionH24 competitions,

scheduled to launch in 2023 and 2024, respectively. In terms of rallies, German engineering company FEV is now supporting French group Green Corp Konnection on the development of a fuel cell system for its e-Blast H₂ vehicle, to be introduced in the 2024 Dakar Rally.

Big plans for fuel cell vans

In Europe, a growing market opportunity is for fuel cell vans, alongside heavy-duty trucks. This contrasts with North America, where the sole focus of domestic fuel cell vehicles is on heavy-duty, and China, where an initial medium-duty focus is becoming heavier.

French brands continue to drive the fuel cell light commercial vehicle (LCV) market in Europe. Most of the activity is centred on Renault and Stellantis NV, in vans. Outside of Europe, there is no real activity in this area.

Renault released the fuel cell variant of its compact van, as the Kangoo ZE Hydrogen, late in 2019 and planned release of the Master ZE Hydrogen van early in 2020, now abandoned. The designs are light hybrids, with 5 kWe stacks and CH₂ storage from the Symbio JV with Michelin and Faurecia. The range extender offers up to 370 km range from a single charge in the Kangoo ZE Hydrogen (140 km more than the all-electric version) and was to be 350 km range in the Master ZE Hydrogen (up from 110 km).

By the end of 2020, over 300 Kangoo ZE Hydrogen vans had been shipped across France mainly, and in Europe. In contrast, over 57,000 Kangoo ZE all electric vans were sold in Europe since 2011. In January 2021, Renault announced a new JV with Plug Power for supply of fuel cell systems, seeking to create in France a vertically-integrated mass manufacturing centre for fuel cells for LCVs. The Hyvia JV with Plug was formalised in July 2021.

Hyvia plans offer to three new LCV models: The Master Van H2-TECH, a panel van based on the Renault Master (with 12 m³ cargo volume and a range of up to 500 km); the Master Chassis Cab H2-TECH for transporting larger goods (19 m³ cargo volume and a range up to 250 km); and the Master Citybus H2-TECH (able to carry up to 15 passengers, with a range of 250 km). The stack for the three van models is upscaled to 30 kW and is combined with a 33 kWh battery. The range is set by the amount of H₂ carried: 6 kg in the Master Van H2-TECH, 2x 1.5 kg in the Master Chassis Cab H2-TECH, and 4.5 kg in the Master Citybus H2-TECH.

Having unveiled the Master Van H2-TECH prototype, Renault expects the van to become commercially available in 2022, followed by the chassis cab and minibus. The JV foresees stack assembly at Renault's Flins plant from late 2021.

Hyvia plans to offer electrolysis solutions (a major competence brought from partner Plug), mobile storage stations and, from the end of 2021, HRS. The HRS, also to be assembled in Flins, will be available for purchase or rental. The JV is targeting 30% market share in fuel cell LCVs in Europe, with turnkey mobility solutions, including delivery of fleet management and maintenance services.

Quite independently, Mahle Powertrain is helping to optimise the integration of Bramble Energy's Printed Circuit Board Fuel Cell (PCBFC) technology within the powertrain of a Renault Kangoo ZE. The vehicle will showcase the claimed reduced-cost, high performance potential of Bramble's high power density liquid-cooled fuel cells. As with the mainstream Kangoo ZE Hydrogen, the vehicle is fitted with a 5 kW stack. At the same event, AVL and Ford presented a prototype of a fuel cell Ford Transit, alongside a digital twin to validate the key functional features.

The French JV Symbio began construction in March 2020 of its new fuel cell factory at Saint-Fons, next to its Venissieux site, in Lyon, planning to extend its current production capacity of 50,000 units a year to 200,000 StackPack units a year by 2030. The expansion is in line with its own ambition to become a leader in fuel cell systems for global hydrogen mobility. The 5kW StackPack modules are scalable, to meet the needs of light commercial vehicles and the 40-300 kW output range of its H2Motive portfolio for heavy-duty vehicles. Symbio has a target of €200m (US\$238m) turnover in fuel cells by 2025 (for cars, buses and trucks) and 12% market share and €1.5bn turnover by 2030. The Lyon base has access to 6 tpd green H₂ from the Auvergne-Rhône-Alpes Hydrogen Valley project.

In September 2020, former PSA Group announced the launch of a fleet of H₂ fuel cell utility vehicles, fitted with Symbio 45 kW mid-range extenders, 10.5 kWh lithium-ion battery storage and 4.4 kg H₂ storage, delivering 400 km (248 mile) range, for trade customers in 2021. The Peugeot e-XPERT van offers a 6 m³ cargo volume, the same as the diesel and all-electric equivalents. The 3 min refuelling time is a major advantage over the all-electric van.

Around 100 Stellantis vans were expected to be sold over the year. By the end of 2021, a single Peugeot e-XPERT Hydrogen van had been delivered to Michelin's green mobility solutions subsidiary Watèa, a single Citroën ë-Jumpy Hydrogen van to the French utility Suez, and a single Opel Vivaro-e Hydrogen van to the domestic appliance maker, Miele, in the Rhine-Main region of Germany. The vehicle will perform "daily field service" in the firm's domestic market. We can expect to see many more of these vehicles in 2022.



Finally, there was an unexpected stay of execution of production of DHL/Deutsche Post's all-electric StreetScooter to the end of 2022, due to increased demand, but this did not extend to the H2 Panel Van. However, in June 2021, EKPO Fuel Cell Technologies was awarded an exclusive, multi-year contract in the high double-digit million Euro range, to supply its NM5-evo PEM fuel cell stacks to AE Driven Solutions GmbH (the start-up that came out of StreetScooter, as it abandoned its FCEV programme), for urban delivery vehicles.

Hydrogen refuelling stations – pressure rising

As the world began to recover from the worst of the COVID pandemic, so the growth in refuelling infrastructure began to resume as was anticipated in last year's Review. IPHE logs 622 sites amongst its partners. LBST's 'H2Stations' website suggests 685 active HRS sites globally at the end of 2021. We expect to see more consistent growth going forwards as countries convert H₂ strategies into action.

By early December 2021, 91 H₂ refuelling stations were operating in Germany (mostly with a 700 bar capability), just missing the 2020 goal for a national network of 100; more than any other nation except for Japan and South Korea. The goal would have been achieved but for older stations, with obsolete facilities, being retired.



We observe that while many new stations globally continue to deliver 350 bar H₂, more are being updated to 700 bar, for use by commercial vehicles. The capacities of many HRS are also being updated, from around 200 kg/day H₂, nearer to 500 kg/day.

The number of operational stations in the rest of Europe also increased, France now at over 50, 18 in the UK (lower in some counts), and Switzerland with nine.

Spain is pushing ahead with its plans to expand its HRS network, although deployed numbers remain small (around 10). In December, Air Liquide and Redexis, the gas infrastructure provider, agreed to study the potential for a network of up to 100 HRS across Spain. Branded 'DESIRE H₂', the project will focus on logistics centres such as Barcelona and Madrid, and access points to the rest of Europe. The proponents are seeking IPCEI (Important Projects of Common European Interest) funding, alongside support from the Spanish government.

Also, in December, Nilsson Energy announced an intention to build out a 24-strong HRS network in Sweden by 2025, with financial support from The Climate Leap (Klimatklivet). The overall budget is estimated as SEK515m (US\$52m). In phase one, nine HRS are to be installed by 2024, with the remaining 15 to be installed by the end of 2025.

In August, Everfuel announced its intention to build its first HRS in Sweden, in cooperation with Trelleborg Municipality. The initial capacity is 120 kg/day, set to rise to 500 kg/day by 2027. The agreement is the first of eight potential stations in the Nordic Hydrogen Corridor project, which is co-financed by the European Union's CEF-program.

Trelleborg intends to invest €1.5bn in developing the green H₂ value chain in Europe, reaching €1bn revenue from the sale of H₂ to vehicles by 2030.

Away from the road sector, Deutsche Bahn intends to trial mobile rapid refuelling stations for use by H₂ trains in Germany. Supplied by Wystrach, these would allow trains to be refuelled within 15 minutes.

The majority of the 86 HRS in operation in North America are in California, with 60 HRS. In 2021, 11 new stations opened, but the number falls short of the CARB target of 64 units by 2020. The target of 200 HRS by 2025, intended to enable economies of scale and growth without further state incentives, is challenging.

In the supply chain, FirstElement, California's biggest operator of HRS, announced late in 2021 that it had received an investment from Air Water, the Japanese industrial gases company. This will be used to accelerate its roll out of HRS but is also expected to be used to strengthen the means of supplying these stations, including liquid hydrogen infrastructure and tube trailers.

In October 2021, the Hydrogen Heavy Duty Vehicle Industry Group (comprising Air Liquide, Hyundai, Nel Hydrogen, Nikola, Shell and Toyota) signed agreements with Tatsuno Corp. and Transfer Oil SpA to industrialise globally standard 70 MPa H₂ HDV high-flow (H70HF) fuelling components, which could be an important factor in stimulating uptake.

Japan is still ahead of other countries, approaching the 2020 target of 160 HRS during 2021. Continued decreases in capex and opex should keep Japan on target to reach 320 stations by 2025. The Olympics finally went ahead in 2021, a valuable opportunity to showcase the country's commitment to H₂.

Meanwhile, Korea's policy of providing subsidies and reducing regulations to stimulate construction of new HRS has, as expected, facilitated expansion to around 100 units by the end of 2021. But the target of 310 HRS by the end of 2022, as set out in its ambitious roadmap, looks more challenging.

The number of refuelling stations in China nearly doubled during 2021 from 37 to around 70, short of their goal for 100 units. H₂ vehicles were targeted in number at the Beijing Winter Olympics: 1,000 trucks and buses, for on-site logistics, with 30 HRS. A 20 MW electrolyser, installed by Shell, to support the vehicles started production in January 2022, just before the start of the Games.

Having established its hydrogen subsidiary, Sinopec reiterated its commitment to spend US\$4.6bn over the next 3 years to realise its H₂ strategy, targeting a refuelling capacity of 200,000 tonnes by 2025. Sinopec already operates over 30 HRS and had a further 60 under construction or in the planning and approval phase in 2021. By the end of the "14th Five-Year Plan" (in 2025), Sinopec aims to build 1,000 HRS, establishing itself as the premier supplier of H₂ to the transport industry in China.

Hiringa Energy is building a green H₂ production and refuelling network across New Zealand, focused on heavy transport, in partnership with Haskel. The first four (350 bar) stations on North Island are due to open in 2022, supported by NZ\$20m (US\$13m) from the Government's Infrastructure Reference Group.

Elsewhere, Saudi Arabia deployed its first HRS, a joint effort between Air Products and Aramco, at the Technology Center in the Dhahran Techno Valley Science Park. The Gulf States have major plans to expand H₂ production and export, and the HRS installation represents the first evidence for hydrogen's use locally to decarbonise transport.

In summary, 2021 provided evidence of gathering activity in the HRS sector, reflecting a revival of the global economy as the threat of COVID recedes. This trend looks set to continue into 2022, in line with developments in the wider H₂ mobility sector.



Fuel cell buses – going places

At COP26, 13 governments across the world committed to the objective that all new medium- and heavy-duty vehicles from 2040 would be zero emission, with 30% as an interim 2030 target. Buses fall into these categories, and although some countries and cities/regions have more ambitious target dates, recognising the environmental and social imperatives of clean transport, the future is indubitably Zero Emission.

Fuel cell electric buses (FCEBs) running on green H₂ are one of the few zero emission choices currently available. The current generation of FCEBs being delivered around the world are superior in almost all respects to those a decade ago. Indeed, FCEBs have (literally) travelled a long way over ten years: proving the technology; then demonstrating at least equal operational performance; now seeking to become cost-competitive with diesel. FCEBs are gradually being seen by operators and governments as an emissions solution that is on the cusp of viability, with an intrinsic rapid charge and long range compared to pure battery electric buses.

Around 150 fuel cell buses, shipped to Europe in the period 2012-2015, remain in operation. We estimate over 3,700 between 2015-2020 in China. So, like trucks, China dominates the segment. But there are plans to reach over 1,200 buses in Europe by 2025 (more in China), and 2021 was a bumper year for Europe, with over 200 new fuel cell buses shipped to the continent (and 158 registrations). But this compares to deliveries of 3,282 fully electric buses in 2021, with over 8,500 fully electric buses registered in the continent since 2012.

Europe – stepping up the gears

The European FCEB journey has been driven for two decades now by the Fuel Cell and Hydrogen Joint Undertaking (FCH JU). A venture between the European Commission and industry, the JU has set a fuel cell bus fleet in motion. FCH JU has now been replaced by the Clean Hydrogen JU, with more of a focus on H₂ infrastructure, but buses continue to be targeted. The journey began with Mercedes-Benz buses in project CUTE (2001-2006), leading to a series of demonstrator projects: HyFleet:CUTE (2006-2009), CHIC (2010-2016), HyTransit (2012-2018), High V.LO-City (2012-2019), and 3Emotion (2015-2022).

The most recent projects funded by FCH JU are JIVE and JIVE 2 (Joint Initiative for hydrogen Vehicles across Europe), aimed at driving down costs through economies of scale. With 300 FCEBs on order or in service, and series production now established for some models, the target of €625k (US\$725k) for a 12m single-decker bus is being met comfortably. So far, FCH JU has contributed €57m to the cost of deploying the buses, over more than 16 cities. 2021 saw FCEBs demonstrated in towns and cities new to the technology, Dublin, Villach in Austria, Brussels, Cascais in Portugal, Weisbaden, to name a few. Operator fleets are now reaching up to 50 units, most notably at RegionalVerkehr Koln, which has Europe's largest operational fleet.

The JIVE projects have a few more years to run. But funding is increasingly coming from other sources: Europe's LIFE project, the UK's Ultra Low Emission Bus scheme, from national governments like the Netherlands, or from the operators themselves.

FlixBus is also looking at fuel cell coaches, working with Freudenberg modules in the German project, Hyfleet. A consortium of 14 partners established project CoachHyfied at the beginning of 2021. The goal is to present solutions in the regional and long distance public transport sectors, developing and trialling six fuel cell coaches at two regions in Latvia and France over two-to-three-years.

Back in September 2020, the H2Bus Consortium of Everfuel, Wrightbus, Ballard, Hexagon Composites, Nel and Ryse Hydrogen, aimed to deploy 1,000 H₂ FCEBs in European cities at commercially attractive rates, along with the supporting infrastructure. The 600 buses in the first phase are meant to reach the focus markets by 2023, supported by €40m aid from the EU's Connecting Europe Facility (CEF). But no further news was forthcoming in 2021.

JIVE's success may be measured from performance improvements, cost reductions, and in the number of bus OEMs entering the market offering choices to operators. From a handful of OEMs in the early years, most now offer a fuel cell product, supplying 259 FCEBs to market between 2012-2021, including Van Hool in Belgium (96 units), Wrightbus in the UK (71), Solaris in Poland (38), Caetano (24) in Portugal, Safran in France (19), VDL in the Netherlands, and Mercedes-Benz in Germany.

WrightBus launched StreetDeck, their fuel cell double-decker with Ballard stacks, in Aberdeen, Birmingham and London (all JIVE supported), and also started trials in Dublin. In Brussels, Van Hool has begun demonstrations, and has supplied buses to Pau in the French Pyrenees.

Caetano has sold its H2.City Gold buses into Düren, Cascais, and Wiesbaden, and has demonstrated its buses in Paris and Madrid. Caetano and its stack provider Toyota has also joined with Snam, to bring buses into Italy's cities and regions.

Symbio announced a tie-up in April with the battery dominant bus OEM, Safra Businova, targeting 1,500 buses over the next ten years. The buses will utilise Symbio's 45 kW module as range extenders. Symbio has plans to construct Europe's largest fuel cell module factory capable of 60,000 units a year (for all platforms). A capacity of 200,000 units a year by 2030 was announced when the Symbio JV was formed in November 2019.

Solaris has been busy, demonstrating its 12 m Urbino Hydrogen bus in Frankfurt, Konin in Poland with local operator MZK, in the Czech city of Ústí nad Labem for operator Dopravni, in the city of Villach in Austria, and for ÖBB Postbus, and in the town of Neuenstadt am Kocher, in Germany. Solaris has also shipped its FCEBs to Köln and to Wuppertal in Germany, to Bolzano in Italy, and to Gelderland in the Netherlands, all as part of JIVE.



The latest OEMs to enter the European market are Hungary's GOLDI Mobility, working with Hy-Hybrid Energy to develop its H12 bus; Italy's Rampini, which launched its E80 hybridised 8 m bus, of which Cittavecchia has ordered two; and UK's ADL which has a 20-unit order for its 300-mile range double decker, the Enviro400FCEV, for Liverpool (being directly purchased through the

regional Transforming Cities Fund). In addition, Hyundai has demonstrated its 500 km (311 mi) range ELEC CITY Fuel Cell bus in Vienna and Munich.



Further afield, Russia is looking to fuel cells as a ZEV solution, as Moscow determined it would no longer purchase diesel buses. One solution is the newly unveiled KAMAZ 6290 FCEB, which will be tested from 2022.

Most converters of OEM chassis are focusing on electric and fuel cell trucks. But pepper motion GmbH, formerly e-troFit, plans to offer conversions of buses to fuel cell powertrains from 2024. The initial focus is on Mercedes-Benz Citaro C1 12 m and Citaro C2 12 m buses, with MAN A21 to follow.



Transdev Normandie is retrofitting a diesel Iveco Crossway bus, with Amiens based IBF H2, aiming to develop retrofit kits which can extend the average lifespan of buses from 14 years to 20-25 years. The German powertrain specialist IAV will contribute expertise in system safety and electronic interfaces. When finished, The Nomad Car Hydrogène will have a range of 450 km on a single refill and cover 380 km/day on the Evreux-Rouen Express route.

It takes about three months to retrofit a coach today in the IBF H2 workshops (excluding homologation). The expected short-term rate will be 10 vehicles per month. An HRS will be installed to support the project; the EAS HyMob du Vieil-Evreux station is expected to have a capacity of 50 kg/day.

The fuel cell module of choice remains those of Ballard, the latest, eighth generation being the FCmove-HD+. This module is reported to be 40% more compact than the previous 100 kW module, 30% lighter and with 50% fewer parts, with an increase in life of up to 40%. But with more OEMs seeking fuel cell power systems there are growing opportunities for others: Toyota is supplying Caetano with its Mirai based module (with Toyota making a strategic investment into CaetanoBus, in December 2020), Safra is using Symbio's modules, and ElringKlinger is working with VDL, independently alongside Ballard, providing modules to the CoachHyfied project.

North America - Moving up the gears?

Fuel cell buses should be more common across North America than they are now. Both the USA and Canada were amongst the first to develop and trial fuel cell buses from the late 1990s (the Georgetown PAFC bus); California deployed bus demonstrators across several transit authorities, while in 2009, BC Transit deployed 20 fuel cell buses from New Flyer (still going strong) in Whistler, Canada, the world's largest at the time. However, more than ten years later, deployments of FCEBs in North America has lagged both Europe and China. That could change.

In summer 2021, Democrats in the Senate pushed the Clean Transit for America Plan. An impressive US\$73bn was proposed to transition the nation's transit fleets, replacing over 155,000 commercial vehicles, from buses to vans, to ZEVs, both electric and fuel cells, and leading by example to 100% ZEV procurements by Federal agencies from 2035. With this – and critically if passed into law – the number of fuel cell buses could increase hugely. Yet today, FCEBs remain largely a specialist interest in the US and are down to one vehicle in Canada.

Progressive California hosts the largest FCEB fleet in the US, accounting for over 50 vehicles in 2021. Driven in part by State support, but more so than ever by tightening emissions regulations from the

California Air Resources Board (CARB), three transit authorities have led the effort: Alameda Contra Costa (AC) Transit in the Bay area, Orange County, and Sunline in Thousand Palms.

These transit authorities have operated FCEBs for more a decade or more, including legacy vehicles, such as Van Hool, plus newer New Flyer's Xcelsior CHARGE H₂ and EIDorado National-California (ENC), first and (from 2019) second-generation Axess-FC buses, in the 40 ft (12 m) length class.

The latest Xcelsior CHARGE H₂ is equipped with a Ballard FCvelocity-HD85 (85 kW) module (as a range extender), with a 160 kW Siemens motor, and 37.5 kg CH₂, coupled with battery storage (with the H₂, equivalent to 700 kWh), to give a 350-mile (563 km) range. A 60 ft (18 m) variant uses a 320 kW motor, 60 kg CH₂, and 1,000 kWh equivalent energy storage. Since 2019, New Flyer has begun delivering 25 buses to the three transit agencies as part of California Climate Investments (CCI), a Cap-and-Trade initiative focused on lower greenhouse and local emissions, and the economy.

The original Axess fuel cell bus was fitted with a Ballard FCvelocity-HD6 (150 kW) module, with a BAE Systems HDS200 (160 kW continuous, 200 kW peak) motor, directly coupled to the fuel cell stack, 50 kg CH₂, and an 11 kWh smoothing battery. By July 2018, ENC had supplied 20 FCEBs to transit agencies throughout California, and to SunLine Transit, for Ohio's Stark Area transit authority.

The latest Axess-FC model, dubbed the Battery Dominant Fuel Cell bus, has a smaller Ballard (85 kW) fuel cell and a larger (50 kWh) battery bank, increasing the range from 260 to 300 miles.

California's transit authorities made further orders in 2021: in Autumn, West Covina's Foothill Transit 20 and then 13 New Flyer Xcelsior CHARGE H₂ buses; AC Transit will increase its fleet by a further 20 vehicles, again the Xcelsior CHARGE H₂, plus one 60 t articulated bus on trial; Bakersfield Golden Empire Transit followed a 2020 order with five more Xcelsiors in 2021; and Sunline ordered a similar number of Xcelsior's to take its fleet to 26 vehicles, which includes 11 EIDorado FCEBs. Orange County Transportation Authority obtained 10 Xcelsiors in 2020, which it is trialling against full electric buses.

California Innovative Clean Transit Regulation has the objective for all State Public Transit agencies to be Zero Emission by 2040. To assist the transition, Californian buses are supported by a state subsidy, but are also able to generate carbon credits, while support from the Federal Transit Administration and the National Fuel Cell Bus Program is available here and elsewhere in the USA.

Outside of California FCEBs are found in Ohio, reported as 24, and led by Stark Area Regional Transit's (SARTA) fleet; Illinois has four vehicles deployed with Champagne-Urbana Transit; Las Vegas, Nevada has two due for delivery in 2021; while Hawaii is reported to have received its first vehicle in the summer. Single or two vehicles are found elsewhere.

In Autumn, Champagne-Urbana unveiled its 'Riding on Sunshine' initiative: buses fuelled by 100% green H₂ from solar power. The MW-scale electrolyser will supply 60 ft Xcelsior articulated buses as well as 40 ft vehicles. The plan is to expand to 12 buses in the future, with an HRS dispensing 35 kg per vehicle in back-to-back refuelling.

SARTA continues to operate its 'Borrow-A-Bus' programme, its Eldorado buses being loaned to operators in Washington State and Oregon, Toronto's Mississauga transit authority (MiWay) and Winnipeg Transit.

After six years in the wilderness, and with only one FCEB still in operation, Canada is beginning to grow its fleets again. MiWay is part of the Pan-Canadian Hydrogen Fuel cell Electric Bus Demonstration and Integration Trial and is due to order ten New Flyer Xcelsior buses, with 475 diesel buses to replace. Winnipeg, home to New Flyer's Canadian operations, is expected to follow suit. Alberta is said to have placed orders for two buses. The orders are likely to be supported by the Canadian Government's C\$20bn (US\$15.5m) public transit fund, which will support the move towards all new medium- and heavy-duty vehicles being zero emissions by 2040.

One of the challenges FCEB deployment faces in North America is the limited number of suppliers. Unlike Europe or China, where customer choice has blossomed in the past few years, the US has just two established suppliers with modest sales. With growing interest, and more public support available, this may change. GILLIG, a bus OEM, is working with Cummins on a US\$3.2m US DOE

project to develop an FCEB. In May, BAE Systems announced a tie-up with Plug Power to develop a fuel cell powertrain, competing with Ballard.

The other challenge, as in all markets, is simply one of cost, both capital and operating costs. US FCEBs are reported to be selling at US\$1.27m a unit (3x that of an equivalent diesel bus), with a near-term possibility of US\$850k a unit in series production. This would bring the FCEB prices closer to Europe.

By other metrics FCEBs are performing well against diesel-hybrid and battery electric buses. AC transit has conducted a 5x5 study of buses in its fleet, five sets of vehicles with five different power systems: diesel, diesel-hybrid, battery-electric, legacy FCEBs and the latest New Flyer Xcelsior fuel cell buses. The Xcelsiors had the lower emissions and better fuel economy than diesel and diesel-hybrids, and better availability than the battery-electric buses. As newer vehicles, with the latest powertrains, the Xcelsiors are clearly performing better than their predecessors but have some way to go on cost.

In Asia, China extends its lead

In November 2020, China issued its New Energy Vehicle Industrial Development Plan for 2021-2035. The New Energy Vehicle (NEV) segment includes battery and fuel cell vehicles. Setting NEVs a target of 20% of vehicle sales by 2025, it looks like China's bus OEMs have arrived early. Of an estimated 150,000 buses sold in 2020, 60,000 were NEVs, although a smaller proportion were FCEBs.

China's NEV sales, dominated by fully-electric cars, and more so by hybrid-electric cars, have been flat between 2018-2020 (at over 1m vehicles a year), but surged to 3.5m in 2021, as reduced COVID lockdowns began to return the economy to something near normal. But the other factor was policy, especially for trucks and buses, as the subsidies transitioned from production to delivering holistic changes at regional level. Ballard remains the main supplier of bus modules, but capacity elsewhere is growing fast. From a peak of nearly 1,900 fuel cell buses shipped in 2019 (where bus sales were inflated as manufacturers rushed to beat the subsidy change), a fall was seen for 2020 (to 1,265 units) and then 2021 (to around 800 units). Between 2015-2021, over 5,500 FCEBs shipped in China.

Foton (a BAIC subsidiary) is the largest fuel cell bus and truck OEM in China. It is followed by Golden Dragon, which sold 288 FCEBs of lengths 8-12m in 2020 (fitted with SinoHytec and Refire fuel cell modules), Feichi Technology and Shanghai SAIC. The OEMs playing into the market change year by year, with Zhengzhou Yutong bus, Foshan and Shanghai Shenlong Bus, and now Chery & Wanda Bus active. Many of the domestic FCEBs in China are minibuses and midibuses rather than full-sized.

China's cities continue to deploy FCEBs in larger numbers than almost anywhere else in the world. For example, early in the year Foshan delivered 20 FCEBs for Gaoming district, in Guangdong. These were Zhongtong 9 m buses using Weichai modules. In March, Dongfeng Electric launched a fleet of 40 FCEBs for the 2021 World University Games, while Dalian commissioned ten buses. In October, Shenzhen started its first FCEB bus route.

Skywell delivered at least ten FCEBs to Nanjing, which are reported to have run up 75,000 km over 45 days by July of this year. Skywell uses Canada's Loop Energy's eFlow modules, supplied by Beijing IN-Power, as 50 kW range extenders. This is part of Nanjing's plan, reported in 2020, to replace its entire bus fleet of 7,000 battery buses with FCEBs.

A big driver of FCEB deliveries were plans to deploy a vast fleet for the 2022 Winter Olympics, in Beijing. During the event, 655 H₂-powered buses were planned for Zhangjiakou City, the Beijing Winter Olympics co-host city, to provide transportation and logistics services for the games. Most of these units are from BAIC's Foton Motor subsidiary (212 buses), Zhongtong (40), Geely (30) and Yutong (25) are also reported suppliers. Module suppliers include China's SPIC Hydrogen Energy business (for Yutong).

Chinese FCEBs have tended to utilise smaller fuel cells as range extenders in 8-9 m length buses. However, there is a growing trend in China to apply larger modules to larger buses, especially where yet longer range is sought. With Foton Motor's buses (for example), the 9 m BJ6906 model uses 85 kW modules and 35 MPa H₂, to give a 400 km range, while the 12 m BJ6122 intercity bus uses 150 kW modules and 70 MPa H₂, to give an astonishing 1,198 km range.



(There is a similar trend in trucks, with fuel cells getting bigger as their application moves to HDV).

Chinese bus OEMs have tended to source fuel cell modules from Western suppliers, notably Ballard, Cummins, and Toyota, either from overseas plants or from manufacturing JVs in China. 2021 saw EKPO (the JV of ElringKlinger and Plastic Omnium), agree a partnership with DR Powertrain System to jointly develop modules with EKPO stacks for the Chinese market. Toyota also expanded its Chinese activity, signing-up with SinoHytec to invest US\$72m in the JV Huafeng Fuel Cell, using Mirai stacks.

State investment in the fuel cell industry is playing out, but slowly. Despite proven designs and low volume production, cost remains an issue, with very few fuel cell buses being exported: Feichi/ReFire with a bus to Malaysia in 2019, Wisdom (Fujian) Motor/Ballard to the US in 2021, and an order for four buses by Foton Mobility in Australia, also for delivery in 2021. This low number contrasts with the 2,807 battery-electric buses exported globally from China in 2021.

Korea

Korea's plans for fuel cell buses are overshadowed by those of China, but the plans are ambitious, and possibly over-optimistic. While it is estimated that 108 buses were operating on Korea's roads at the end of 2021 (81 more units than 2020), the 2022 target of 2,000 buses is clearly beyond reach, with COVID likely partially responsible. The 2040 target is for 41,000 vehicles.

Korea's automotive giant Hyundai is leading the deployment of FCEBs with its 11 m ELEC CITY Fuel Cell bus. This uses two NEXO modules, delivering 180 kW of power, from a 34.5 kg, 700 bar, CH₂

storage tank, integrated with a 78.4 kWh battery. First delivered in 2019, the bus is being deployed across Korea's cities. For example, five ELEC CITY Fuel Cell buses started services from Incheon airport in Autumn following the opening of an HRS at the airport by Air Liquide. Incheon has plans to replace its current fleet of 2,000 vehicles with FCEBs by 2030. Other cities have added to their FCEB fleets; Seoul placed another four ELEC CITY Fuel Cell buses in service in December.

The ELEC CITY Fuel Cell bus continues to cost more than pure battery buses from China, and this may be behind Hyundai looking to markets further afield. This year, Hyundai announced trials of the ELEC CITY Fuel Cell bus with Wiener Linien in Austria, and earlier in the summer with an operator in Munich, Germany.

Achieving Korea's FCEB targets will require more than one OEM. Edison Motors has ambitions for the technology with its current battery electric bus but has struggled to secure module supplies from Hyundai. Unsurprisingly, it has sought alternative sources and in November 2021 signed a deal with UK's Intelligent Energy to access its fuel cells in motive applications, including buses and UAVs, in South Korea. And then, in December 2021, Edison came to another agreement with Plug Power, specific to city buses, to bring a bus to market in South Korea. Using the 125 kW ProGen, the companies expect to have a FCEB prototype completed by H2 2022 and launch mass-market platform by H1 2023.

Other Korean businesses have also looked overseas for supplies, and in August Canada's Loop Energy reached an agreement with Korea's NGVI business to supply Loop's eFlow fuel cell module and other sub-systems such as DC-DC power conditioning. NGVI supplies NG-fuelled powertrains and H₂ storage systems for heavy vehicle conversions. Partner to the agreement, Ulsan Metropolitan City, has an ambition to replace its 949 strong bus fleet with zero emission buses, including FCEBs by 2030. Ulsan is to invest ₩2.3bn (US\$2m) by 2024 in testing and certification of H₂ bus technologies, supplied by a consortium including NGVI.

Doosan Fuel Cells is intent on entering the heavy vehicle markets with its fuel cell module offering, PEM and possibly SOFC, but this is yet to start.

Refuelling both buses and other fuel cell vehicles requires a refuelling infrastructure. In Autumn 2021, a consortium of Korean and other actors, including KOGAS and Woodside Petroleum, agreed to establish an HRS network across Korea. The first is due to be operational for the end of 2022.

Japan

Japan's fuel cell bus ambitions, with a target of 1,200 vehicles on the road by 2030, are more modest than Korea. At the end of 2021, 110 fuel cell buses were in operation in Japan. These have been primarily in the Tokyo area where 100 plus vehicles supported the delayed Olympics. The only domestic OEM is Toyota, which supplies its SORA 12 m vehicle powered by two Mirai fuel cell modules totalling 228 kW of power, plus a nickel metal hydride battery, with the few sales to date mainly to meet the demands of the Olympics.

Although the SORA has performed as expected the issue of costs, capital and operating, remains a big hurdle. In the summer of 2021, it was reported that the SORA, at a cost of US\$900k for a six-year lease, requires 80% subsidies, while fuel costs alone were 2.6 times diesel costs. The differential in fuel costs ignores the societal pricing of greenhouse emissions and local pollutants.

India

India's urban areas, especially cities such as New Delhi, suffer particularly from smog caused in a large part by vehicle emissions. To date, however, the progress of fuel cell buses has been slow, with only six FCEBs reported to be on the roads in early 2021. Tata Motors, part of the Tata conglomerate, has developed its H₂ StarBus but until this year there have been few orders. However, in August Tata won a tender to supply fifteen of its buses to the India Oil Corporation for demonstration and testing. These use Ballard FCmove-HD modules. India Oil Corporation will supply the hydrogen. India's other major bus OEM, Ashok Leyland, was reported in November to be developing a hydrogen bus, along with other commercial vehicles, but no details were provided. By the end of 2021, IPHE indicated a leap in FCEB numbers in India, with 58 units fielded in the country.

Other Countries

The FCEB is being pursued by other countries in Asia and Oceania. In Malaysia, Australia's H2X was reported to have done a deal with Sarawak Economic Development Corporation to establish a local production line, with the first buses earmarked for the Sarawak Transportation System. Sarawak expanded its FCEB bus services in early 2021, using Foshan Feichi vehicles imported from China.

In Australia, zero emission bus deployment is accelerating (from a slow start) and FCEBs will be part of the mix. In February, Foton Motor announced a strategic partnership with the impact investment group TrueGreen, to form a new company, Foton Mobility Pty. The company plans to introduce a range of FCEBs powered by Toyota models, commencing in early 2021 with the first 12.5 m low-floor city bus, with 4 buses expected over the year in total. It is hoped the deal will see up to 200 H₂ buses a year made available to the Australian market.

In March, Volgren, a battery electric bus maker located in Melbourne, announced optimistic plans to build a FCEB using indigenous components in the next two years.

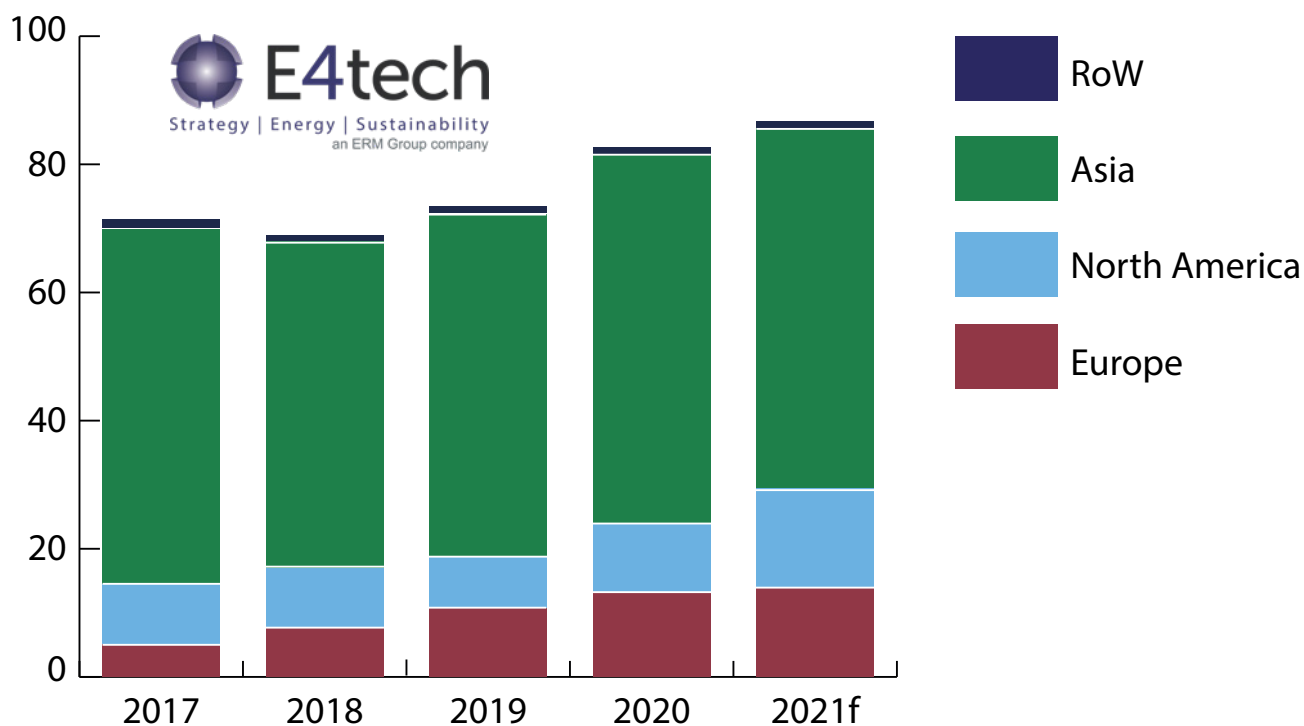
In June 2021, Hyzon completed a 15,000 km (9,321 mi) test run in a harsh, remote region in Western Australia, keeping the delivery of the ten coaches agreed in September 2020 on schedule. The Hyzon coaches have a range of 800 km before refuelling.

In November 2021, the family-owned regional bus company, Emerald Coaches, announced it will switch its 120-strong diesel fleet to H₂ fuel cell powertrains by 2040, starting 2022. How it will achieve this aim was not enunciated at the time.

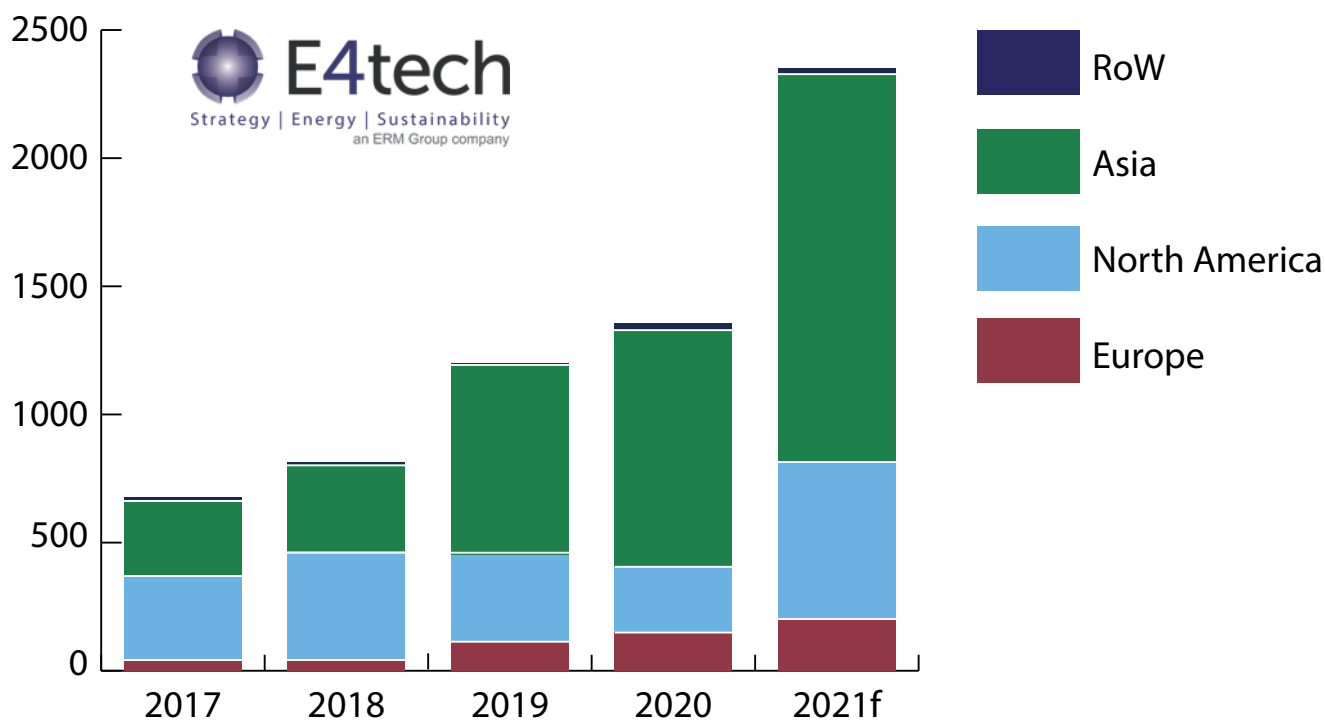
Across the Tasman Sea, Auckland Transport unveiled its first fuel cell bus in March, built by Christchurch-based Global Bus Ventures. The bus has a Ballard module. Auckland Transport is committed to a zero-emission fleet by 2030 and from this year has banned any further diesel bus purchases. Hyzon is also active in New Zealand but the present focus of Hirlinga is on filling stations for heavy-duty trucks, which might benefit bus fleets.

Shipments by region

Shipments by region of adoption 2017 - 2021 (1,000 units)



Megawatts by region of adoption 2017 - 2021



2021f is our forecast for the full year, based on firm data from January to September, and in most cases to as late as December. We have revised the figures for 2020 in this report, now with firm full year data where previously a final quarter forecast was required.

Shipments by region

Each year, we correct our final quarter forecasts with confirmed end of year figures. More buses shipped in Korea than forecast in 2020, and fewer micro-CHP units to Ene-Farm, resulting in a small change to our overall shipments, with 81,800 units shipped in 2020 (down from 82,500 units), equating to 1,338 MW output (up from the forecast of 1,319 MW).

2020 was a record year, despite the ravages of COVID. This followed a previous record in 2019, in which annual fuel cell shipments finally exceeded one-Gigawatt in aggregate power. But 2021 has been even more remarkable, with 85,850 units forecast, equating to 2,313 MW, even with COVID still hanging over markets.

Superficially, the 2.31 GW shipped capacity may appear as the beginning of the classic 'hockey stick' phenomenon often applied to emerging markets. But this is not a single industry, and the simplification ignores the ever-increasing share of shipments of NEXOs and Mirais, which now dominate the capacity. Hyundai now accounts for 38% of global fuel cell power shipments, and Toyota 33%. The cars have large effects on PEMFC share, share to Korea (NEXOs), and Japan and the USA (Mirais).

Asia has continued its strong lead, both in unit numbers (dominated by Ene-Farm) and in MW. Alongside the 8,500 NEXOs in Korea and 2,450 Mirais in Japan; 1,800 buses and trucks deployed in China. The contribution to MW by vehicles is strong, given even the smallest stacks for light hybrids are typically upwards of 30 kW, while the latest Toyota Sora buses are equipped with a total 228 kW from two Mirai stacks.

Asia overall had similar unit shipments in 2021 (56,100 units) to 2020 (57,600 units). An increase from 8,100 to 13,000 vehicles was offset by a fall of micro-CHP units to Ene-Farm, dropping to 39,800 units from 46,200. In MW, shipments to Asia moved to 1,493 MW (65% of global shipments), dominated by vehicles. Korea got 65% of this, Japan and China 23% and 12%, respectively. Deliveries to other Asian countries, including fuel cells in telecoms backup systems, remain negligible.

Korea strength in SOFC and PAFC for stationary power, and PEM systems in vehicles continues to be driven by the clear policy direction of the Hydrogen Economy Law in Korea. The Strategic Road Map for Hydrogen and Fuel Cells helps in Japan, and the New Energy Vehicles and Low Carbon Development policies of China are increasingly focused on long-term cluster development rather than simple volume driven by subsidy.

Second to Asia in MW, with a substantial increase over previous years is North America (mainly the USA). Shipments grew from 253 MW to 613 MW in 2021, with Bloom seeing an uptick alongside the increased flow of Mirais. The latter was up fivefold over 2020, following the release of the latest model. We estimate over 15,400 units shipped in North America in 2021, compared to 10,800 in 2020. Materials handling remains an important contributor, with increasing sales in volume terms, and larger output stacks for use in platforms beyond the traditional 'Class I' electric motor rider forklifts. Across all segments, North America represented 27% of global shipments by MW capacity in 2021.

Despite nominally favourable policy in Europe, the lack of specific fiscal incentives to deploy fuel cells outside Germany's KfW 433 initiative means only a modest increase in MW shipments took place, up to 198 MW from 156 MW in 2020, so 9% of global capacity. Unit shipments to Europe increased marginally, from 13,200 to 13,950, with gains in forklifts and portable offset by a fall in fuel cells for micro-CHP in Germany. Larger fuel cell CHP and prime power installations remain insignificant, with light duty fuel cell vehicle shipments relatively flat and bus, truck and other vehicle placements doubling to just over 630 units. Europe's buses are starting to compete, but trucks are at the early demonstration phase. Overall numbers of medium- and heavy-duty fuel cell vehicles are lower than China, albeit with a significant increase in capability over recent years.

We don't see any significant regional changes near-term (as we wait for policy to feed through), but are positive about the potential for greater heavy-duty numbers in Europe over the coming years.

Medium- and heavy-duty trucks – new growth

Trucks are gathering momentum. Outside China, the focus is mainly on heavy-duty, which are only slowly reaching customers, with shipments lagging ever-growing order books. Major players and newcomers are promising consistent series production is not far away. Partnering between major supply chain actors continues and roll-out strategies are being set. And the small EU trials funded by HFC2 JU, like H2-Share and H2Haul, are giving way to larger shipments of fuel cell trucks.

Major players want to lead the way...

Daimler and Volvo announced their 50:50 joint venture in 2020, and details were confirmed in 2021. Named cellcentric GmbH & Co KG, the JV formed as Volvo Group acquired 50% of Daimler Truck Fuel Cell GmbH for approximately €600m (US\$714m), cellcentric intends to be the leading global PEM fuel cell manufacturer for mobility. cellcentric will develop and manufacture systems from the Daimler site near Stuttgart, primarily for use in HD trucks, reaching customers in 2023.



Little additional activity has been publicised by Volvo so far, whereas Daimler Truck has had more to say. Daimler announced it has started testing its GenH2 truck on roads ahead of customer testing. The trucks use CH₂ storage now but will move to prototype LH₂ tank systems during 2022. Daimler signed agreements with Linde and Air Liquide to develop the refuelling and supply of the LH₂. The group is now working towards a global standard for refuelling with sub-cooled LH₂. Over 2021, Daimler has partnered with energy companies Shell New Energies and TotalEnergies to ramp up deployment of HRS and to encourage vehicle adoption for customers in Northern Europe.

Shell intends to rollout an initial HDV H₂-refuelling network by joining three green H₂ production hubs at the Port of Rotterdam, in the Netherlands, and Cologne and Hamburg in Germany. From 2024, Shell aims to launch HRS between the three hubs and Daimler aims to hand over the first heavy-duty H₂ trucks to customers in 2025. The partners aim to continuously expand the H₂ freight corridor, to cover 1,200 km by 2025, with 150 HRS meeting the needs of around 5,000 heavy-duty fuel cell trucks by 2030. This is in a context of huge and advancing plans for increased used of H₂ across NW Europe.

.. but the newcomers mean serious business

Hyzon Motors, a relative newcomer, is now a leading potential player. In July, Hyzon merged with Decarbonisation Plus Acquisition Corporation, in a deal which generated around US\$600m in cash, supporting company growth, and was later publicly listed, at a value suggested to be as high as US\$2.7bn.

Hyzon is expanding fuel cell production facilities in Honeoye Falls, close to its HQ in Rochester NY, and plans to build the largest US membrane electrode assembly (MEA) production facility in Bolingbroke, Illinois, at Hyzon's newly built Innovation centre for fuel cells, H₂, electric drive and autonomous driving technologies. The facility, coming online in Q3, will have an MEA capacity for 12,000 vehicles a year, clearly stating Hyzon's ambitions to compete at scale. Until online, the company will continue to obtain stacks for trucks from Horizon in Singapore.

Hyzon Motors' small volume truck production is underway in Holland, delivering refuse collection, sewer-cleaning and heavy-duty delivery vehicles for the Municipality of Groningen. The facility produced the first trucks for Hiringa Energy in New Zealand, as part of its supply agreement of 1,500 vehicles by 2026. Hiringa itself commenced the construction phase of four, high capacity, green HRS in the country as part of the same agreement.



Hyzon had a busy 2021, with 87 deliveries of 18-49 t heavy-duty fuel cell trucks. A further 20 vehicles are scheduled for delivery in the Netherlands in 2022 and 70 vehicles in Austria from 2021 to 2024. The Netherlands is emerging as a major mobility centre, given Utrecht's commitment to adopt 300 fuel cell trucks, 1,500 light duty vehicles, 2-5 coaches, and up to 10 HRS across the province by 2025.

The number and pace of agreements entered by Hyzon in 2021 far exceeds those of its competitors. Only a flavour of the supply agreements is listed below. The agreements range from vehicle supply to strategic linkages to build the H₂ truck market.

In May, Hyzon announced it will enter a JV with Raven of Pinedale, Wyoming, to build waste-to-H₂ hubs. Raven, a renewable fuels company, with a proprietary steam/CO₂ reformer, will help Hyzon install 250 hubs across the US and globally. The first hub, at Republic Services' West Contra Costa Sanitary Landfill in Northern California, is expected to become operation from summer 2022.

In June, Hyzon Motors signed an agreement to supply up to 70 H₂ fuel cell powered heavy trucks to a MPreis, Austria's leading grocery store chain with ~300 locations, through JuVe Automation, an MPreis spin-out. The trucks will be delivered over a three-year period.

In July, Hyzon signed an MoU with TotalEnergies to evaluate and develop hydrogen refuelling and vehicle supply solutions for long-haul transport to customers across Europe. A second MoU commits TotalEnergies to secure support to produce 80 H₂ fuel cell-powered trucks for TotalEnergies' French customers. Also, in July, Hyzon signed an MoU with Superior Pak, a leading Australian manufacturer of waste handling equipment, for the supply of up to 20 refuse trucks in 2022, starting in Brisbane, Melbourne and Sydney, where H₂ supply infrastructure exists. The first five trucks are expected to be operational in Q2 2022.

In August, Hyzon signed a trial agreement with Total Transport Services Inc (TTSI), a prominent port trucking company in Southern California. Under the agreement, Hyzon was to provide a Class 8 heavy-duty truck for a 30-day trial in Q4 2021. The truck, built on a 2022 Freightliner Cascadia chassis, has so far appeared at three trade shows. The truck offers a peak 600 HP (447 kW) and a range of up to 400 miles (644 km).

In September, Hyzon received an order to supply five 154-ton trucks from Ark Energy Corporation, the Australian subsidiary of the world's largest zinc, lead and silver producer, Korea Zinc. Hyzon is obligated to deliver the trucks by the end of 2022. Also, in September, Hyzon signed an MoU with the logistics company, Shanghai Hydrogen HongYun Automotive Co Ltd, for purchase of 500 H₂ fuel cell trucks. The trucks are fitted with 170 kW stacks. The first batch was to be delivered over 2021 and the remaining 400 trucks in 2022.

In November, Hyzon indicated it would deploy 49 t trucks to Sha Steel Group's operating base in the Port of Zhangjiagang for 60-day trials. In the same month, delivery of the first 29 units to HongYun was announced, destined for a major steel conglomerate in China. HongYun placed an order for a further 33 units.

In December, Hyzon Motors signed an exclusive supply contract for H₂-powered fuel cell trucks with the Dutch waste collection truck builder, Geesinknorba. 300 trucks or more are expected to be supplied by Hyzon during the three-year contract. It also contracted to deliver a Class 3 commercial service truck to SoCalGas by 2022. The truck is expected to reach a maximum power of 200 kW, with a range of 300 mi, and will be built on an existing chassis OEM used by SoCalGas. In the same month, Hyzon entered into an MoU with the MiTAC-Synnex Group, an industrial conglomerate, to jointly develop commercial FCEV and distribution models optimized for the Taiwan market. Hyzon anticipates orders from municipalities and private business, targeting commercial shipments in 2022.

Liquefied as well as compressed hydrogen is on Hyzon's roadmap. In July 2021, Hyzon indicated it is working with Chart Industries to create an onboard storage tank to deliver a 1,000 mile (1,600 km) range. In December, Hyzon indicated it would work with Woodside to develop green H₂ production hubs to support growth in Australia and the US, supplying LH₂ to onboard mobility use cases.

Hyzon is unique now in starting to deploy heavy-duty trucks in numbers over four continents. A short-selling report on Hyzon from Blue Orca, published in September, however, was less than complimentary, though largely inconsistent with events on the ground and the company balance sheet of more than US\$500m in cash and cash equivalents. Whether Hyzon's accomplishments in 2021 gather pace in future years is yet to play out.

Daimler, Volvo, Hyundai and Hyzon are vying for European market share through various programmes. H2Accelerate, which includes Volvo, Iveco, Shell and OMV, aims to deploy hundreds of trucks in Europe before 2025 and thousands each year in the latter part of the decade. Hyzon joined the HyTrucks programme alongside Air Liquide, DATS 24 and major ports in northern Europe pledging 1,000 vehicles by 2025, and Hyzon joined The Covenant on Hydrogen in Mobility in Utrecht, Netherlands, targeting 300 trucks, 1,500 light duty vehicles and 10 refuelling stations by 2025. These numbers present a big escalation over units that are presently fielded.

With a global focus, Hyzon announced the Hyzon Zero Carbon Alliance, which includes existing customers and infrastructure providers Ark and Hiringa, but also adds fuels companies Raven SR and ReCarbon Inc, and finance and insurance players Bank of America and AXA. Joining the alliance are Saudi companies Modern Group and NEOM, intending to set up a facility for 10,000 vehicles, with detailed plans to be set out in the next 18 months.

Nikola also reached a pivotal step in its journey, by opening its 50,000 m² manufacturing facility in Ulm, Germany. Through the JV with Iveco, Nikola Tre fuel cell vehicles built on the Iveco S-Way chassis will start road testing in 2022 and could be produced at a rate of 1,000 per shift, per year, from 2023 and ramping up in the following years. Nikola's facility in Arizona, US will also build the 500-mile range Tre and, additionally, the longer, 900-mile range Two, a sleeper variant specifically for the US market, planned for production in 2024.

In May, Nikola signed a letter of intent to test two BPEVs and two FCEVs in 2022 with TTSI at the Port of Long Beach and Los Angeles, with potential for 70 follow-on fuel cell truck orders in 2023.

In September 2021, Nikola announced agreements with Bosch targeting Nikola Class 7 and 8 fuel cell trucks. Bosch will supply fully assembled modules as well as major components to Nikola for assembly at its manufacturing facility in Coolidge. The parties will work together for sourcing of remaining components for the assemblies.

Nikola shows intent to focus on gaseous H₂, in April signing a multi-year agreement with Hexagon Purus to take more than €200m (US\$238m) of storage tanks. True to its mission to provide energy solutions as well as vehicles, Nikola is establishing partnerships with refuelling station providers, like TravelCentres of America for two US sites, and with the German pipeline network operator OGE for supply of CH₂ to filling stations in Germany.

In January 2021, Navistar said it would partner with General Motors to develop fuel cell trucks for long-haul duty. The Navistar regional haul International RH tractor will use GM Hydrotec 80 kW FC cubes to create a H₂-powered variant of the Class 8 truck. Navistar expects commercial production in 2024.

Quality and quantity for Asian truck OEMs

In May, HHM, the joint venture of Hyundai Motor and H2 Energy, outlined its Xcient redesign, now fitted with a 180 kW fuel cell, consisting of two stacks of 90 kW (previously two stacks of 95 kW). The longevity of the fuel cell and the overall fuel efficiency have been improved. The 350 kW electric motor offers about 2,200 Nm of torque, assisting driving on inclines in mountainous regions. The new Xcient is available as a 6x2 chassis with a double rear axle from the 2021 model year, in addition to the 4x2 variant.

The Xcient stores 31 kg H₂ in seven tanks, with three 72-kWh high-performance batteries acting as an additional energy source. The heavy-duty truck can travel around 400 km (250 mi) on one tank of H₂. Depending on the ambient temperature, the seven tanks can be completely refilled in 8-20 minutes.

Hyundai delivered 46 Xcient units to Switzerland in 2021. As part of its plan to deliver 1,600 units to Europe by 2025, Hyundai expects to ship another 140 units to Switzerland by the end of 2022.

Hyundai is in talks with several local governments and logistics companies in the US to establish a possible joint operation of H₂-powered trucks. In July 2021, Hyundai was also awarded a US\$500k grant from the SCAQMD to demonstrate two Class 8 Xcient heavy-duty trucks in Southern California. Hyundai's fleet partner planned to operate the trucks from August. The trucks will be used for long-haul freight between warehouses for a year. Hyundai is working with First Element Fuel to utilise three HRS in the region to refuel the trucks.

Also, in July, Hyundai announced its participation in the NorCAL ZERO project. Hyundai is to deploy 30 Xcient trucks to the fleet operator, Glovis America, starting Q3 2023, for regional freight distribution in California. The driving range of the US trucks will be 500 miles (800 km) to meet market needs, achieved by moving from 350 to 700 bar CH₂. After six years operation is reached, the fuel cell trucks are expected to exhibit a similar total cost of ownership as diesel. The project has been granted US\$29m funding from the CARB, the CEC, Alameda County Transportation Commission and the Bay Area Air Quality Management District and will be the largest commercial fleet trial to date in the US.

Toyota has spent several years designing a fuel cell heavy-duty truck, relying on Paccar's Kenworth brand as a vehicle partner. The companies are in the process of building about a dozen trucks for testing at the Port of Los Angeles. The latest vehicles have more compact CH₂ tanks and a larger battery, with a 300 mile range.

Toyota's truck subsidiary Hino announced its plans to also develop a fuel cell truck last October. The automaker will launch a fuel cell module assembly line for H₂-powered, heavy-duty commercial trucks at its Toyota Motor Kentucky factory in 2023, unveiling its Class 8 XL8 prototype in August 2021.

In Japan, commercial LDVs are more the focus for Toyota and Hino, with a trial ongoing for 3 t, 250-mile range delivery vehicles for grocery stores.

China is a key focus country for Toyota, with a first JV in the country in June 2020, creating United Fuel Cell System R&D, with FAW, Dongfeng, GAC, BAIC and SinoHytec. The JV was set up to create open R&D architectures to shorten the time to develop fuel cell stacks, controls and systems for commercial vehicles. Building on the first JV, Toyota signed a further contract with SinoHytec, in March 2021, to form a 50:50 JV with a capital injection of ¥8bn (€62m). The new company will be based in Beijing and will begin operations in 2023 with a capacity of 3,000 fuel-cell components per year. The JV will deliver both buses and trucks to China.

In July, Air Products and Cummins announced an MoU to accelerate the integration of H₂ fuel cell trucks in the Americas, Europe and Asia. Cummins will provide powertrains integrated into selected OEM partners' heavy-duty trucks for Air Products. Assuming a successful demonstration and pilot, Air Products plans to convert its global fleet of nearly 2,000 distribution trucks to operation with H₂ fuel cells. The demonstration is expected to begin in 2022. The partners will also work to increase the accessibility of green H₂, including H₂ infrastructure opportunities to promote H₂ mobility futures.

In addition to the efforts of the major truck OEMs, there is a growing momentum on powertrain conversions, using third-party diesel chassis, led mainly by established electric vehicle converters.

It has been a busy year for Proton Motor, with orders and interest ranging from maritime to rail. In July, E-Trucks Europe made an order for seven HyRange 43 (42.6 kW) H₂ fuel cell modules to be deployed in refuse collection trucks, following a previous order in January 2020 for five modules. The trucks are fully electrified (drive train and waste collector) with 136 kWh batteries, the Proton modules as range extenders delivering near continuous daily usage. The refuse trucks have been used in Groningen, Best, Breda, Eindhoven and Helmond. Proton is also contracted to deliver maintenance services for the next five years.



In June, Proton Motor signed an MoU with the UK company Electra Commercial Vehicles, to develop the fuel cell truck market in the UK and Ireland. Electra will place an initial order for five Proton fuel cell systems and a prototype refuse collection truck will be developed for serial testing. Electra will act as system integrator to integrate Proton's systems into its existing electric truck portfolio. Proton will provide engineering support and training during the development and qualification of the trucks. The companies also committed to joint sales and marketing activities in the UK.

In September, Ballard and Quantron AG formed a strategic partnership for the development of H₂ fuel cell electric trucks. The initial collaboration will focus on the integration of Ballard's FCmove family of heavy-duty power modules into Quantron's electric drivetrain and vehicles. Fuel cell truck platforms currently in development include a 7.5 t delivery truck, a 44 t heavy duty

truck, and a municipal waste collection truck. An initial deployment of the fuel cell trucks in Germany is scheduled for the second half of 2022.



In July 2021, H2GVMids began, a 9-month study led by EDF R&D UK, with partners Cenex, Arcola Energy, Toyota, Intelligent Energy and ITM Motive. Funded by Innovate UK through the Zero Emissions Road Freight Competition, pre-deployment work for a 44 t H₂ fuel cell truck demonstration in the Midlands will take place, involving the full value chain for H₂ HGV operation, development and refuelling, with a lease-based delivery model. A Green Book ready business case, with preliminary engineering designs, site surveys, a full costing, and identification of risks and pre-authorisations, will be core deliverables.

Liverpool-based ULEMCo offers a range of clean transportation solutions: hydrogen ICEs, dual fuel engines, and fuel cell designs. In August, ULEMCo was awarded an Innovate UK award for HySPERT, a fuel cell electric powertrain engineering design leading to a fire-fighting truck. This follows an OZEV (Office for Zero Emission Vehicles) award in February for a lightweight ambulance design, with a fuel cell range extender, now going to prototype.



China, still king of the road

2021 showed a significant uptick in activity in fuel cell HDVs and in vans, but China remains king in medium- and heavy-duty deployments, with nearly 1,200 trucks of all sizes produced in the country in 2021. Around 800 of these were sold in the year, representing 99% of truck shipments to Asia, and 64% of all truck shipments globally.

The Chinese government is increasingly supportive of H₂ for regional mobility, with an emphasis on trucks and buses. Consequently, a lot of the global OEMs remain focused on China, with several JVs in play.

At the end of 2020, Hyundai signed agreements with two groups of Chinese actors. The first MoU, with Shanghai Electric Power Co, Shanghai Sunwise Energy Systems Co, and Shanghai Ronghe Electric Technology Financial Leasing Co, was for the supply of 3,000 H₂ FCEVs in the next five years, to be operated in the Yangtze River Delta region.

Hyundai plans to set up a 'business cluster' which covers H₂ vehicle sales, lease programmes and HRS, noting China as one of the global H₂ markets with the most growth potential. The second MoU is with Advanced Technology & Materials Company and HBIS Group, based in the Beijing-Tianjin-Hebei economic zone, for the supply of 1,000 H₂ trucks.

The Technology Roadmap for Energy-saving & New Energy Vehicles (Version 2.0) released by China SAE in 2020 suggests a 1m cumulative FCEV target by 2030, with Hyundai Motor positioned to play a central role. At the end of 2020, Hyundai said it aims to export 64,000 H₂ commercial vehicles per year by 2030, comprising 27,000 to China, 25,000 to Europe and 12,000 to the US.

In April, Symbio unveiled its multi-stack system at Auto Shanghai, rated 150 kW, 225 kW (3x 75 kW), and 300 kW (2x 150 kW), to fit all trucks to 44 t. The stacks are claimed as compact and efficient, with low pressure and losses, controlled hydrogen recirculation and operating temperatures that are compatible with the cooling requirements of HDVs.

Hydrogen strategies and roadmaps

As part of global efforts to implement the Paris Agreement towards a low-carbon economy, the fuel cells and hydrogen industry has gained unprecedented political and business momentum, with an increasing number of countries revealing their long-term hydrogen ambitions. By the October 2021, more than 20 jurisdictions worldwide had published hydrogen strategies or roadmaps, and several more were in development.

By and large, these strategies provide a vision and a supportive policy framework for the development and rollout of hydrogen technologies. The focus is often on hydrogen production and utilisation in hard-to-decarbonise sectors, with fuel cells seen generally as a key enabler to decarbonise heavy transport.

Further to the main objective of reducing carbon emissions, many hydrogen strategies highlight country-specific opportunities, often related to the establishment of activities across the hydrogen value chain. In consequence, different strategies may have distinct strategic goals, depending on local comparative advantages, which results in a somewhat fragmented global approach.

The combined impact of this raft of strategy announcements is a pipeline of over 500 clean hydrogen projects on the drawing board today, with spending plans that could reach more than US\$700bn to 2030.

Japan envisions a hydrogen society

Japan was the first country to call for the adoption of a hydrogen-based society, in the aftermath of the 2011 earthquake and tsunami leading to Fukushima's nuclear accident. But a national vision for H₂ had been around for decades. The nation's Basic Hydrogen Strategy aims for a hydrogen society in the 2050 timeframe, with FC deployment targets on the way, including 800k cars, 1.2k buses, 10k forklifts, 900 HRS and 5.3m Ene-Farm units by 2030.

Based on strong public-private support and collaboration, the country seeks to promote the utilisation of hydrogen across multiple sectors, together with international cooperation and

public dissemination. On the latter two, Japan continues to organise the Hydrogen Energy Ministerial Meeting, and exhibited its fuel cell and hydrogen technology in the Tokyo 2020 Olympics, held eventually in 2021 because of the COVID pandemic.

South Korea's pathway to a hydrogen economy

South Korea's *Hydrogen Economy Roadmap* sees hydrogen as leading to environmental benefits and economic growth, setting the world's most ambitious deployment targets to date including 2.9m FC cars (plus 3.3m for export), 80k FC taxis, 40k FC buses, 30k FC trucks, 1.2k HRSs, 8 GW of FC large-scale domestic power generation (plus 7 GW for export) and 2.1 GW of FC domestic power generation for homes and buildings by 2040.

The *Hydrogen Act*, claimed to be the world's first hydrogen-related law, took effect in February 2021, while *hydrogen pilot cities* Ulsan, Ansan and Wanju-Jeonju will use hydrogen as their primary energy source starting in 2022. The *Hydrogen Economy Committee*, chaired by the Prime Minister, is set to supervise the development of the hydrogen economy.

Hydrogen to play a key role in the EU

Multiple hydrogen strategies have recently emerged in Europe, at EU and national levels. The European Commission's *Hydrogen Strategy for a Climate-Neutral Europe* recognises the pivotal role that green hydrogen could play in achieving climate neutrality, targeting 40 GW of installed electrolyser capacity by 2030 and large-scale fuel cell deployment in hard-to-abate sectors by 2050. These ambitions are largely supported by the hydrogen strategies from Member States, which also touch on country specific drivers and objectives as discussed below.

On top of this, industry association Hydrogen Europe suggests importing hydrogen from North Africa and Ukraine in its supplementary *2x40 GW Initiative*. The organisation has also published its *Hydrogen Roadmap Europe*, which outlines an ambitious scenario with 3.7m FC cars, 500k FC light commercial vehicles, 45k FC trucks and buses, 570 FC trains and 3.7k HRS by 2030, as well as 2.5m FC CHP units by 2040.

Laying the foundations in the US

Although a US hydrogen strategy is not yet available, the Department of Energy (DOE) has released its overarching Hydrogen Program Plan, seeking to provide strategic direction to all DOE hydrogen activities. The objective is to accelerate the development, demonstration and adoption of hydrogen-related technologies, envisioning these as an integral part of multiple sectors across the economy.

Like in Europe, US industry representatives have put forward a *Road Map to a US Hydrogen Economy*, including an ambitious pathway that would lead to 1.2m FCEVs, 300k FC forklifts and 4.3k HRS by 2030. Meanwhile, the long-standing California Fuel Cell Partnership envisages 1m FCEVs, including cars, buses and trucks, and 1k HRS in the State by 2030.

Significant progress in China

While a national hydrogen strategy is not yet available, China has recently made significant hydrogen-related policy announcements. The nation's *14th Five-Year Plan (2021-2025)* identifies hydrogen as a frontier development area, as well as one of the six industries for future focus. 1m FCEVs by 2030 remains a widely-accepted goal, based on technological roadmaps released by industrial and government-affiliated stakeholders.

Broad-brush subsidies for FCEVs have now been replaced by demonstration rewards under the *Pilot Cities* programme, intended to support a selection of local governments in developing hydrogen value chains. Furthermore, multiple provinces and municipalities have formulated their own hydrogen development plans, often driven by promising hydrogen production potential or existing industry presence.

Pursuing technology leadership

As previously mentioned, hydrogen strategies in different countries may include distinct drivers and aspirations. One of the common targets among industrialised countries is the pursuit of technology leadership, looking to create global market opportunities for local players. This is built into the strategies of Japan and South Korea, and also to Germany's strategy, which aims to develop a market for hydrogen technologies, with specific measures to establish a competitive fuel cell supply chain for the automotive industry.

France plans to foster hydrogen-based mobility for commercial applications, providing opportunities for local companies to develop key components and capabilities, targeting 20-50k light duty vehicles, 800-2,000 heavy duty vehicles, and 400-1,000 HRS by 2028. Symbio's location reflects this emphasis, benefiting from favourable national policy.

The UK seeks to build 'world-class' low-carbon hydrogen supply chains to underpin the deployment of hydrogen technologies, including hydrogen buses, trucks and rail, together with early-stage commercial shipping and aviation.

The Netherlands strives to become a hydrogen energy hub, capitalising on its ports and location, with a target of 300k FCEVs by 2030.

And Denmark aspires to play an important role in Power-to-X, building on its currently strong position throughout the value chain, comprising wind turbine and electrolyser manufacturers as well as e-fuels consumers.

The race for green H₂ production

Not surprisingly, the strategies tend to promote green H₂ production, often looking to capitalise on favourable renewable energy resources. In Europe, many nations have reported plans to increase their electrolyser capacity, setting significant targets by 2030: 6.5 GW in France, 5 GW in Germany and Italy, 4-6 GW in Denmark, 4 GW in Spain, 3-4 GW in the Netherlands and 2 GW in Portugal.

Elsewhere, the Australian hydrogen strategy recognises the country's potential to become a major green hydrogen producer (built on its solar resource), with a current focus on demonstration projects and building supply chains and hydrogen hubs. South Africa is attempting to become a global player in green H₂, hoping this will help address the country's poverty, inequality, and unemployment challenges. Chile sees green H₂ as a unique opportunity, comparable to the country's prominent mining sector, with ambitious plans to deploy 25 GW of electrolyser capacity by 2030. And India and Morocco have reported big plans regarding green hydrogen production too.

Blue hydrogen still on the table

Despite the existing focus on green hydrogen, the generation of blue hydrogen is also considered, especially in regions with large natural gas reserves. The Canadian hydrogen strategy is intended as a call to action, urging stakeholders to seize the opportunities related to producing both green and blue hydrogen. Norway draws on the country's resources and sectorial experience to produce both green and blue hydrogen, calling for equal competition between the two in the European market. The UAE is set to develop green and blue hydrogen production capabilities, looking for new growth opportunities within the low-carbon economy. And the UK and others have set low-carbon hydrogen production targets, which may include using CCUS or biomethane, especially in the near term.

Increasing focus on exports

Several hydrogen strategies put an emphasis on export opportunities, given the potential for hydrogen production in certain geographies, notably with high solar insolation to create low-cost electricity, combined with the expected high hydrogen demand in other areas. In Europe, Spain and Portugal see themselves as future hydrogen exporters to Germany, which does not anticipate meeting its hydrogen demand only from domestic production. North African countries like Morocco are also well positioned to export into Europe, as reflected in Hydrogen Europe's *2x40 GW Initiative*.

In addition, Australia is set to make hydrogen its next major energy export, having already signed a cooperation agreement with Japan and a letter of intent with South Korea. Chile claims it will be able to produce the cheapest green H₂ worldwide, from its abundant and cheap renewable power. And the UAE aspires to capture 25% of the low-carbon hydrogen market share in key export markets including Japan, South Korea and Germany.

The impact on fuel cell players

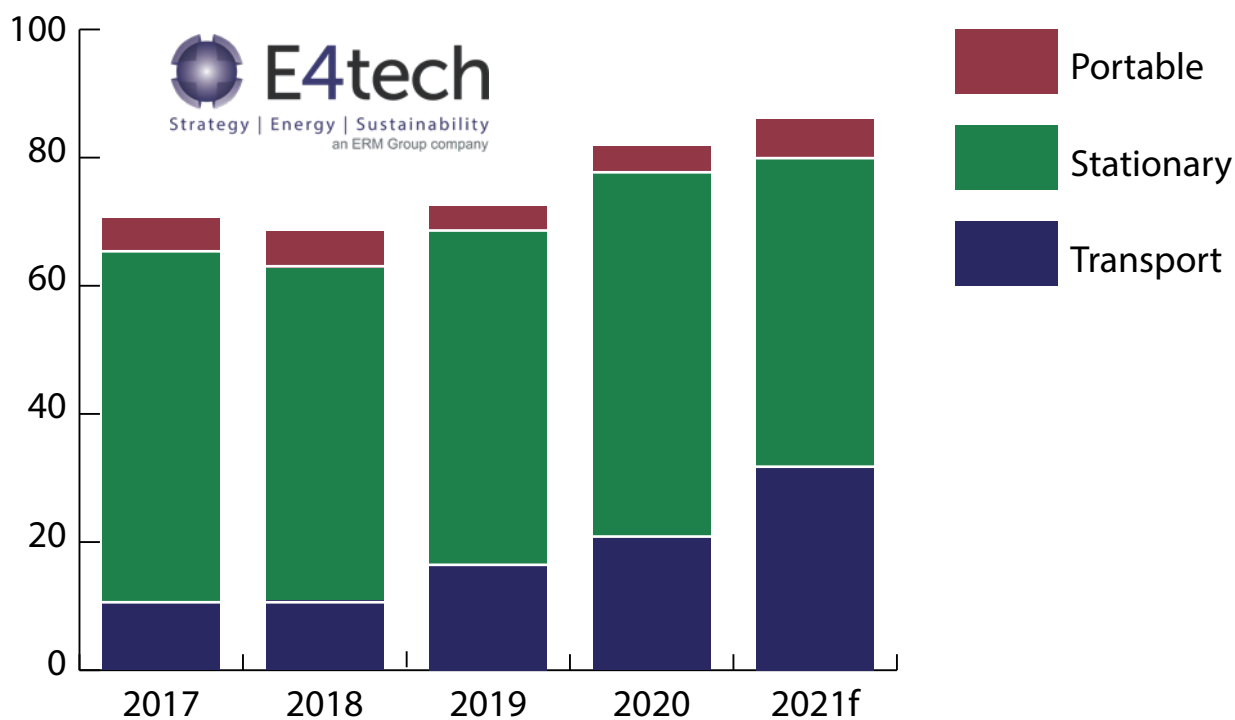
None of this has been lost on fuel cell producers. Plug Power has reinvented itself, from a supplier mostly of forklift battery box replacement units with a small-scale refuelling ability, to a major green hydrogen player, spanning electrolytic production, storage and supply of H₂. In December 2021, as part of its transition strategy, Plug Power closed its acquisition of Frames Group for €115m (US\$137m). Plug's plan is to combine its PEM electrolyser stack technology with Frames' systems integration capabilities to offer turnkey electrolyser solutions, ranging in size from 1 MW containers to 1,000 MW standalone plants. The PEMEL platform itself arose from Plug's acquisition of Giner ELX, in July 2020.

Plug aims to achieve an installed electrolyser capacity of 3 GW by 2025 and will also seek to produce over 1,000 tonnes of green hydrogen daily by 2028. In September 2021, Plug also committed to the build of a 30 tpd LH2 plant in Fresno County, California. The plant should complete commissioning in early 2024. The plant joins the company's growing national network of plants in New York, Tennessee, and Georgia that will together supply 500 tpd green LH2 by 2025.

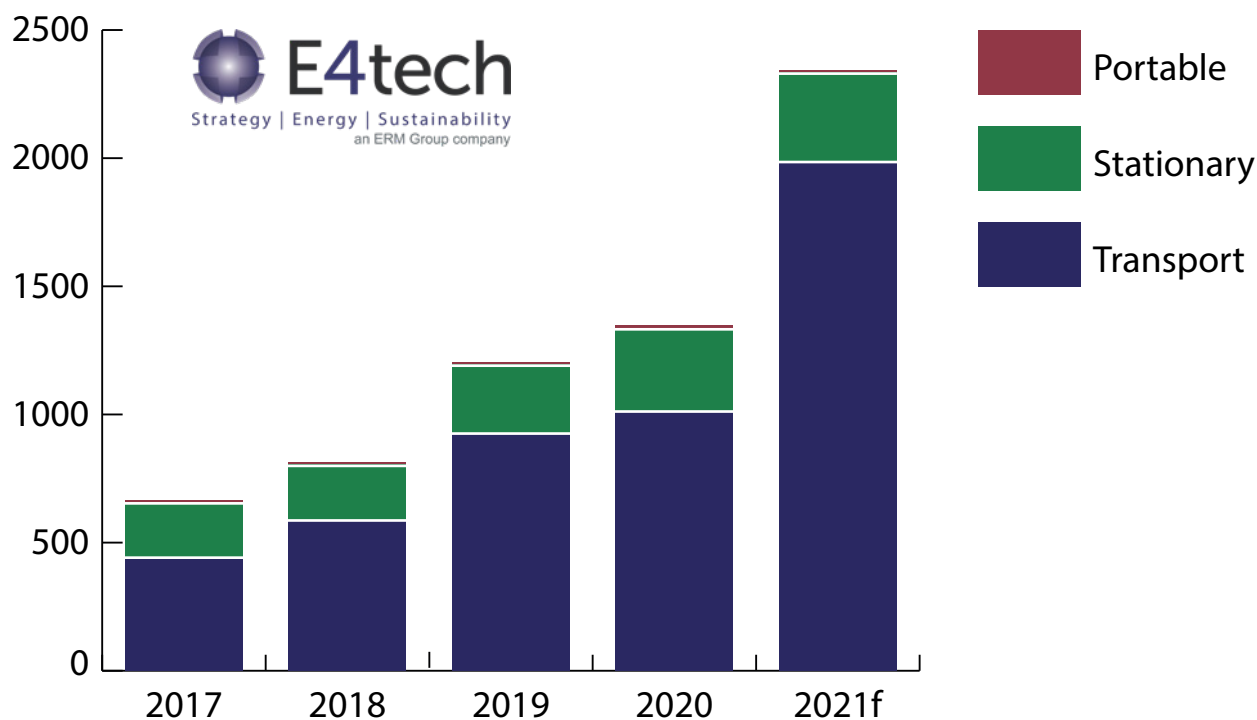
Likewise, a raft of SOFC players, including Ceres, are now targeting electrolysers, either to create hydrogen directly or (as with Sunfire) for efuels manufacture. There is also a small but discernible move by some fuel cell players to target renewable ensembles, from green H₂ production, to buffering, to arbitrage using fuel cells to create power, from domestic homes to industrial embedded systems.

Shipments by application

Shipments by application 2017 - 2021 (1,000 units)



Megawatts by application 2017 - 2021



2021f is our forecast for the full year, based on firm data from January to September, and in most cases to as late as December. We have revised the figures for 2020 in this report, now with firm full year data where previously a final quarter forecast was required.

Shipments by application

The several-year trend continues, with the two fuel cell cars dominating the MW count, at 72% of capacity shipped. Including buses and trucks the figure rises to 83%, and to 85% when materials handling vehicles are included. This increase to nearly 2 GW of total shipments contrasts with the much slower growth in stationary and portable applications, which together account for 348 MW of the overall 2021 total.

As noted in the 2020 Review, the large contribution from only two car models (from two just OEMs) contributes to major volatility in shipments. Hyundai and Toyota contributed to a near doubling of fuel cell cars from 2020, and without the NEXOs and Mirais the global fuel cell market would be back at around 680 MW, roughly the total in 2017.

The case for fuel cells is also being proven in other markets, notably in portable APUs for consumers, remote power (monitoring, telecoms, control and works units), and increasingly in prime power (led by Bloom and Doosan). The latter, as with domestic micro-CHP, is still driven by policy and incentives, and without them would likely collapse. Energy markets and emissions drivers have changed over the two decades of small volume manufacture and cost reduction, meaning the path to profitability for the companies selling these devices remains elusive.

Bus shipments increased slightly over 2021, with lower units in China offset by more in Europe and elsewhere. Truck shipments tripled in number, with the MW capacity increasing six times, as China increasingly targets heavy-duty commercial vehicles over medium-duty models. Our 'Transport – Other' count includes a growing contribution from maritime, train and aviation fuel cell units.

Fuel cells in prime power now overhauls large CHP. South Korea remains the largest market, with Bloom shipments growing fast, but overall shipments of larger (100 kW+) units to Korea have declined slightly in 2021, as industry waited for the supportive Clean Hydrogen Energy Portfolio Standards to be written into secondary legislation flowing from the Hydrogen Energy Act. The 2021 market in this area is around 146 MW out of a global market of 298 MW.

Most of the balance is in the US, led by Bloom, with negligible shipments of large units to Europe. There is an increasing focus, particularly in Korea, in large hydrogen-fuelled units, integrated with chemical works, over natural gas-fuelled units.

Shipments of smaller fuel cells for domestic CHP have fallen somewhat over 2021, at nearly 44,000 units, from over 52,000 units globally in 2020. The fall may be partly due to the COVID pandemic, in terms of access to residential premises. Japan still leads Europe in micro-CHP by a 10:1 ratio, with negligible shipments outside these two areas.

Fuel cells for telecoms backup is seeing renewed success, and in some remote areas is even used as the primary energy supply. The commercial argument for fuel cells may improve in this sector as costs continue to drop.

Portable remains patchy – in leisure, APUs are used as battery chargers when camping in pristine locations, but commercial applications are increasing: chiefly monitoring and temporary signage and works. Dominated by SFC Energy, with smaller sales from BOC's Hymera, Adaptive Energy and others, over 6,000 portable fuel cells were sold in 2021. The military continues to buy portable fuel cells for evaluation purposes, but also applies tens of units in silent watch and other niche areas.

Educational kits continue to be sold by Inenergy and Horizon Fuel Cell but we do not publish these as part of the overall FCIR figures. Mind you, this segment is probably one of the very few volume applications in which fuel cells presently make a true profit!



Trains and trams – also going places

Fuel cell and hydrogen trains hit the limelight in 2021 at Glasgow's COP26. Two UK fuel cell and hydrogen trains were on display: the HydroFLEX, and the Arcola Energy static conversion of a retired class 314. These are just two of many projects either underway or announced in 2021. Activity in this area is now accelerating from a slow start, begun decades ago.

Capable of similar performance to diesel-electric powertrains, fuel cell trains offer an affordable and potentially emission free future for non-electrified lines across the world's rail networks. They are not, yet at least, perfect substitutes, but with tighter emissions regulations due over the next five years for leading economies diesel fuelled trains have a limited shelf life. Most of the fuel cell train trials use compressed H₂ fuel.

Europe – full 'steam' ahead

Europe has led the application of fuel cells in trains, though activity is now growing elsewhere. Alstom, with its Coradia iLint, estimates that 5,000 passenger trains in Europe currently running on diesel will be replaced by fuel cell or electric trains by 2035. The primary markets are Germany, France, Italy and the UK. Looking ahead, Morgan Stanley estimates the European H₂ rail sector could be worth €24-48bn (US\$28.5-57m) by 2050.

While the first two Coradia iLints continue commercial service on the Elbe-Weser line in Lower Saxony, the next 14 are still on order. They are operated on behalf of LNVG, the regional public transport authority. With 126 diesels on its books and an intent not to buy further diesels, LNVG will need to look further alternative drives sometime in the future.

The iLint uses Cummins (formerly Hydrogenics) HyPM HD 180 modules, hybridised with batteries, with 89 kg CH₂ storage. Cummins is setting up module manufacturing in Herten, Germany, not far from Saltzgitter where the hydrogen iLints are manufactured. With an estimated order book of over 50 units, these include 27 units for the Rhein-Main rail system for use around Frankfurt. Alstom is the market leader at present, though with customers still assessing the potential of the iLint, including total cost of ownership and (proven 95%) reliability, and few actual sales.

Several other German rail operators and public transport authorities are looking at deployment of fuel cell trains as a replacement to diesels. An iLint started in Baden-Württemberg in May 2021, with tests on the Tübingen to Sigmaringen line. In spring 2021, the Brandenburg Government announced a €25m package to reactivate the Heidekrautbahn line on the outskirts of Berlin. €9m is earmarked for six fuel cell trains, as diesel trains are no longer considered acceptable. ENERTRAG will provide H₂ for refuelling, drawing upon the regions' wind farms as a power source for electrolysis.

Outside Germany, Alstom has continued to heavily market the Coradia iLint to other European rail operators. Following trials in the Netherlands and Austria last year, there were further tests at Östersund in Sweden, and trials began this September at the Centre d'Essais Ferroviaires rail research centre at Valenciennes, Northern France.

France's SNCF Voyagers placed a €190m order for 12 Alstom Polyvalent Régiolis units (the French version of the iLint) in April. These will be dual mode vehicles capable of operating on catenary systems and under fuel cell power offering a range up to 600 km (375 miles) on non-electrified sections. The units will be operated over four rail systems across France, in Occitanie, Bourgogne-Franche-Comté, Grand Est and Auvergne-Rhône-Alps. Trials are due to start in 2022 in the Centre-Val de Loire. These are forerunners of potentially many more units, as France still operates a fleet of 1,200 diesel units, while 45% of its lines are not yet electrified.

Alstom also started testing the iLint at the rail research facility at Zmigrod, Poland, from June. Interest in the train stems in part from Poland's National Recovery Plan which has earmarked funds for 30 low emission trains for regional operators by 2026. The diesel version of the Coradia LINT is currently manufactured in the country at Chorzow.

However, Alstom faces competition from Poland's indigenous rolling stock business, Pesa Bydgoszcz. Pesa has designed its electric Regio 160 to be able to operate on H₂ fuel cells or just

batteries. Tests are expected in 2025/26. In the meantime, Pesa unveiled its fuel cell shunter at the Trako 21 rail fair in September. The new SM42 Dn shunter was designed in cooperation with Polish State Railways PKP SA and the refiner PKN Orlen, and uses two 85 kW Ballard fuel cell modules, hydrogen tanks with a 175 kg capacity, and a 167 kWh lithium titanate battery. Once tests have been completed, it will be operated at a refinery.

The Czech company CZ LOKO is working on the concept of a shunting locomotive powered by H₂. The decision was prompted by the assumptions of the European Green Deal, promoting emission-free solutions. The locomotive will be based on the HybridShunter 1000, which has batteries with a capacity of 600 kWh. The HydrogenShunter 800 locomotive will have an 800 kW engine. The CZ LOKO hydrogen locomotive is expected to be certified throughout the EU and is expected to be competitive in terms of total cost of ownership.

Elsewhere in Europe, the three-car Mireo Plus H passenger train continues to be developed by Siemens through the German H2goesRail project, with construction of body units starting this year. Based on the diesel electric Mireo platform, the Mireo Plus H will be powered by Ballard fuel cell modules, and capable of 160 km/hour (99 mph) with a range of up to 1,000 km (621 miles) before refuelling. The timeline appears to have been bought forward in July 2021 when Siemens signed an MoU with the Bavarian Government to build a two-car unit. Testing will now begin in 2023 on the Augsburg-Füssen route, a year earlier than the previous agreement with Deutsche Bahn to test in Tübingen, Horb and Pforzheim. Service entry is expected from 2024.



January 2021 saw the EU FCH2Rail (Fuel Cell Hybrid Power Pack for Rail Applications) project begin. Spain's CAF is converting a three-car Class 463 Civia EMU to a fuel cell powertrain for Renfe. Toyota Europe will provide Mirai-based modules to the €14m project, which is supported by €10m from FCH2 JU. The powertrain will incorporate lithium-titanate batteries to deliver the power needed to overcome the inertia of the train.



Talgo, another Spanish trains business, has fuel cell ambitions, and in October placed an order for eight Ballard 70 kW FCmove-HD modules for its Vittal-One train. This is now expected to begin testing in 2023. In addition, Talgo is converting an electric locomotive to operate with a fuel cell, although due to locomotive space constraints the H₂ will be stored in carriages. In July, Talgo also announced an agreement with Repsol, the Spanish energy business (which is also an H₂ producer), to promote a H₂ train in Iberia.

Elsewhere, in Southern Europe, AECOM, the infrastructure multinational, and Iberdrola, the European renewables business, announced a plan to upgrade the 300 km (186 mile) Apennine line in Italy using hydrogen. This too is being supported by the EU, through the European Clean Hydrogen Alliance. Russia too has been looking at fuel cell trains for the future; the State Railways stating that it would not purchase any diesel fuelled vehicles after 2025.

The UK continues to operate a fleet of 2,500 diesel fuelled trains, with only 38% of the rail network electrified. The UK government has set 2040 as the date by which diesel will be phased out, and the UK's Hydrogen Strategy of August 2021 acknowledges the role that H₂-fuelled trains can

play in the future. To this end, three projects are focused on converting older EMUs to fuel cell powertrains, delivering emissions savings and extending the asset lifetimes: HydroFLEX is based on the 30-year old Class 319s, undertaken by Porterbrook (a train leasing business) and University of Birmingham; Eversholt (another leasing business) has developed the Breeze in a venture with Alstom and uses the former 321 class; and, in Scotland, where the Government is looking to phase out diesels by 2035, Arcola Energy is working with Angel Trains on the conversion of a class 314 EMU (following its conversion, now reclassified as a 614). Arcola has another prospective conversion, a class 158, for Highlands and Islands Transport.

A key objective of the Arcola work on the 314/614 on the Bo'ness and Kinneil Railway is to establish opportunities for the Scottish rail supply chain to industrialise the technology and develop skills. The powertrain is based around Arcola's A-Drive fuel cell platform, developed in the Dundee manufacturing facility. Arcola's new class 614 has a Ballard 70 kW module under each driving car, plus the 210 kg 700 bar H₂ total tanks; the centre-car is fitted with lithium-titanate batteries in place of the transformer.

A challenge facing all the UK's fuel cell conversions is loading gauge, which is smaller than the rest of Europe. Finding the space for the fuel cell modules, batteries and less energy dense CH₂ is challenging. The HydroFLEX (itself now reclassified as the 799), uses space inside the passenger cabin for its single Ballard FCveloCity-HD 100 kW fuel cell (as a range extender) and 277 kg H₂ storage within 36 pressure tanks, not an ideal solution. A HydroFLEX 2 is planned, to improve the layout and increase the power and performance.

The HydroFLEX and Breeze trains started tests, but it is not clear whether any orders for either train is due, though the Tees Valley in North East England has been mentioned as a possible first pilot site.

Hydrogen availability is a key factor in the viability of the fuel, whatever the domain. In July 2021, Alstom signed an MoU with Plastic Omnium, setting up a joint team to manage the technical and commercial development of on-board H₂ storage solutions for the railway market, with development projects already under way. The partners aim to launch these solutions for regional trains in France and Italy from 2022.

Also, in July, Siemens Mobility and the Helmholtz Institute Erlangen-Nurnberg for Renewable Energy (HI ERN) signed an MoU to conduct joint research on the use of liquid organic hydrogen carrier (LOHC) technology in rail transport. The LOHC technology is from Hydrogenious.

In August 2021, Eversholt Rail partnered H2 Green, the Edinburgh-based green H₂ supply facilitator, to establish the production and filling infrastructure needed to support wide-scale deployment of H₂-powered rolling stock fleets, focusing on low-cost green H₂. H2 Green has an exclusive deal with SGN (the Scottish gas network operator) to develop otherwise redundant assets for H₂ production and storage.

Finally, in April, in Germany, HeiterBlick in Leipzig announced it would collaborate with Chemnitz companies Hörmann Vehicle Engineering and Flexiva Automation & Robotik to develop an H₂ fuel cell powered tram. The four-year project is subject of €2.1m funding award from the Federal Ministry of Transport and Digital Infrastructure (BMVI).

Asia – All change

Asia's interest in fuel cell trains can be traced back to at least the late 1990s with projects undertaken in Japan. While Japan's efforts continue, it is clear Korea is now leading the way. A major driver for Korea is the Government's ambition to eliminate diesel passenger trains by 2029. There is also activity in fuel cell heavy rail and trams in China.

Many of the projects underway in Korea include the Korean Railroad Research Institute (KRRI) as a partner, to facilitate trials, and Hyundai Rotem, the rolling stock business of Hyundai Motor Group, with direct access to the NEXO fuel cell module.

As 2021 opened, KRRI was already working with Hyundai Rotem to develop a fuel cell train, capable of 110 km/hour (68 mph), and a 600 km (373 mile) range from a charge of CH₂. A pilot is expected to run from 2022 on a restored section of the Donghae Bukbu Line, between Gangneung and Jejin.



In April 2021, Rotem showcased its 'K-Hydrogen Tram' concept car at its Changwon plant in South Gyeongsang Province. The prototype consists of three cars, capable of carrying up to 100 people. The tram uses four NEXO modules (380 kW total), with a 700 bar CH₂ tank (twice the pressure of the iLint), and a lithium-ion battery. The prototype tram can travel at 70 km/hour (43 mph), with 150 km (93 miles) range on a 42 kg CH₂ charge. Mass production of the H₂ tram is targeting 2024.

Rotem plans to make improvements to the tram in test runs from March 2022 to late 2023, on a 4.6 km (2.9 mile) stretch of the Ulsanhang Line, from Taehwagang to Ulsan Port. The tram development follows the MoU with Ulsan City in August 2020.

The budget for the Ulsan demonstration is ₩42bn (US\$35.6m), with ₩28.2bn from MOTIE, Korea's Ministry of Trade, Industry and Energy. MOTIE plans to first discuss the application of H₂ trams with local governments that have new urban railroad projects (such as Ulsan and Dongtan), and then to export to regions with growing demand, such as Europe and Southeast Asia. KRRI and Hyundai Rotem are working with local components companies to establish a domestic supply chain.

The city of Changwon also plans to use the trams for its city rail service, scheduled to open in 2030. Busan has also been mentioned as a test site, for a catenary-free tram line covering 1.9 km.

LH2 has 1.6 times higher energy density than CH₂, facilitating longer ranges. In January 2021, KRRI, Hyundai Rotem, VC Tech, and Parity,

established a ₩18.6bn (US\$15.8m) project to develop a 2.7 MW module-based fuel cell light rail vehicle capable of 150 km/hour (93 mph), using LH₂, claimed to deliver a 1,000 km (621 mile) range, much greater than other energy storage systems in development in Korea. The aim is to test the full system in 2024, with commercial operation from 2025. Rotem is aiming at LH₂-fuelled high-speed trains from 2030.

Japan's Hybari EMU set, powered by Toyota Mirai fuel cells and Hitachi batteries, has been under development with East Japan Railway Company (JR East) since 2020, and is due to start demonstration in early 2022. The two-car unit will operate on JR East's Tsurumi line and the Nambu line in Tokyo, reaching speeds of 100 km/hour (62 mph) and with a range of 140 km (87 miles).

China launched one of the world's first fuel cell trams on city networks in Qingdao and Tangshan using vehicles developed by CRRC, China's premier rolling stock business. Foshan has seen trams running on its 17 km (10.5 mile) Gaoming line since 2019, again built by a CRRC subsidiary Qingdao Sifang. Attention is now turning to heavier rail vehicles.

In January, trial operations commenced for the Shanghai Pilot Free Trade Zone T1 Demonstration Line in the Lin-gang New Area. The Line will begin operation on pure electric power while HRS are being constructed, with plans to fully switch to hydrogen power once applicable.

Early 2021 saw a CRRC subsidiary, CRRC Datong, announcing its first fuel cell hybrid shunting locomotive using fuel cell systems from SPIC. This locomotive, capable of 80 km/hour (50 mph) speed, started demonstration at the end of October in Inner Mongolia, ironically on a coal railway. In July 2021, a locomotive with a 400 kW fuel cell system was unveiled at Changzhou in East China. The locomotive top speed is reported to be 100 km/hour (62 mph), and it appears to have higher traction capability than the Inner Mongolian locomotive. There are reports that more powerful locomotives are under development.

The demonstration in India of Patiala's Locomotive Works four-car, formerly diesel powered, fuel cell EMU is also due to start. Fuel cell trains could find a large market on one of the world's largest railway networks, but although a number of fuel cell train projects have been announced in the past for the country, there remains little to show.

The most recent initiative was by the Alternate Fuel Organisation of Indian Railways. In August AFO invited bids to convert two diesel-electric multiple units to H₂ fuel cell propulsion, for operation in Haryana State. Unfortunately, in September it was reported that AFO was closed with immediate effect; where this leaves the initiative remains unclear.

North America – Back to the future

North America, like India, has an extensive, continent-wide railway network for which diesel is the primary form of traction. Although there have been past projects converting diesel locomotives to fuel cell hydrogen technologies, notably a DoD supported switcher (shunter) locomotive in the early 2000s, there has been little to show. That may be about to change.

Driven in part by imminent tightening of emissions regulations for diesel locomotives, to very low levels in the USA with the EPA Tier 5 standards, the past year has seen an explosion of fuel cell rail vehicle projects around switcher and linehaul diesel locomotives.

In December 2020, Canadian Pacific announced its investment of C\$15m (US\$15m) to retrofit a SD40-2F diesel linehaul locomotive with fuel cells. In November 2021, the company indicated the first train will run by the end of 2021 and be in service in 2022. The Hydrogen Zero Emissions Locomotive (H₂ OEL) will have six Ballard 200 kW modules, 1.2 MW total.

Also announced was a matching grant from Emissions Reduction Alberta, expanding the scope to cover a switcher and high horsepower unit. The grant also covers H₂ production and refuelling facilities at Canadian Pacific's yards in Calgary and Edmonton. Assuming success, Canadian Pacific is talking about a longer-term partnership with OEMs to develop and commercialise the technology more widely.

In March 2021, Sierra Northern Railway announced a US\$4m grant from California Energy Commission that will enable Ballard fuel cell modules to be fitted to a locomotive. California is reported to have 260 switchers and 500 linehaul diesel locomotives operating in the State, all of which face tightening emissions standards.

A similar project was reported in September 2021, when the Southern Railway of British Columbia (BC) announced that it was seeking to convert a switcher locomotive to fuel cells. Funded in part by the BC and Canadian governments, the project will use Loop Energy's 50 kW eFlow fuel cell modules and Hydrogen in Motion's solid state hydrogen storage system to prove out the concept.

In June 2021, General Motors signed an MoU with Wabtec, to supply its Ultium Li-ion pouch cells and Hydrotec hydrogen fuel cell power cubes. Wabtec plans delivery of its electric trains from 2023, with the fuel cell trains to follow. The electric version, the FLXDriver, uses 20 racks of 20,000 battery cells to deliver 2.4 MWh energy storage. Hybridising the locomotive with fuel cells is a logical next step, to extend range.

In December 2021, BNSF, one of the largest freight railroad operators in the US, Caterpillar, and Chevron signed an MoU to establish the feasibility and performance of H₂ fuel for rail operations. Progress Rail, a Caterpillar company, would design and build a prototype fuel cell powered locomotive for linehaul service; Chevron the fuelling concept and infrastructure; and BNSF would make available its lines for prototype testing.

The MoU is preliminary, and we will need to wait to see what comes of it. Progress has developed EMD Joule, a battery electric locomotive with 2.1 MW of power and 1.9 MWh lithium-ion phosphate storage, which could also benefit from fuel cell hybridisation.

Switzerland's Stadler Rail remains on track to deliver a fuel cell version of its FLIRT DMU to the San Bernardino County Transport authority in 2024. But in Toronto, MetroLinx, responsible for the regional rail commuter service, announced in March 2021 that it was dropping the ambition for a H₂ railway. Citing issues with "fuel production, storage and transport, as well as refuelling" it concluded the technology wasn't suitable for the "immediate term". However, the prospect of a pilot using H₂ fuel cell technology may still be part of bids into its procurement of future services.

And it's not all PEM. In February 2021, the start-up NextGenPropulsion, LLC, in North Carolina signed an MoU in February with Georgia-based start-up Fuel Cell Enabling Technologies, to purchase SOFCs for its light-rail trains and freight locomotives. Though as with most ventures involving early technologies from start-ups, the progression from concept to market may be some years away.

Materials handling and forklift trucks

Materials handling equipment continues to be a major adopter of fuel cells with application in forklifts, logistics and port machinery. In unit numbers, fuel cells for materials handling reached 16% of overall shipments in 2021.

Plug Power remains the leader in this sector and 2021 was another busy year with around a further 10,000 FC systems being deployed, bringing the total number deployed to over 50,000 by the year end with over 150 fuelling stations in operation to support them, and their new Rochester, NY, Gigafactory opening in November.

Plug were also busy in the capital markets, completing a US\$2bn capital raise in February, in addition to the US\$1.6bn investment announced in January by South Korea's SK Group, with whom Plug joined in a strategic cooperation, with a new JV formed for expansion in Asia. The JV includes plans for a new Gigafactory in South Korea by 2023. In October, Plug also partnered with Fortescue, in Australia, signing a letter of intent for a 50:50 JV to build a Gigafactory in Queensland.

Plug also continued its expansion into green hydrogen, announcing four new green plants, with a total capacity of 100 tonnes per day, to be located in New York, Georgia, Texas and California. The first two plants are expected to be operational by 2022 and the others by 2024.



The cooperation between Plug and Gaussin, the French logistics vehicle company, announced last year, saw Plug order 20 ATM-H2 yard trucks, based on Gaussin's TM 38T electric skateboard, already in operation at over 35 sites in Europe. The 38-tonne vehicles were to be delivered starting in November 2021 and will be deployed to Plug's customers. The fuel cell trucks are higher power platforms than most vehicles to date, part of an industry trend.

Gaussin also unveiled its Zero-Emission Yard Automation autonomous tractor equipped with a robotic arm, based on Gaussin's ATM and TSBM hydrogen powered vehicle platforms, intended for deployment with logistics and e-commerce companies.

The news during the year wasn't only from Plug, with plenty of activity from other companies too. In Europe, the StasHH consortium was formed by eleven fuel cell suppliers and nine OEMs to define, develop and validate the first European standard for fuel cells in heavy duty-mobility applications.

PowerCell, Sweden, unveiled a complete product portfolio for H₂-electrification in the off-road segment with power ranges from 60 kW up to the MW scale. PowerCell won follow-on orders for two 100 kW FC systems from a US agricultural equipment manufacturer for testing with tractors as well as an order from their Japanese distributor for two feasibility studies on fuel cell systems for the off-road market, including materials handling.

Also in Sweden, myFC, silent for the last two years, entered into an agreement with an unnamed European OEM to develop fuel cell solutions for automated guided vehicles used as warehouse robots, and Volvo Construction Equipment opened a Fuel Cell Test Lab at their Technical Centre in Eskilstuna, Sweden.

Swiss-based fuel cell developer EH Group started collaborating with DOKING, which manufactures specialised robotic vehicles (bulldozers, etc.) for applications such as underground mining, to trial the use of fuel cells.

Ballard Power joined the Hydra consortium, which aims to develop a 200 kW-plus electric powertrain prototype using Ballard fuel cells hybridised with batteries for the mining industry, with funding from the Chilean Economic Development Agency. If successful, the plan is to scale this to replace the diesel engine in a 2 MW hybrid H₂ mining truck.

In March 2021, Loop Energy, Canada, and Morello Giovanni, Italy, signed a strategic cooperation to develop and manufacture heavy duty FC materials handling equipment using Loop's eFlow fuel cells.

BMW expanded its use of fuel cells, announcing it would use fuel cell powered forklifts, tuggers and stackers in their South Carolina plant, working with Plug and Linde for supply of the equipment, initially 85 vehicles, and refuelling infrastructure. BMW also expanded its H₂-fuel cell powered fleet in their Leipzig plant with an additional 37 vehicles to be deployed, bringing the total number of fuel cell powered vehicles in the plant to 118 units.

Hyzon has now made a play in this sphere, in May entering a strategic collaboration with Sojitz Machinery Corporation of America to explore possibilities to develop new fuel cell-powered machinery and applications, including forklifts.

Unsurprisingly, ports remained active areas both for H₂ distribution and H₂ materials handling. In the Netherlands, real-world testing continued with a Terberg YT203-H2 terminal tractor. The tractor, with its fuel cell developed by Zepp solutions, completed an almost 6-month trial at the Port of Rotterdam and has been transferred to the Antwerp Euroterminal for further testing, with the commercial launch of the tractor planned for 2023.



Ports are also a popular testbed for fuel cells in the US. The Zero Emissions for California Ports (ZECAP) project moved ahead on its two fuel cell electric terminal tractors, Capacity of Texas Trailer Jockey Series TJ9000 gliders fitted with FCveloCity-HD85 85 kW stacks from Ballard, starting 12-month trials at the Port of Los Angeles and Long Beach.

Initial smaller fuel cell engine investments for forklifts are providing a springboard to larger vehicle application. Nuvera's latest E-45 and E-60 engines extends its offering to larger materials handling applications, as well as to buses, trucks,

and other on- and off-road vehicles. In December 2020, the cargo truck maker Capacity Trucks and Nuvera's owner, Hyster-Yale, announced plans to incorporate the latest engines into two prototypes for market testing over 2021.



North American container handling crane maker PACECO and Mitsui E&S Machinery (MES-M) in Japan are developing a H₂ fuel cell powered Rubber-Tired-Gantry (RTG) crane for use in ports with funding from the New Energy and Industrial Technology Development Organization (NEDO), with initial testing planned for 2022.

Meanwhile, in China, Hangcha reported sales of 209 units of their fuel cell powered forklifts over the year, while compatriot Heli released their new forklift, with plans to extend the range, to include tractors and storage trucks. There were also several demonstration projects for fuel cell powered forklifts announced, including at the Shanghai Qingpu Industrial Park. However, fuel cell forklifts face a subsidy barrier, which has been focused on vehicles of 40 kW power and above.

In South Korea, in July 2021, Doosan Fuel Cell and STX Corporation signed an MoU to develop a new fuel cell business targeting the agricultural centre.

Overall, fuel cells in materials handling are growing, in unit numbers, range of power outputs and range of applicable vehicles. The numbers look set to grow further as costs reduce and the slow but now sure move to renewables gains momentum. Presently, cost is the major barrier to more rapid growth, with the investment in H₂ generation and storage systems requiring a fleet of 90+ forklifts at any one location to be financially viable.

Bicycles and motorcycles

Intelligent Energy and Suzuki's Crosscage concept of 2007 and the Burgman moped of 2011, trialled by UK police, are rare examples of fuel cell and hydrogen 2-wheelers. A notable mention was in 2019, when Pragma Industries made headlines at the 45th G7 Summit where the H₂ fuel cell powered 'Alpha' bicycles were provided to journalists to cover the event, able to travel up to 150 km on single charge. That's a long way on a bicycle, and perhaps why it has struggled to challenge the rapid advance of the pure battery ebike market. With electric assistance of the mobility category limited to 25km/h in Europe, electric motors are small, and batteries can typically do the job well, packaging the batteries on or even in the frame. Charging can be done at home, or batteries can be swapped.

Rapid replenishment of stored energy is perhaps the reason for the reinvigorated interest, but this time in motorcycles and in hydrogen. Mob-ion is exploring the use of H₂ canisters from STOR-H, the Swiss based hydrogen storage company. The moped, planned for production in 2023 in France, will use 3 canisters, about the size of two soda cans, to achieve a range of 60km. In comparison to its battery-powered eMoped, able to travel nearly 400km it doesn't sound very impressive, but the hydrogen fuel cell powertrain is lighter, allows for more storage and could allow for fast recharging with the right recharge retail infrastructure.



STOR-H itself is seeking series B funding, with a price tag of €10m. It sees its canisters being used in applications requiring 200 W to 12 kW.

New concepts have also been presented but with little of substance yet. Segway has developed a concept H₂-powered 2-wheeler. It would have a 60 kW fuel cell to achieve 0-100 kph in less than three seconds, but little other information is available, except sketches showing three side-mounted H₂ canisters and reports of 1 g H₂/km consumption which could lead to significant range.

Even less detail is available on the XCELL from China's X-IDEA Industry Design Group, founded in 2009 by specialists formerly of the Honda Research Institute. Its motorcycle concept utilises four canisters.

The project with most credibility is the H₂ Kompact from French motorbike racing team Tecmas and sensor manufacturer TEXYS. The R&D group delivering the H₂ MOTRONICS project are aiming to showcase compact, lightweight FC applications, with a proof-of-concept racing motorcycle. Models suggest the bike could run eleven laps of Spain's Ricardo Tormo Circuit on 1.5 kg of H₂ at Moto3 levels of performance. The stacks and components are being delivered by EKPO, with the 'halo' product to be a demonstrator, transferrable to other 2 and 4-wheel urban light vehicles, marine applications, snowmobiles and off-road buggies.

While an alternative to battery electric may offer weight saving, and fast re-charging could provide more autonomy, personal mobility requires convenience. This will require a well-developed retail infrastructure to exchange spent canisters, or direct access to H₂ refills. HRS builds are proving challenging for high volume applications like cars and will be even more challenging for smaller niches. A standardised canister may be the route forward, but it has stiff competition from batteries.



Boats giving way to ships

The focus for decarbonising shipping in 2021 remained on the long-term, large-scale, use of cleaner fuels, with batteries, fuel cell hybrids and internal combustion engines using hydrogen being just some of the many paths being explored.

Interest in fuel cells and hydrogen continued to grow in 2021, with new orders, new entrants, and companies looking to use fuel cells in ever-larger platforms, but with margins for freight and for ferries being low until recently, still at a slow pace. The most powerful marine system so far was ordered, the first of shipping-company Silversea's Evolution class, set to enter operation by 2023. A H₂ fuel cell system, hybridised with a battery, will supplement the main power supply and carry the ship's total hotel load of up to 4 MW. Liquefied natural gas will be consumed as the main fuel in dual-fuel engines. The year also saw the first commercial fuel cell powered ferries delivering to their owners, with operations to start from 2022.

The regulatory environment is also adapting, with draft guidelines for fuel cell power installations agreed by IMO for approval in 2022. ABS awarded Bloom a Concept Verified Statement of Maturity, another step on the path to commercial use, and we saw new designs for fuel cell powered vessels receiving approvals from classification societies.

The fuel choices are many: compressed hydrogen for smaller vessels, liquid hydrogen for large ships; ammonia and LNG. The use of these fuels in fuel cells vies with combustion engines. Ammonia is favoured by many actors, given its high energy density and ease of production from green H₂.



Norway continues to be a focus country

Norway remains very active, given the country's rugged coastline, intensity of ferry operation and position of the country as a major ship-owning nation.

In July 2021, Norled took delivery of its first LH₂ ferry, MF Hydra (with Ballard FCwave fuel cells). Initial operations will be on battery power alone, operation on hydrogen is expected within 2022.

The Norwegian Public Roads Administration announced the winning tender for the 15-year operation of a hydrogen-powered ferry on the Bodø-Røst-Værøy-Moskenes route from 2025, on this occasion Norled losing out to Torghatten Nord. The Topeka project, reported last year, remains on course, with NOK219m (€22m) in state aid from ENOVA receiving approval.

It was busy for Norwegian fuel cell developer TECO 2030, receiving an Approval in Principle ("AIP") for its 400 kW marine PEM module (FCM 400), developed in partnership with AVL, and moving into their new production facility. The plan is to start pilot production in 2022, ramping up to 1.2 GW of fuel cells annually. TECO also signed an agreement with Chemgas Shipping BV to supply up to 200 MW of fuel cell systems for installation on 120 barges and 40-60 tugboats to transport green H₂ made in Romania to Germany and Austria as part of the Blue Danube project as outlined last year. First deliveries are scheduled for 2023 but the majority after 2025.

In December 2020, the Norwegian energy storage company, Corvus Energy, announced an MoU with Toyota. Corvus' new dedicated fuel cell division will design and certify the marine fuel cell system using the Toyota fuel cell technology as a building block for larger systems. Toyota itself established a new Fuel Cell Business Group in Brussels to deliver on its growing portfolio of maritime opportunities.

The MoU facilitated Corvus as lead to the H2NOR collaboration, with €5.9m funding from Innovation Norway and the Research Council of Norway. The project aims to develop cost-effective, marinised, PEM fuel cells based on Toyota modules. Partners Equinor, Norled, Wilhelmsen, LMG Marin, the NCE Maritime CleanTech cluster and the University of South-Eastern Norway, aim to have a system installed by 2023 and the system marine-certified and commercially available by 2024. To deliver flexibility, a second system – designated as SOFC/HTPEM – is to be launched in 2025.

Ulstein continues to evaluate the use of fuel cells, in July 2021 announcing a teaming with EDGE, a Norwegian start-up focused on green maritime, ABB and Ballard to deliver a concept design for X-BOW, a future zero-emissions container ship.

In April 2021, following years of trialling, CMR Prototech A/S signed an MoU with Sunfire Fuel Cells to cooperate on the further development and scaling of Sunfire's SOFC stacks in anticipation of mass-market roll-out to the maritime industry.

In December 2021, CMR Prototech A/S was taken over by Aker and rebranded as Clara, entering into an agreement with Aker and Eidesvik to study the use Clara's fuel cell systems in shipping and announcing their 32 MW LNG fuel cell concept developed in cooperation with Statoil and Shell.

Focus is growing on implementing the infrastructure required to supply ships with H₂. Aurora, launched by BKK, Air Liquide, and Equinor aims to build a complete liquid hydrogen (LH2) supply chain for ships in western Norway by 2024. It includes a newbuild LH2 facility at Mongstad, Norway with plans to deliver 6 tpd of renewable LH2 from electrolysis.

Europe helped by FCH2 JU

Activity wasn't limited to Norway, with plenty of progress in other European countries. Kongsberg tested and verified a full-scale, zero-emissions drivetrain powered by hydrogen fuel cell intended to verify the final design for a H₂-powered ferry as part of the EU funded project HySeas III, involving partners from Scotland, Denmark, France, Germany, Sweden and England.

Further FCH2 JU projects include HySHIP, with its coastal goods-carrying RoRo by Topeka, with a 3 MW fuel cell engine using LH2 from the Aurora facility at Mongstad scheduled for 2024; ShipFC, the platform support ship, with NH₃ fuel (with Prototech/Clara partnering Sunfire to deliver a 2 MW FC engine late 2023); hySafe (bunkering and offloading of H2); H2ports, and others. The 14-partner ShipFC project includes Norwegian actors Wärtsilä (Norway), NCE Maritime CleanTech, Equinor, Eidesvik, as well as Clara. It remains to be seen whether the Clean Hydrogen PPP will sustain support, now driven more by corporate sustainability concerns and fuel savings than R&D.

In January 2021, Alfa Laval, DTU Energy, Haldor Topsøe, towage company Svitzer and the Maersk Mc-Kinney Møller Centre for Zero Carbon Shipping began the SOFC4Maritime project to accelerate the development of SOFC for ships,

with funding from the Danish Energy Technology Development and Demonstration Program (EUDP). Alfa Laval will head the initiative, Topsøe will provide stack technology and DTU Energy will aid system layout and component testing. The gross budget is DKK 17.4m (€2.3m).

In April, another EUDP project funded fuel cell maker Blue World Technologies, Alfa Laval and vessel owners DFDS, Maersk Drilling and Hafnia to build a 200 kW methanol-fuelled PBI fuel cell APU, aiming to produce a scalable system up to 5 MW. Gross budget is DKK 21m (€2.8m).

In June 2021, CMB.TECH opened the world's first multi-modal HRS in the port of Antwerp, supplying green H₂ to small ships, cars, trucks and industrial customers. The HRS will be used to fill the CH2 tanks of the Hydroville ferry launched in 2017, used in its internal combustion engines.

Inshore as well as offshore

The race is on for the first sizeable commercial fuel cell powered inland vessel. The ZULU 06, a demo vessel of the FLAGSHIPS project with 2x 200 kW Ballard PEM FC modules, should start operations on the Seine within 2022. Likewise, Future Proof Shipping (FPS) is retrofitting the FPS Maas with 3x 275 kW PEM FCs from Koedood Marine Group (supplied by Nedstack), the vessel expected to be sailing on H₂ by Q3 2022. FPS purchased a further two vessels for retrofit, the FPS Rijn and FPS Waal, with plans for them to be operating by 2023. The WEVA project progresses, with Concordia Damen receiving an order from Lenten Scheepvaart for a 3,700 tonne fuel cell powered vessel, with delivery in 2023.

Much of the activity remains centred on smaller vessels, however. In November 2021, Proton Motor announced it was developing a modular marine H₂ system, able to deliver powers between 30-120 kW, Torqeedo, part of the DEUTZ group.

In the same month, as part of a £1.05m (€1.21m) project under the UK DfT's Clean Maritime Demonstration Competition, Proton was commissioned by ACUA Ocean to produce a FC power source for a marine drone vessel. In the £2.2m HIMET (Hydrogen in an Integrated Maritime Energy Transition) project, France's Genevos was chosen as the module supplier to provide a fuel cell APU to be trialled on a RoRo ferry in the Orkneys. Genevos uses Cummins stacks rated from 15 to 45 kW, connected in parallel to provide up to 500 kW.

It has been a busy year for EODev. In April 2021, Toyota injected capital to become a direct investor. Also, in April, Fountaine Pajot indicated a REXH2 range extender will be fitted to a Semana 59 catamaran. In this first configuration, the 70 kW range extender will be hybridised with a 44 kWh battery with 7.5 kg H₂ storage. A demonstration is expected in 2022. In May 2021, HYNova 40, a 12 m, 12-passenger pleasure boat was unveiled. The boat has a REXH2 unit, and autonomy of 8 hours at a speed of 12 knots. The refill time is 20 min. Each Mirai module delivers 70 kW net power, with up to 1 MW available by stacking the modules.



However, 2021 wasn't all positive. DFDS's ambitious plans to develop a fully H₂-powered ferry, the Europa Seaways, with 23 MW Ballard fuel cells, for the Copenhagen to Oslo route failed to receive funding from the EU.

Activity in the United States

Further afield, Switch Maritime's Sea Change, a 75-passenger ferry built by All American Marine, with a H₂ fuel cell system from ZEI, including 360 kW of fuel cells from Cummins, remains on track to enter service in the San Francisco Bay Area in 2022.



Activity in Asia

In November 2020, Doosan announced it will work with London-based global shipping company Navig8 delivering SOFCs to a 50,000 tonne petrochemical carrier.

Major shipbuilders in South Korea are increasingly engaged with fuel cells. Korea Shipbuilding & Offshore Engineering Co. (KSOE, owner of Hyundai Heavy Industries), the largest shipbuilder in the world, unveiled its business roadmap for H₂-fuelled vessels. In March 2021, KSOE signed an MoU with Doosan to supply SOFCs for integration into ships by KSOE. In September, KSOE signed a further MoU with AVL, to jointly develop PEM H₂ systems with outputs of 200 kW to 1.5 MW for smaller vessels. The PEM fuel cells will be used as engines for domestic coastal island ferries, tugboat inland waterway cargo ships, and medium-sized H₂ carriers.

In July 2021, Hyundai Global Service signed an MoU with Hyundai Motors to manufacture and commercialise its fuel cell systems in the marine market, with the first small sized model planned for 2H 2022. Meanwhile, Samsung's co-operation with Bloom Energy, announced July 2020, gained AIP from DNV for their 100% fuel cell powered LNG carrier design. Samsung also received AIP for its FC-powered wind turbine installation vessel design.

The 2030 Green Ship-K Promotion Strategy (part of the New Green Deal), a ₩960bn (US\$870m), the South Korean government initiative launched late in 2020 targeting a move to low-carbon shipping, saw Korea's first commercial H₂ pleasure boat unveiled in June. The Hydrogenia is 32.8 ft (10 m) long, and can hold six people and operate at 10 knots for six hours. Built by Vinssen, powered by a Danfoss Editron electric drivetrain, the stacks are likely from Nuvera. Vinssen plans 50 further boats using similar H₂-electric drivetrains over the next year.



In October, Vinszen and KIER announced an MoU to develop and commercialise NH₃-cracking technology for H₂-powered fuel cell ships.

While Japan has ambitious goals to move to hydrogen, the maritime focus has been on H₂ ICE. However, there is interest in FCs too. e5 Lab, funded by Mitsui O.S.K Lines, Mitsubishi Corp. and others teamed with Swiss Almatech to promote its FC-powered ZESST passenger shuttle ferry.

Yanmar is developing a 300 kW-class maritime fuel cell system using Mirai modules. Yanmar started its marinisation journey in 2013, first testing fuel cell components and then in 2016 developing a battery electric drivetrain. In March 2021, Yanmar began its boat trials. The 38 ft (11.6 m) boat uses CH₂ at 700 MPa. Yanmar will obtain type approval so that the system can be installed in boats from 2023.

In China, the few projects so far have been limited to smaller demonstrations: in January 2021 Dalian Maritime University launched motor yacht 'Lihu', powered by a 70 kW FC system fed by CH₂; joined by 'Jiahong 01', a small ferry powered by a methanol-PBI stack from Zhongke Jiahong (Foshan) New Energy Technology; and, May saw the Foshan launch of 'Xianhu 1', a 12 m long, 30-passenger cruise ship, with a 30 kW PEM stack from Pearl Hydrogen using CH₂. 2021 also saw the China Classification Society (CCS) grant the first type-approval for a domestically-sourced marine fuel cell, a PEM from Troowin Power.

Big news in cruise

The COVID pandemic hit cruising hard, with Freudenberg Sealing Technologies (FST) methanol FC on Carnival Corp.'s Aida Nova delayed until summer 2022. But progress was made elsewhere. In December 2021, MSC revealed plans for MSC World Europa, being built at Chantiers de l'Atlantique in France, and expected within 2022. Bloom will fit the ship with a 150 kW APU running off LNG. In July, MSC, Fincantieri and Snam announced an MoU to study the feasibility of building an ocean-going H₂-powered cruise ship.

In September 2021, Ceres was awarded UK government funding for two feasibility projects targeted at MW-scale propulsion. A consortium involving GE Power Conversion, MSC and Lloyd's Register will explore the integration and trade-offs of SOFCs into a ship's operational functionality, existing power and propulsion architecture and layout. Ceres' SOFC technology is also being evaluated as a replacement to the diesel generators used for 10 MW hotel loads in large cruise ships, with Carnival UK, Southampton University, Shell and Lloyd's Register.

The Lürssen shipyard started construction of a new mega-yacht with an FST reformed methanol fuel cell in June. This will allow a ship to spend more than 15 days at anchor or cruise for more than 1,000 miles with zero emissions, building on the learning of the 'Pa-X-ell 2' project. But the big news was Silversea Cruises' (Royal Caribbean) order for two new 'Project Evolution' vessels from Meyer Werft with delivery from 2023. These will have an FST reformed methanol system capable of carrying the total hotel load (up to 4 MW) whilst in port.

Perhaps maritime fuel cells are just about to take off: In May, 20 students from TU Delft conducted initial tests on the 'Hydro Motion' purpose-built trimaran. The boat has a 30 kW Cummins HyPM-HD30 fuel cell and batteries in a hybrid drivetrain. A 350 litre CH₂ tank stores 265 kWh energy. Transitioning to the hydrofoils happens above 13.6 mph, when the fuel cell alone can power the boat. So far, the trials have been limited to speeds of 20 km/hour.

Aviation – lifting-off

Most of the CO₂ from aviation arises from short and medium-range flights, with aircraft deployed on such routes accounting for 70% of the global fleet. Routes shorter than 3,000 km account for 90% of all flights and more than 50% of aviation CO₂ emissions overall. These factors, alongside the high power to weight ratio needed of the prime mover and the range impact of fuel energy density, dictate the viability of alternatives and push towards a focus for these on shorter flights.

The climate impact of aviation may be reduced by using synthetic fuels from gasification of biomass or from electrolysis. Combustion of H₂ in the turbine goes a step further but this still carries a NO_x impact, as well as promoting contrails. PEM fuel cells are generally seen as most suitable to aviation. However, challenges such as weight, cooling and packaging have dented their take-up.

Stack heat rejection in low temperature PEM is a key challenge, with oversized stacks to improve efficiency. Companies like Ballard and Horizon have stacks with specific powers of 4.7 and 5.50 kW/kg but these values do not include endplates. Allowing for the balance of plant, the specific power of LT-PEM systems is below 1 kW/kg (compared to 2.75 kW/kg for a small turboprop).

Uncompressed hydrogen has a specific energy of 33 kWh/kg but this reduces to around 2.5 kWh/kg for LH₂ storage, including the system, and around 1.8 kWh/kg for CH₂ storage (jet fuel in a tank is around 10 kWh/kg).

These power and energy challenges require large decreases in airframe masses if range is not to be compromised severely. Together with the specific power and cooling improvements needed in PEM systems, commercial fuel cell powered aircraft are generally considered to be 10 years away (for short flights), or 15 years away (for regional flights).

High temperature PEM and SOFC systems are also being considered. With HT-PEM, a significant delta between ambient and stack operating temperatures exists, facilitating heat rejection, simplifying the balance of plant, increasing system specific power, and with a potential to reduce costs. But today, the HT-PEM stack level specific powers are less than 0.5 kW/kg, stack durability is low, and membrane and system costs are higher than LT-PEM.

The power density of SOFC is significantly lower than that of PEM fuel cells, so these are generally targeted at APU applications.

Despite the difficulties in delivering practical fuel cell powertrains for aviation, activity has grown greatly over the last year. Airlines appreciate the efficiency benefits of sizing engines for cruising altitude, as opposed to the take-off phase as in previous generations. This poses a challenge for pure electric aircraft, where the battery mass is carried even when discharged. Consequently, demonstrators like ZeroAvia use a battery for take-off, switching to a fuel cell at cruising speeds and altitudes. Today, much of the activity focuses on establishing system designs and testing concepts, using the most power-dense stacks available, increasingly at kW-MW power scales.

ErlingKlinger signed an agreement with Airbus on a long-term partnership in fuel cells in October 2020. DLR is active with BALIS and DLR-HY4. APUS H₂ and H2FLY are further industry projects in Germany. PowerCell, the HyPoint and Hyzon Motors have all supplied fuel cells to ZeroAvia, which is attracting increasing levels of UK grant aid and investment funding. Plug is increasing its attention on aviation. In Canada, the Low-emission Aviation initiative is aiding the integration of fuel cells into aircraft propulsion systems. And in China, state-owned COMAC has developed a H₂ fuel cell aircraft, with test flights during 2019. Japan (JAXA) and Korea (Hanwha Aerospace) are also active in the area.

The 6th-generation HY4 4-seater passenger aircraft, powered by a fuel cell-battery hybrid, was unveiled at its home airport in Stuttgart, in December 2020. The HY4 has twin fuselages, each with room for two passengers, on either side of the central engine. The project began in 2015, with 30 test flights since.



The aircraft is operated by H2FLY, a start-up of the German Aerospace Centre, DLR. The powertrain was developed by the DLR Institute of Engineering Thermodynamics, partnered with Diehl Aerospace, aircraft manufacturer Pipistrel, and four universities. TU Delft delivered the overall system design, of H₂ tanks, fuel cell-battery, hybrid, power distribution and electric motor.

Once the aircraft received its permit-to-fly, it was to undergo further testing at Stuttgart Airport for six months. HY4 uses a 65 kW PEM from Cummins, with a lithium-ion battery to augment power for take-off and while climbing. The 120 kW motor enables a top speed of around 200 kph (108 knots), a cruising speed of 165 kph (89 knots), and a range of 750-1,500 km (470-940 miles) depending on speed, altitude and payload. The stack incorporates a liquid cooling system with a novel aerodynamic solution for cooling air flow.

In August 2021, the EnaBLE project was awarded €8m in BMWi funding to develop and optimise a modular fuel cell hybrid powertrain for H₂-electric aviation. The consortium, led by Diehl Aerospace, includes MTU Aero Engines, DLR, H2FLY and the University of Ulm. The project is focused on developing a 250 kW module, with the aim of implementing this in small aircraft with up to 19 seats. The scope of delivery includes operation at higher altitudes, simulated by a pressure chamber.

In April 2021, the Project Fresson consortium, led by Cranfield Aerospace Solutions, with partners Ricardo (providing the fuel cell powertrain and controller to manage the balance-of-plant), Innovatus Technologies (developer of SHyFT, a lightweight H₂ tank design with a composite cellular core), and Britten-Norman, won a £9m (US\$12m) grant to develop a flying demonstrator by September next year. The target 9-seat Islander light utility aircraft is used in regional commercial and military transport and was designed in the 1960s. A fleet of around 750 operates around the world today according to maker Britten-Norman.

In December 2020, ZeroAvia was awarded two grants from the UK governments' Future Flight Challenge. The share to the company is £1.2m (US\$1.7m). In Project HEART (Hydrogen-Electric and Automated Regional Transportation), a £3.7m programme in total, ZeroAvia is developing enabling systems: green-H₂ infrastructure at airports, maintenance regimes for H₂-electric aircraft, and will demonstrate flight

capabilities on routes of its airline partner Loganair. In project SATE (Sustainable Aviation Test Environment), also valued at £3.7m, ZeroAvia will conduct flight testing in support of the Highlands and Islands Airports' (HIAL) ambition to set up Kirkwall airport as the UK's first operational, low-carbon aviation test centre.

In January 2021, ZeroAvia gained a further £12.3m (US\$16.9m) UK government grant, plus US\$21.4m in Series A funding, to deliver a certifiable 19-seat H₂ aircraft, in a 350 NM (650 km) test flight, in early 2023. The ATI grant followed ZeroAvia's 8-minute, 1,000 ft (300 m) high test flight in September 2020, using a smaller (250 kW) version of ZeroAvia's PEM powertrain in a 6-seat Piper Malibu M350. The grant to the HyFlyer II project facilitated the European Marine Energy Centre (EMEC) and air compressor specialist Aeristech to deliver a platform-agnostic 'ZA-600' (600 kW) H₂-electric powertrain.

ZeroAvia is also partnering with British Airways in IAG's 'Hangar 51' start-up accelerator, to establish how H₂-powered aircraft can play a leading role in future sustainable flying.

In April, ZeroAvia started development of a 2 MW H₂-electric powertrain for full-size regional aircraft capable of carrying 50+ passengers, aiming for a test flight by 2026. The project is supported by US\$24.3m in new funds, led by Horizons Ventures, British Airway and Shell Ventures. In August 2021, ZeroAvia said it would use two Dornier 228 aircraft previously in service for regional flights in its fuel cell engine development. The ZeroAvia 600 kW H₂-electric powertrains will replace the twin engines, along with tanks holding 100 kg of compressed H₂, to support the target 500-mile (800 km) range.

Also, in August, ZeroAvia demonstrated its 'ZA-600' powertrain, pulling its new 15 t HyperTruck mobile ground test platform across the tarmac at its HQ in Hollister, CA. The HyperTruck, based on a military HD truck, is sized for the company's 'ZA-2000' (2 MW+) powertrain, to test systems for 40-80 seat aircraft. In November, ZeroAvia announced Alaska Airlines was collaborating in the ZA-2000 fuel cell engine development, aiming to deploy the engine in a De Havilland Q400 aircraft, able to carry 76 passengers. ZeroAvia will set up a location in the Seattle area to support the initiative. Alaska also secured options for up to 50 conversion kits.

It was further announced in August that ZeroAvia had secured an additional US\$13m for its 50+ seat aircraft engine development programme, from AP Ventures, Horizon Ventures, Shell Ventures and others. Alongside a US\$35m investment by United Airlines and Alaska Airlines, over US\$115m had been invested by stakeholders by December 2021.

Over 2021, ZeroAvia made a series of orders to PowerCell for MS-100 stacks for its aircraft powertrain developments. It also placed an order for a Gen 3 stack from Hyzon in August 2021. Hyzon's stack claims a volumetric power density above 6.0 kW/litre and a specific power density more than 5.5 kW/kg. ZeroAvia will test the stack through simulated airplane duty cycles, including take-off, cruising, landing and taxiing, and more demanding situations including rapid changes in altitude and other ambient conditions. Once the stack has been validated in a ground test programme, the next step will be to test it in flight.

In January 2021, project BALIS, led by DLR, was awarded €26m (US\$32m) funding, to build a powertrain competence and test bed facility, encompassing the fuel cell sub-system, LH2 tanks, electric motor and control technologies. BALIS targets a 1.5 MW PEM fuel cell, for a Dornier 328 regional aircraft with 40-60 seats and a range of 1,000 km (625-mile).

In July, H2FLY and Deutsche Aircraft, an OEM focused on the commercial development of the Dornier 328 platform, signed an MoU to work on H₂ fuel cell technology. The companies plan to deliver a Dornier 328 demonstrator by 2025, with a commercial system being available in 2028. Fuel cell propulsion is just one aspect of Deutsche Aircraft's development scope, which also includes the creation of a SAF compatible airframe and more efficient turboprop engines for the D328.

Later in July, Deutsche Aircraft and Universal Hydrogen announced a collaboration in a design study to incorporate Universal's modular capsule technology into the Dornier 328. The joint effort will analyse the size and integration of Universal's capsules into the aircraft structure and systems (including loading and unloading considerations); aircraft weight and balance; H₂ cost and logistics; mission performance.



Universal aims to build a fuel distribution network, supplying drop-in modules to aircraft, which are swapped-out with fresh modules once discharged. In March 2021, Plug Power took a minority stake in Universal, extending the agreement last year to develop a fuel cell powertrain for regional aircraft, starting with a Dash 8-300. Universal planned to build its first subscale aircraft powertrain by Q2.

The companies also agreed to an offtake model for green H₂ to become cost-competitive with jet fuel by 2025, fitting in with Plug's strategic positioning into green H₂. Assuming a successful ground proof, a PEM powertrain will be fitted into a Dornier 328, with a first flight set for 2023 and ambitious hopes for entry into revenue service in 2025, targeting retrofits for existing regional aircraft.

In August 2021, Plug Power, Universal Hydrogen, magniX, and AeroTEC set up a Hydrogen Aviation Test and Service Centre at Grant County Airport, in WA state. The centre will focus on test flights and certification of Universal's retrofit conversions.

In November, ASL Aviation Holdings, an aviation services group based in Dublin, announced plans to purchase up to ten ATR 72 conversion kits for installation into its fleet, for the turboprop cargo market. Also, in November, Universal secured US\$62m in funding from investors including Mitsubishi HC Capital, Stratos and GE Aviation, bringing Universal's total capital raised to US\$85m.

In December 2021, the American start-up Connect Airlines ordered 12 Dash 8-300 conversion kits, with an option for a further 12 kits for other aircraft types. The kits consist of a H₂ fuel cell powertrain compatible with Universal Hydrogen's modular capsule technology. The target date for introduction into service was again set for 2025.

Although Universal's business model is novel, similar in concept to the swap-out of batteries for electric vehicles, it does not appear to change the fundamental of compressed H₂ being a low energy density vector. Were the capsules to be fitted to a transatlantic airliner, a 9 m extension to an A321 fuselage length would be needed to retain the same passenger capacity as existing aircraft.

In January 2021, Airbus unveiled its own powertrain concept, within the ZEROe initiative. The concept features six, eight-bladed pod engines mounted beneath the aircraft wing. Each pod is a standalone propulsion system comprising composite propeller, electric motor, fuel cell, power electronics, LH2 tank, cooling system, and auxiliary equipment. The pod configuration still requires work to determine whether it could be a practical solution.

In October 2021, Plug announced a partnership with Airbus to assess the feasibility of bringing green H₂ both from an airport infrastructure perspective as well as aviation technology. Airbus has committed to production-ready, zero-emission aircraft by 2035, with green H₂ a potential enabler. As the largest buyer of liquid hydrogen globally, Plug Power will focus on deployment scenarios for green hydrogen infrastructure, while aircraft-specialist Airbus will focus on the technical characteristics of aircraft powered by hydrogen.

LH2 offers higher energy density than CH₂, though at higher cost. In January 2021, GKN Aerospace announced it will lead H2GEAR, a collaboration aiming to develop an LH2 propulsion system for sub-regional aircraft that could be scaled up to larger aircraft, with partners Intelligent Energy (developer of lightweight, compact PEM fuel cells), Aeristech, and the Universities of Birmingham, Manchester and Newcastle. The programme is supported by £27m of Aerospace Technology Institute funding, matched by contributions from the project industrials. The entry-into-service of the first hydrogen-powered aircraft could be as early as 2026.

In April, California-based HyPoint unveiled the first operable prototype of its turbo air-cooled H₂ fuel cell system for aviation and urban air mobility. The company claims its technology delivers up to 2 kW/kg specific power and up to 1.5 kWh/kg energy density and has passed key validation testing. Full-scale versions are expected to ship from 2022. Last summer, HyPoint signed an agreement with Israeli company Urban Aeronautics, to incorporate H₂ fuel cell power in the latter's CityHawk eVTOL design.

HyPoint uses compressed air for cooling and for the O₂ supply to a HT-PEM stack. HyPoint claims stack weights a third of comparable liquid-cooled, LT-PEM systems. Its technical innovations include lightweight bipolar plates and a highly conductive, corrosion-resistant coating, leading to a claimed 50% reduction in total cost of ownership relative to turbine-powered rotorcraft. HyPoint is working with the National Renewable Energy Laboratory (NREL) to further test and validate its technology.

In August 2021, HyPoint entered into a multiphase collaborative agreement with Piasecki Aircraft Corporation, PA, to develop and certify a H₂ fuel cell system for eVTOL aircraft. The initial US\$6.5m agreement will culminate in five 650 kW fuel cell systems for Piasecki's eVTOL PA-890 compound helicopter. The partners aim to bring FAA-certified, customisable systems to the global eVTOL market, with 4x the energy density of Li-ion and at least 2x the specific power of current fuel cells.



Interest in fuel cells is now extending to the wider supply chain. In June, GM and Liebherr-Aerospace, a leading integrated on-board aircraft system supplier, signed a joint development agreement for an electric power generation system to show how H₂ PEM fuel cell-based power systems could be used in aircraft applications. The construction and testing of the demonstrator, incorporating GM Hydrotec power cubes, along with GM controls, will take place in Toulouse, France.

Overall, interest in H₂ fuel cells for manned and unmanned flight has increased significantly over the last year or two, as has work in H₂ turbines.

Ground Support

Work continues on ground support infrastructure. In August 2021, the aerospace cluster in Hamburg, Germany, announced it is setting up a development platform to design and test extensive maintenance and ground processes for handling cryogenic LH2. Over the next two years, with funding from the city of Hamburg, Lufthansa Technik will collaborate with DLR, ZAL Centre of Applied Aeronautical Research and Hamburg Airport to convert an A320 aircraft into a stationary laboratory at Lufthansa's facility in Hamburg. ZAL will contribute know-how in fuel cells and in virtual twinning, while Hamburg Airport will provide an operator's perspective.

In October 2021, Airbus, Air Liquide and Vinci Airports announced a collaboration to promote the use of H₂ at airports. Lyon-Saint-Exupéry Airport in France will host the first installations. From 2023, an HRS will be deployed, to supply the airport's ground vehicles (airside buses, trucks, handling equipment), as well as heavy goods vehicles driving around the airport. This first phase will test the airport's facilities and dynamics as a H₂ hub. Between 2023 and 2030, an LH2 infrastructure will be rolled out, to supply future H₂-powered aircraft. Beyond 2030 a complete infrastructure, from LH2 production to LH2 distribution, will be established.

Also, in October, AFC Energy stated it will provide zero-emission, off-grid power for Urban-Air Port's sustainable transport hubs that, in addition to aircraft, will serve battery electric vehicles, buses and scooters. Urban-Air Port's 'Air-One' site – its first fully operational hub for eVTOL aircraft – will be unveiled in Coventry city centre in early 2022.

In December 2021, the Civil Aviation Authority of Singapore and Airbus signed an MoU to study the demand and supply of alternative aviation fuels and how they may contribute to decarbonisation. The first project to be launched under the MoU is a technical feasibility study of an airport H₂ hub and the infrastructure requirements to support future H₂-powered aircraft operations. The study will commence in early 2022 and run for two years.

Drones

Drones using internal combustion engines have long endurance but also high acoustic and thermal signatures, and for smaller platforms are heavy. Consequently, electric drones are gaining share, particularly in military markets for silent watch, but also in monitoring of utility infrastructures.

For small lightweight vertical take-off and landing aircraft, and fixed wing aircraft undertaking short journeys, a pure lithium-polymer battery system (with a specific energy of ~150 Wh/kg) is sufficient. However, batteries impose a weight penalty above 30 min flight time, so for smaller aircraft and UAVs fuel cells are slowly gaining share for missions of an hour or more.

Doosan Mobility Innovation (DMI) is making great strides in the area, issuing a press release almost every month. 100% owned by its parent Doosan Corporation, this Korean company markets its DM15/DP15 (rated at 1.25 kW) and DM30 (2.6 kW) modules, packaged into DS30W, DT30N, and DJ25 drones, with payloads up to 4.9 kg, flight times up to 330 min (payload dependent), and ranges up to 50 km. All use compressed hydrogen fuel, stored in lightweight tanks from Korean ILJIN Composites.

In October 2020, DMI signed a preliminary deal with the Korea Electric Power Research Institute (KEPRI), an R&D subsidiary of the state-run Korea Electric Power Corp. (KEPCO), targeting automated remote power cable checking. In November 2020, DMI demonstrated a flight in a construction project in Jeju Island, over 44 km (27 mile), taking 90 min to monitor gas pipelines. Korea Gas (KOGAS) plans to use the H₂ drones for monitoring of trenches. In April 2021, DMI announced it will provide drones to the Maritime Emerging Technologies Innovation Park (METIP) project, delivering goods and providing inspection and monitoring to gas and wind platforms up to 60 km offshore of The Netherlands. A further agreement was signed with DroneQ Robotics in October 2021.

Many of the press releases from DMI focus on extending the network of resellers and bringing UAV and other competences into DMI's offering, from refuelling, to beyond visual line-of-sight control, to data acquisition. In February 2021, UK-based NanoSUN delivered a mobile refueller to DMI. The 300 bar H₂ refueller is 8 cm wide and 60 cm high, weighing 50 kg. In March 2021, an MoU with POSCO SPS was announced, aiming to develop a 20 µm metal separator. The development, contributing to lighter mass, will facilitate DMI entering the cargo drone business, targeting delivery of a 15 kW fuel cell module.

Intelligent Energy markets its IE-Soar series of fuel cells for UAVs. Rated between 800 W and 2.4 kW, these extend flight times by 3x over batteries. In October 2020, IE reported its 2.4 kW module had been integrated into ISS Aerospace's heavy-lift, FC drone, achieving a flight time of 100 min with an 8 kg payload. The target Sensus 6 hexacopter is designed for long-endurance commercial, energy, defence and security applications. In November, Luce Search, a customer of IE-Soar, announced they would work with Japan's Chugoku Electric Power T&D to develop a drone using a 2.4 kW module. Chugoku Electric uses helicopters and more than 110 conventional drones for inspection work on power transmission and distribution lines. By doubling the flight time, IE's fuel cell module will reduce labour overheads and inspection costs. Also, In November, an MoU was signed with the Korean electric bus and truck maker Edison Motors and Hogleen Air, IE's Korean reseller since June 2020, to further push the IE-Soar technology.

The drone producer, Horizon Energy Systems, since 2015 a subsidiary of H3 Dynamics, continues to market its systems but with little news since 2019. The Element One rotor plane, using HES fuel cells, continues its development for unveiling in 2022. Its Hywing H-25 Cargo prototype has a 55 lb (25 kg) take-off weight and features the company's unique H₂ fuel cell nacelle for long flights in winged craft.

There has also been little news from Honeywell, which purchased Ballard Unmanned Systems in October 2020. In August 2021, Honeywell added BVLOS capability to its 600 W and 1.2 kW multi-rotor drones. The underlying liquid-cooled PEM stacks are made in-house. The service life is 3,000 hr, with a 1,000 hr overhaul interval. The fuel is CH₂, delivering a 3x runtime increase over batteries.

In January, Scottish Hy-Hybrid Energy, Hungarian GOLDI Mobility and Shenzhen MicroMultiCopter (MMC) commenced a strategic partnership, aiming to push H₂ drones into Europe. Hy-Hybrid will give technical and project management aid to GOLDI, enabling local assembly and then manufacturing. A year prior, GOLDI entered an MoU with HES aimed at building a market for H₂ drones in Hungary.

Defence plays

There is a lot of crossover now between civil and defence UAVs, given commonality in camera/IR systems and the increasing payload and mission times facilitated by fuel cell powertrains.

In December 2020, Insitu, the Boeing subsidiary, completed the first flight of its ScanEagle3 UAV powered by a H₂ PEM fuel cell. In February 2021, an LH₂ tank was added, targeting a 10-hour flight endurance. The JP-8 version offers an 18 hour endurance and carry loads up to 20 lb (9.1 kg).

In May 2021, DMI signed a ₩831m (US\$750k) contract to supply a H₂ drone to South Korea's Defense Acquisition Program Administration (DAPA). Pilot operation by the Air Force was scheduled to begin in November.

In September 2021, Intelligent Energy announced participation Project Pegasus, funded by the UK Ministry of Defence, to improve the robustness of IE's 800 W module, with a focus on delivering H₂ fuel to the field. If successful, operational deployment is expected in 2023.

Plug Power's 1 kW ProGen fuel cell introduced in August 2020 is targeted at UAVs and unmanned ground vehicles, and derives from the EnergyOR buyout in 2019. Since October, an alliance with HevenDrones is targeting heavy-lift capability, H₂ supply, and refuelling networks, with the Israeli Ministry of Defense seeking to procure a drone fleet.

Adaptive Energy's 450W propane-fuelled Defender Series SOFC provides a six-fold increase in mission duration compared to battery-only systems. The fuel cell can replace 90% of onboard batteries. Adaptive is working with multiple drone actors, including Lockheed Martin.

Not just drones

In January 2021, DMI supplied its hydrogen fuel cells to RBT Motors, a small-volume premium custom sports car manufacturing start-up in Korea. In February, DMI moved into ground mobility, signing an MoU with CITIC HIC Kaicheng Intelligence, a Chinese robotics company, to develop H₂-powered robots for fire control and field monitoring. CITIC markets over 50 types of robots and has a 70% market share in China for robots in firefighting.



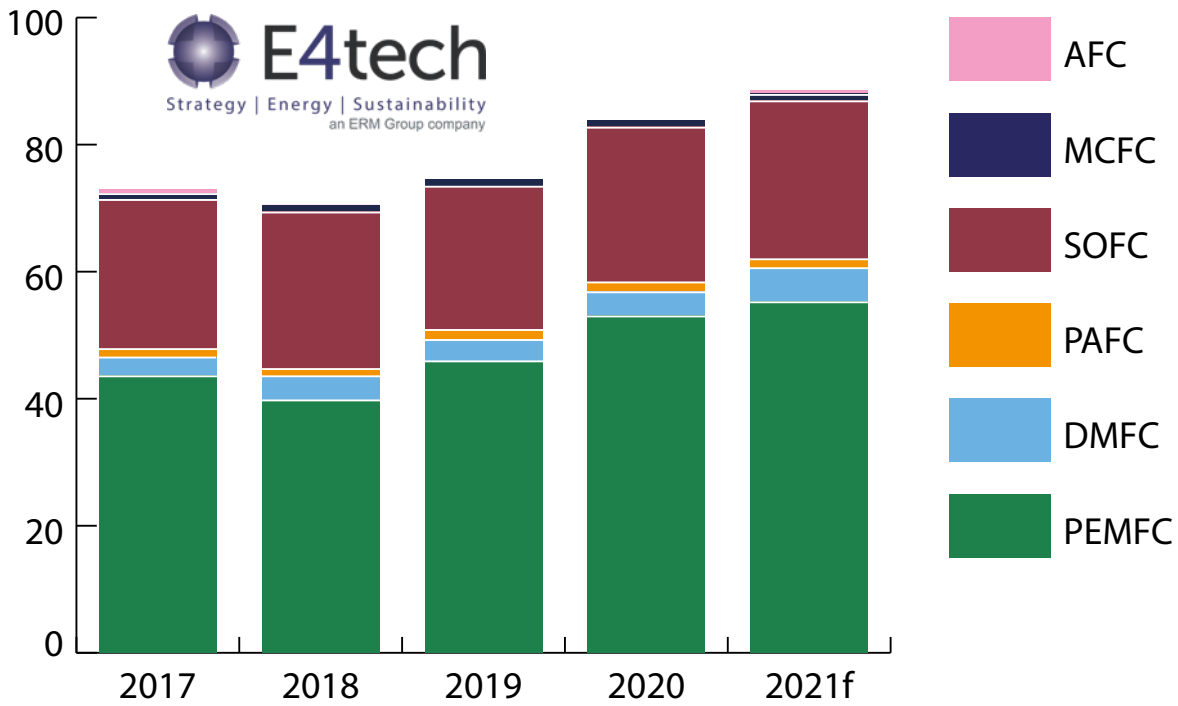
Space

In August, Connecticut-based Infinity Fuel Cell reported that its air-independent, zero gravity, Non-Flow-Through H₂ fuel cell power plant is on track to be onboard an upcoming unmanned launch of Blue Origin's New Shepard commercial space vehicle. Developed under a NASA 'Tipping Point' cooperative agreement started in 2020, the 2022 launch should demonstrate survival of the fuel cell from launch rigours and operation in a weightless environment.

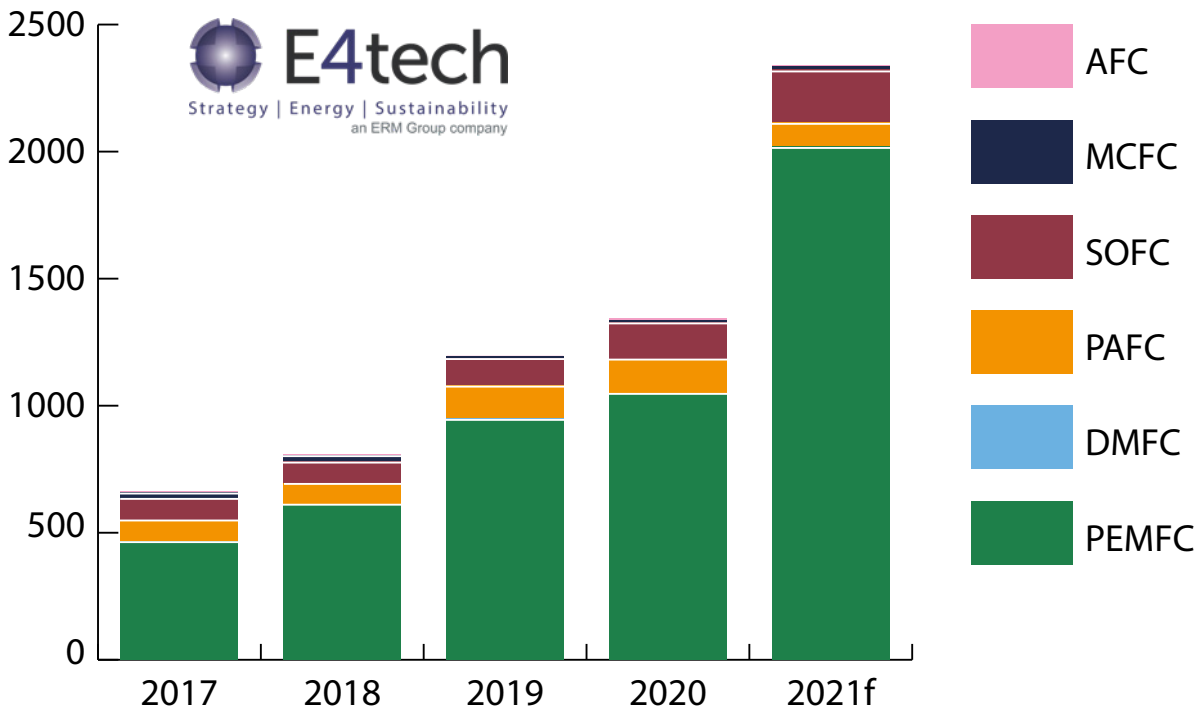
Also, in August, Estonian PowerUP said it would apply its fuel cell stack to robotic rovers as well as to Lunar cargo ships. Most small PEM stacks are open cathode, but due to the lack of oxygen on Mars and on the moon, closed cathode designs are needed. With funding from ESA, PowerUP will develop a 1 kW stack for space missions, for integration with solar panels and batteries. PowerUP hopes to have a prototype stack by 2023.

Shipments by fuel cell type

Shipments by fuel cell type 2017 - 2021 (1,000 units)



Megawatts by fuel cell type 2017 - 2021



2021f is our forecast for the full year, based on firm data from January to September, and in most cases to as late as December. We have revised the figures for 2020 in this report, now with firm full year data where previously a final quarter forecast was required.

Shipments by fuel cell type

As usual, **PEM** fuel cells lead both in units and shipped MW capacity, driven by ever-larger passenger car numbers. Over 53,000 PEM units were shipped to a range of applications in 2020, increasing to around 55,000 units during 2021. Although this count is barely higher, a drop in micro-CHP units to the Ene-Farm, PACE and KfW 433 initiatives, many of them PEM, was offset by a 1.8x increase in car shipments in 2021, fitted with much larger stacks. The net effect has been a doubling in PEM capacity, from over 1,000 MW in 2020 (78% of capacity) to almost 2,000 MW in 2021 (86% of capacity).

SOFC has also gained in share, reaching 207 MW capacity (up from 148 MW in 2020). SOFC has been gaining share in the Ene-Farm programme, due to the higher efficiency and higher-grade heat from the stack, but overall Ene-Farm shipments fell in 2021, affecting SOFC as much as PEM. The net increase in SOFC shipments by MW capacity is associated with increased shipments of Bloom units for prime power in the USA and Korea. Other suppliers, such as Ceres/Bosch contribute to the totals but at much lower volume. SOFC is poised to grow substantially in maritime and other areas but we are not there yet. By 2030, Doosan sees a potential 1.8 GW/year order volume for marine SOFCs, according to Samsung Securities.

Hydrogen is increasingly seen as a fuel for SOFCs, and for **PAFCs**. Doosan, the largest PAFC shipper, reported a fall in volume due to delays in translating the objectives of Korea's Hydrogen Energy Act into a supportive fiscal environment. PAFCs represent the next largest volume shipped, though the 96 MW is down from 132 MW in 2020. Doosan expect sales to recover through 2023 and 2024 to meet pent-up demand.

In MW capacity, then next category is **MCFC**, with the sole supplier being FuelCell Energy and its affiliates. Volumes of new stacks have been bumping along at around 10 MW over the last few years, with larger volumes (not included in our count) of stack refurbishments, mainly for Korea. There is no immediate evidence for large growth of this technology as a pure fuel cell play, though work on carbon capture with ExxonMobil continues, as does FCE's SOFC development.



By unit numbers, and still (just) by MW capacity, the next category is the **DMFC**, led by SFC Energy. Nearly 5,300 units were shipped in 2021, up from nearly 4,000. The MW shipped stayed at 0.5 MW, reflecting increased sales of smaller capacity units. Notably, SFC is receiving DMFC orders now in the 100s of units, in addition to single-unit consumer sales through agents and the occasional significant Emily and Jenny sales to the Bundeswehr and other military forces.

AFC is making a comeback, led by Israeli company GenCell. Between its founding in 2011 and IPO in November 2020, the company had shipped only 19 units. This has jumped to just over 100 units by the end of 2021. UK-based AFC Energy continues to develop new plays and product but has yet to ship meaningful numbers. The 0.5 MW count is a 5x increase on 2020, though minuscule compared to PEMFC. The low-cost potential of AFC and an increase in available hydrogen may help the uptake of this technology.



The very low volumes of **PBI** are reported within our PEM figures. Advent now owns UltraCell and SerEnergy, with steady unit sales. Blue World Technologies continues to invest in capacity to deliver PBIs to the automotive world from 2022.

Stationary fuel cells – growing bigger

2021 saw fewer stationary fuel cell units shipped than 2020, but more total power. This shows the slight shift in balance between very small units (e.g., Ene-Farm) and the bigger fuel cells put out by Doosan and Bloom. These different stationary fuel cells cover many stack types and can operate on conventional fuels, fuel mixes and synthetic fuels, white (by-product) and green (renewable) hydrogen.

Slow sales have been a result of the brutal economics of power and heat. But with sky-high energy prices and COP 26 in Glasgow once again emphasizing humanity's need to limit climate change, perhaps more of the world should be looking closely at stationary fuel cells.

Japan – Ene-Farm's sluggishness

The world's largest deployment of fuel cell systems by unit numbers continues to be the Ene-Farm project in Japan. A fleet now of almost 424,000 domestic CHP units utilising both PEM and SOFC technology has been deployed across Japan since 2009. The start of the demonstration phase of the project saw fuel cell units installed into Japan's homes, from apartments to single family homes.

Leading gas companies, notably Osaka Gas and Tokyo Gas, have worked with Japanese suppliers to introduce the technology to the public, typically with units of 700 W, meeting much of a household's baseload power and hot water needs. However, expected unit sales have not transpired, despite continual price reductions and performance increases. At the end of 2021 Tokyo Gas, the largest utility, had installed only 150,000 units. And even though Japan retains a 2030 target of 5.3 million deployed systems, the number of established manufacturers has now dwindled to just two, Panasonic and Aisin Seiki, plus a relative newcomer Dainichi.

Panasonic's 6th generation 700 W PEM system is 97% efficient in CHP mode, complete with hot water tank. Since 2009 unit size has halved and durability more than doubled to 90,000 hours. Government subsidy for PEM units closed in 2019 and units are now sold 'commercially'. Notable deployments include the Harumi Flag property development, part of the 2021 Tokyo Olympic Games, with over 4,000 Panasonic units planned.

Aisin Seiki's 'Type S' 700 W fuel cell system uses an SOFC stack with a cited 55% electrical efficiency, and 87% in CHP mode. Aisin works in partnership with Kyocera and Toyota Motor. The latest Type S released in 2020 is also an improvement on the preceding model: the size has been reduced by 20%, durability has increased to a projected stack life of 12 years.

Dainichi, working with Kyocera and Tokyo Gas, fielded a 400 W SOFC Type S mini Ene-Farm unit in 2019, the world's smallest CHP system, but with no news releases since then.



With direct subsidies stopped for PEM and in the final wind-down for SOFC, efforts are being made to expand the value proposition of Ene-Farm fuel cell systems. In June 2021 Aisin Seiki and Toyota City in Aichi Prefecture announced a plan to encourage the take-up of the 'Type S' with City subsidies, and for the CO₂ savings to be tracked using IoT technology, to then be traded under a Japanese Government CO₂ credit scheme. In the same month Tokyo Gas and Kansai Electric Power announced a demonstration project which would control and coordinate Ene-Farm units to act as a virtual power plant. This follows a similar project announced by Osaka Gas in 2020. Whilst these efforts seek to improve the attractiveness of systems, after more than a decade of slower-than-anticipated growth, it is unclear whether domestic CHP will take off dramatically.

Pure Hydrogen's Pastures New...

Some of Japan's fuel cell manufacturers have entered from the Ene-Farm project to the commercial sector. Fuel cell systems of several kW and above are now being promoted by Toshiba and Panasonic, with a growing emphasis on pure hydrogen systems.

In mid-2021 Panasonic announced the launch of its RE100 5 kW H₂ KIBOU (Hope). The KIBOU uses the core Ene-Farm PEM stack technology, delivering a 56% electrical efficiency when running on pure H₂. The system is designed to be modular and hence scalable, with 1 MW systems being targeted.



Pure hydrogen fuel cell generator (5 kW)

H₂ KIBOU



Image of multiple connection

Panasonic will install a renewable energy demonstration system at its Kusatsu factory in Shiga Prefecture, which currently produces the Ene-Farm CHP system. The system will comprise 100x RE100 units (totalling 500 kW) alongside 570 kW solar PV array and 1.1 MWh battery energy storage. The combination of power systems should provide greater system resilience and reliable power, and is due to start operation in 2022. Iwatani Corporation, the Japanese gas business, will provide trucked-in H₂. The project follows an earlier demonstration of a single 5 kW system in Yokohama in 2018 and three 5 kW systems at Yamanashi in 2019/2020.

Toshiba withdrew from the Ene-Farm project in 2017. The core PEM technology, however, became the basis of TESS' pure hydrogen PEM system, the H₂Rex. The initial 700 W demonstrators have now progressed to 100 kW and larger systems.

Toshiba is reported to have delivered 120 systems by end of 2020. These units have 50-55% electrical efficiency, rising to 90%+ in CHP mode, and are in service for a range of applications: hotels, markets, stores, service stations and now industrial sites. In November 2021, a 100 kW H₂Rex began CHP operation at Toyota's Honsha

plant. Earlier in the year a similar 100 kW H₂Rex system was installed in a commercial building for the Shimizu Corporation in Hokuriku.

The challenge for such systems is a reliable source of hydrogen. To date, most H₂ is the product of natural gas. The H₂Rex 3.5 kW system installed at a roadside service station in Michinoeki-Namie is now reported to be operating on green H₂ made using power from a 10 MW solar PV array at the Fukushima Hydrogen Energy Research Field.

The TESS H₂One system also uses PEM fuel cell technology with an electrolyser and H₂ storage to provide power and green H₂ to a vehicle HRS or for use elsewhere. The H₂One uses excess cheaper power to produce and store H₂, generating power when demand and prices are higher. An H₂One began demonstration in Tsuruga City in Fukui Prefecture in March 2021.

Toshiba is also making inroads into China. In December 2021, an agreement was signed with Shandong Energy to cooperate on pure hydrogen stationary systems, including technology transfer.

Another PEM systems developer is Toyota, using its forklift and Mirai stacks to extend its offering to stationary. In February 2021, it announced 60 and 80 kW standard modules for a range of applications. (8, 24, and 50 kW units also exist). Given the high stack volumes produced for the Mirai, cost should be competitive and could lead to greater market share. In May 2021, ENEOS agreed to supply hydrogen for a development at Woven City, which will include Hydrogen Refuelling Stations and stationary power generation systems.



Meanwhile, Honda, which has significantly slowed its light duty vehicle fuel cell programme, is keeping the door open to applying its fuel cell know-how elsewhere, exploring the use of its systems "for a wide range of applications, including commercial trucks, stationary and movable power sources."

...while natural gas fuelled systems are struggling

Few other stationary systems released by Japanese corporations have achieved real traction. Brother Industries' 4.4 kW PEM system is now being touted for possible use in a H₂-ecosystem demonstrator in Palau, the Pacific Island nation, using H₂ imported from Australia. Kyocera's SOFC efforts include its own 3 kW system, alongside Ene-Farm work with Aisin Seiki and Dainichi. And Miura, the Japanese heat and boiler systems manufacturer, has an agreement to package Ceres SOFC stacks in the 4.2kW FC-5B. Updates on commercial success of these systems is scarce, joining others that have been proposed in the past, such as Denso and Hitachi Zosen.

Fuji Electric has been selling its PAFC FP-100i systems since 2009, operating on natural gas, biogas and pure H₂, with electrical efficiencies of 42-48%. Given growing interest in H₂, the FP-100i hydrogen version may attract more interest but electrical efficiency remains below the latest PEM technology.

Finally, Mitsubishi Power continues to promote its 250kW class Megamie pressurised hybrid-SOFC system, which runs on natural gas at an 53% electrical efficiency. Uprated to 1 MW, efficiency could reach 57%, and the low 70s in CHP mode. The 1 MW system could be available from 2023. Pressurised systems were once being developed by several global engineering businesses but Mitsubishi Power is the last standing.

The Megamie has sold slowly, primarily in the CHP mode to supply chain and R&D centres in Japan. Nine systems are reported to be installed, including with Asahi Breweries, Tokyo Gas, and Mitsubishi Estates, a commercial property business. The agreement with the Gas- und Wärme Institut in Essen, Germany represents the only unit exported to date, due to start operations in 2022 following ground-breaking in mid-2021. The unit is part-funded by the European Union's ERDF and by the State Government of North-Rhine Westphalia.

South Korea – the land of plenty

Unlike Japan, the larger Korean stationary fuel cell business is being built mainly around imported technology, albeit improved and industrialised. Doosan Fuel Cell has built a business around PAFC technology developed in the USA by UTC, and SK Engineering and Construction is partnered with Bloom Energy, commercialising SOFC technology. POSCO sold FCE technology into Korea.

Korean corporations' interest in fuel cells reflects a joint Government/Industry ambition for 'green' technologies that reduce emissions, enhance energy security and can develop an indigenous industry capable of generating economic growth and exports. Strong Government drivers support these ambitions, which exceed those of most other countries.

Reflecting its ambition, the Korean Government's Hydrogen Roadmap has a fuel cell target of 1.5 GW installed stationary capacity for power generation by 2022, reaching >8 GW by 2040, plus a further 7 GW of exports. The 2022 target will be missed, with the IPHE suggesting 688 MW installed capacity by the 2021 year-end – still very impressive. The forthcoming Clean Hydrogen Energy Portfolio Standard will provide specific support for fuel cell systems for power companies generating less than 500 MW. But the delay in this being set led to a fall in large shipments in 2021.

The 2040 target implies an annual deployment of 350-400 MW per annum. This is one of the world's largest fleets by capacity and progress is being made with ever-larger installations. The largest players are Doosan and Bloom Energy.

Doosan has invested heavily in the sector, constructing a new manufacturing facility at Iksan. By 2021, 1,156 systems totalling 508 MW capacity had been reported as sold by Doosan in Korea, with 433 MW operational and a further 169 systems at 76 MW capacity under construction. Doosan Fuel Cell claims to be winning as much as two-thirds of the Korean stationary fuel cell systems market.

Doosan's PureCell Model 400 is 43% efficient (90 % in CHP) mode when running on natural gas. In early 2021 Doosan announced a dual-fuel LNG/LPG variant, now also being applied to biogas markets with KEPCO. Electrical efficiencies of 50% are possible using H₂.

For many years, POSCO Energy's 57 MW MCFC Gyeonggi Green Energy fuel cell park was the world's largest single fuel cell installation, but Doosan overtook in December 2021 with its 79 MW PAFC array in Incheon for Korea Southern Power. The four-phase build, beginning in 2017, cost ₩340bn (US\$292m) and uses Pure Cell 440 kW modules fed by pure H₂. The plant, at the Shinincheon Bitdream HQ, will produce 760 GWh electricity annually, powering 250,000 households in the capital and heating 44,000 homes. A 30 ktpa liquefied hydrogen supply facility from SK E&S will service the fuel cell plant from 2023.



The slightly smaller Seoincheon Fuel Cell park, totalling 77 MW, was completed in Autumn 2021 for Korea Western Power. Built over five phases, with further Doosan PureCell modules, the plant will power 240,000 households and also deliver heat. In March, Korea Western Power announced another 80 MW H₂ fuel cell plant, again using Doosan fuel cells, at Hwaseong City, 30 km from Seoul. The facility will power 185,000 homes by 2024. Partner Korea Hydro & Nuclear Power completed another plant at Dong-gu, Incheon, in July 2021. The 39.6 MW plant, costing ₩254bn (US\$224m), uses 90 Doosan PureCell modules to deliver 320 GWh of electricity that can be used to power 110,000 homes and provide heat to 26,000.

In July, Doosan announced its MoU with POSCO, focused on the build of a 105.6 MW fuel cell park at Chuncheon in Gangwon province. 240 PureCell modules, running on H₂, will generate 800 GWh power to service 220,000 households by 2025.

Over 2021, Doosan Fuel Cell also concluded an agreement with STX Corporation to develop tri-generation and CCUS technologies; cooperation in a virtual power plant demonstrator at Hwaseong's Smart Energy Project; and an order for 12.3 MW of dual-fuel PureCell systems for Bitgoeul EcoPark, due to come on stream in August 2022.

In Autumn 2021, Doosan announced its first export units to China from its Iksan facility: four PureCell modules to deliver CHP to a property development in Nanhai District, Foshan City, China, at US\$13m.

In the light of this and domestic orders of 131 MW in 2021, Doosan is planning to ramp its Iksan manufacturing capacity to 275 MW a year by 2022. The 2022 sales target is for 240 MW as part of an ambition to become the leading global player in H₂ energy, including expanding its capability to encompass PEM for transportation and SOFC for stationary and marine. Doosan FC remains on track to open a 50 MW capacity SOFC manufacturing site by 2023, using Ceres stacks, and to offer pre-commercial units from 2024. As of September 2021, 10 kW systems were being demonstrated, at 40% electrical efficiency and with a claimed doubling of the power density of a PEM system of the same output.

Bloom's second biggest market (after the USA) is Korea where it has been contracted to deliver 200 MW of systems since 2018 through its JV Bloom SK Fuel Cell, in partnership with SK Engineering and Construction.

In 2021, deliveries to SK E&C (mainly) in Korea accounted for 38% of Bloom's revenues. In 2021, Bloom SK Fuel Cell started operations at the Gumi manufacturing facility. Initial capacity is 50 MW per annum, intended to grow to 400 MW by 2027.

Completed or near-completed SK power plants in 2021 included a 19.8 MW facility at the Cheongju Eco Park, 15 MW for Korea Southern Power's Yeongwol Fuel Cell project Phase 1, and the 15 MW Honan Fuel Cell Project of Korea East West Power. All the plants are operating on natural gas.

October 2021 saw SK EcoPlant commit to ordering 500 MW of the Bloom systems to 2025, and investing US\$500m in Bloom itself. The shipments would translate to around US\$4.5bn in equipment and future service revenue.



Further Bloom developments within South Korea include a 4.2 MW CHP system for Donghae City, built around a 1.8 MW vertically-assembled PowerTower, announced in April; and a pure H₂-fuelled 100 kW system installed and operating in Ulsan since July. Bloom remains second to Doosan in Korea, but is growing fast.

In January 2021, Plug and SK Group committed to a joint venture to provide PEMFC systems, HRS and electrolysers to the Korean and broader Asian markets. SK invested US\$1.5bn into Plug for just under 10% of Plug's share capital. The JV was created in October, 51% owned by SK. The partners plan to build a 'Gigafactory' for fuel cells and electrolysers in a key metropolitan area in South Korea by 2024. Over time, the JV is also expected to distribute the LH2 produced by SK E&S to about 100 charging stations across the country.

POSCO was a major supplier to the Korean fuel cell market, prior to a dispute with FuelCell Energy. Until 2017, POSCO Energy had constructed ~172 MW of fuel cell power plants to local customers but stopped pursuing new orders in 2016 following claims that premature stack failures caused mounting losses in its service business. The fallout led to a collapse in FCE sales to Korea from 48% of revenues in 2016 to 3% in 2019. Late in 2021, the companies came to a legal resolution, with POSCO surrendering its rights to sell FCE's technology in Korea. POSCO now partners other companies (such as Doosan, at the Shinincheon power plant) and continues to invest in PEM bipolar plates with an intention to produce 10,000 tpa at its Cheonan plant.

Korea's other fuel cell developers are also looking to sell into power generation. In July, Hyundai Motor and Hyundai Electric & Energy Systems agreed to develop a mobile power generator package using NEXO modules, and to explore business models for marketing it in Korea and beyond. Hyundai has also worked with Doosan. Autumn 2021 saw it demonstrate a microgrid of 500 kW of PEM NEXO-derived units with 440 kW PureCell systems at Ulsan City.

Doosan's FuelCell Power Business Unit continues to actively sell PEM systems for microgeneration, with NG units from 1-10 kW and H₂ units between 1-100 kW. S-Fuel Cell, a smaller Korean company, sell its PEM systems of 5-10 kW for buildings, at 35% electrical efficiency (85% overall) on NG fuel rising to 85%+ with pure H₂. In Korea, Bumhan has been appointed as distributor for PowerCell PEM systems. Small SOFC units are being developed for homes and businesses (e.g., KD Navien with Ceres; MiCo) with Korean microgeneration volume at around 1,000 PEM units pa.

In January 2021, Hyundai started a 1 MW fuel cell power generation pilot system, based on NEXO technology. The installation has been developed with Korea East-West Power and the industrial gases company Deokyang. It comprises two 500 kW containerised modules, which can be scaled-out to hundreds of MW. The facility gets by-product H₂ by pipe from Ulsan's petrochemical complex.

North America, the two-speed country

When it comes to stationary FC systems for North America, read USA. The US was the first to deploy stationary FC systems at scale globally and for years had the world's largest fleet of 550-600 MW, only overtaken by Korea at the end of 2020. These are primarily commercial sized units of 100s of kW and low MW.

Unlike Korea, large utility-scale deployments at tens of MW capacity have been the exception. This reflects the economics of power generation in the US, where self-generation has been encouraged by Federal and State regulations and incentives, and by individual corporate environmental policies.

The stationary FC developers driving deployments in the USA are Bloom Energy of California, with its 200 kW and 300 kW SOFC server building blocks; FCE of Danbury, CT, with its SureSource MW-scale modules, and Doosan Fuel Cell America, of South Windsor, CT, supplying PureCell Model 400 PAFC systems. The domiciles represent the States with the most attractive policies for fuel cells and are the locations for most of the installations. Over the past few years, Bloom has been leading the charge, with FCE and Doosan stuck in the slow lane.

Over the years, California's power and emissions challenges have driven State legislation in favour of alternative technologies, including fuel cells for DG. 2021 saw the State Government extend its Fuel Cell Net Energy Metering Program, providing relief from power utility charges to end users of FC systems. California is estimated to have around 550 stationary units totalling 320 MW, way ahead of any other State.

Connecticut, with a fleet of about 100 stationary units and an 84 MW installed base, is the only State to classify fuel cell systems as Class 1 Renewable Energy Sources, equivalent to PV and Wind, even when running on NG. Over the years the State, with an eye on growth and jobs, has enacted legislation requiring State power utilities to purchase home-grown technology. The Department of Energy & Environmental Protection (DEEP) initiative has sought bids for plants from renewable technology suppliers, including FC systems. The latest legislation, passed in Summer 2021, requires the State's utilities to solicit 30 MW of systems from fuel cell companies, which include Doosan and FuelCell Energy.

For FuelCell Energy, 2021 has been unspectacular, with a retained backlog of over US\$1bn. It continues to rebuild, following an existential crisis in 2019 and then COVID. It has increased its annualised production capability to 45 MW, up from 17 MW in 2020, with the glimmerings of new orders for Korea. FCE gained a cash injection of US\$162.5m in December 2020 through a public offering of stock.

Although FCE reports a cumulative deployment of 220 MW over 50 plants globally, 2021 saw a little over 10 MW commissioned: 1.4 MW at San Bernardino's wastewater treatment facility in July; 7.4 MW at Yaphank in New York, at the end of 2021; and the completion of its 2.8 MW plant in Derby, Connecticut. Further systems underway include the 7.4 MW US Navy Base power plant at Groton, CT, (delayed from 2020, and still to be accepted), another 14 MW power plant at Derby, CT, a 7.4 MW plant in Hartford CT and the 2.3 MW Tri-generation system for Toyota in California.

FCE's business model is increasingly built on Power Purchasing Agreements (PPA), secured for new and existing plants. The apparently healthy backlog of generation income derives from a nine-project 34 MW fleet over the next 20 years. Few new PPAs seem to have been captured in 2021.

At the end of 2020 three of four projects initially awarded under CT's Shared Clean Energy Facility programme were rescinded, leaving just one going into 2021. FCE's prospects for 2022 seem more promising. It should benefit from the CT State Government Bill, signed in Summer 2021. It is now able to market and sell its technology throughout Asia and expects to receive orders for 20 modules from POSCO, to service and maintain the systems of POSCO's existing Korean customers.

Doosan Fuel Cell America should also benefit from the CT State initiative to purchase fuel cells, but this cannot be taken for granted. First announced in 2018, Energy Innovation Park, LLC planned to build a 20 MW microgrid in a redundant factory in New Britain, CT, eventually expanding to a 44 MW data centre. Prospects for Doosan were dashed by the onset of the pandemic and then by a report that the initial 45 Doosan units are to be replaced by 74 Bloom servers. Whatever the prospects for the 290 workers at Doosan's South Windsor facility, they seem to be the poor relation to Doosan's highly successful Korean operations.

Bloom Energy is now the predominant stationary supplier in the USA, installing its SOFC Energy Servers across the USA and increasingly overseas (mainly Korea, with few in Europe). In 2020, Bloom reported 1,326 units (as 100 kW modules in its reports), totalling 132 MW. This increased to 1,897 units at an aggregate capacity of 190 MW in 2021. For FCIR, we use a weighted average of system ensembles for Bloom.

The US remains the single largest market in which Bloom partners with energy developers and investors to install systems as part of PPAs and other services agreements. One of Bloom's largest partners is Duke Energy, which in 2020 accounted for 28% of revenues. Smaller partners include Daroga Power, Captona and NineDot, all part of its Community Distributed Generation Program, which in 2021 began to install 40 MW of systems across the North East USA. These will provide grid support and strengthening, alongside community resilience. In July Daroga Power agreed to take on more Bloom Servers: 33 MW of systems will be placed with 17 industrial and commercial long term energy service customers across CA and the Eastern Seaboard by end of 2022. Bloom also benefits from State Government assistance, with 10 MW of Servers installed at Colchester, CT under the DEEP initiative.

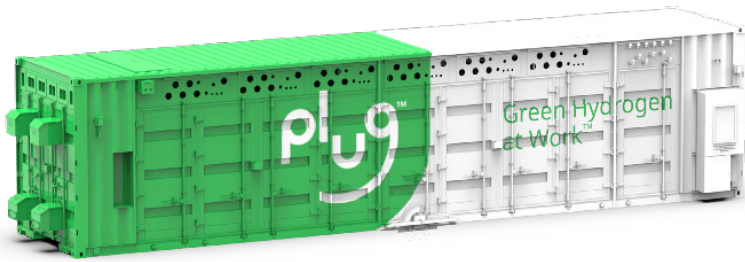
In an effort to diversify the product line and tap into the growth of alternative fuels, Bloom announced several developments in 2021. In autumn Bloom commissioned 1 MW of servers at a dairy farm in California, fuelled with biogas from cow manure. In September its Hydrogen Energy Server technology was released for commercial sale. Bloom is also heavily investing in Solid Oxide electrolyser technology with its Bloom Electrolyser, claimed to be 15%-45% more efficient than low temperature systems, due to go on sale in 2022. Bloom signed up with Idaho National Laboratory to trial the electrolyser with nuclear power. The Bloom Electrolyser is also to be part of a larger renewable energy system incorporating Bloom's Hydrogen Energy Servers and a floating solar PV array in Visakhapatnam, India. The system will provide 100% renewable power plus storage.

Overseas markets other than Korea are only just beginning for Bloom: in 2021 it opened an office in Dubai, UAE, whilst in November it signed up with Conrad Energy and Electricity North West to develop market opportunities in the UK.

North America's PEM Journey

Although Canadian fuel cell developers, Ballard and Cummins, and Plug Power of the USA have fielded stationary systems (mainly for backup or off-grid applications) based on their PEM technology in the past, their focus has been primarily on transport markets for volume. However, ever-larger systems – now with MW potential – are being developed.

Plug launched its GenSure High Power system in 2020. Based on 125 kW ProGen modules, these systems are scalable from 500 kW to 1.5 MW. Production started early 2021, with a view to deploying units at data centres after mid-year.



Ballard's steps towards stationary units at MW-scale include an announcement of two 1.5 MW systems, based on its ClearGen-II module, to be delivered to HDF Energy for a 'Renewstable' power plant in French Guyana. The US\$200m CEOG project will combine a solar park, H₂, and short-term battery storage and fuel cells. Later in the year, Ballard signed an agreement with Caterpillar to provide a 1.5 MW system to a Microsoft data centre. The project will run for three years, part-funded by the US DoE. In July, Ballard also signed up with Portugal's Fusion-Fuel business to supply a 200 kW FCwave system to run on hydrogen from Fusion's electrolyser. Like Plug Power, Ballard is chasing renewable ensembles, not just fuel cells.

There is little micro-CHP activity in the US. Watt Fuel Cell continues to work with Peoples Gas, trialling units in homes. In January, Watt reported it had doubled the stack output of its SOFC to 2 kW, and improved system efficiency to more than 40%, using its proprietary additive manufacturing process to transition to a steam-based system. The advances in technology and lessons learned from the residential field trials should be implemented in the new Beta Hybrid system.

Sluggish Europe

Europe's FC journey has been one of enormous promise, but glacial progress. Deployment of stationary fuel cell systems is way behind other leading economies. Very few utility or commercial-scale stationary systems have been deployed (none published in 2021), and few micro-CHP units shipped in comparison with Japan.

Ambition amongst Europe's developers is not lacking, nor is technical competence. But the energy markets are tougher, the grid more reliable, Government subsidy regimes far less generous and regulations less favourable than in some other economies. Despite the efforts of the European Union, through FCH2 JU and from countries like Germany, the economic case for stationary fuel cells has proven hard to make for domestic and commercial end-users alike.

The last large commercial stationary systems installed were three Doosan PureCell Model 400s in 2019 for an event complex in Aberdeen, UK. Other initiatives, such as the Electrou Project to install a stationary fuel cell for London's Kings Cross development, have fallen by the wayside. Ground was finally broken in Summer 2021 for a Mitsubishi Power MEGAMIE 250 kW hybrid SOFC system in Essen, Germany. Due to start operation in 2022, the unit is a demonstrator rather than a commercial installation. And in December, it was reported a term-sheet had been agreed between Renovit (Snam's energy efficiency subsidiary) and SAGAT SpA, Torino's airport management company, for the construction of a 1.2 MW hydrogen-ready FuelCell Energy system at the airport.

Europe's efforts for much of the past five years have been focused on smaller-scale fuel cell systems: domestic CHP in the thousands, and more recently on smaller commercial units in the single and tens of kW power output, though with hardly any shipments. The efforts have been supported by FCH2 JU projects PACE for domestic and small commercial CHP systems, COMSOS, for larger commercial systems, as well as Germany's KfW 433 initiative.

2021 was the last full year of PACE, with completion due in 2022. The €90m (US\$107m) project's objective was to drive down costs by supporting deployment of 2,800 systems, enabling the switch from single system building to a series production. Five of Europe's leading domestic micro-CHP developers have been involved: BDR Thermea, Bosch, SOLIDpower, Sunfire and Viessmann. They committed to deploying between 500 and 750 micro-CHP units each across ten EU countries.

To date, most units have been deployed in Germany and in Flanders in Belgium. Both countries have national or regional subsidies adding to the PACE incentives. Units have also been installed in the UK, France, Italy and a few in the Netherlands and Austria. It is difficult at this stage to determine the impact. The cost reductions are only part of what is required to successfully market and sell systems to the public. But in the absence of a follow-on programme to PACE (itself a follower of the ene.field project), future deployments of domestic and small commercial CHP systems will depend on national and regional support. The only consistent government support available, at least at reasonable scale, has been KfW 433. Since 2016, it is reported to have supported over 18,300 units (the initial target was 15,000 systems), of between 250 W and 5 kW, through a mix of grants and tariffs now worth up to €34,300 (US\$40,800) a unit. As most of Europe's fuel cell developers are either based in or have a presence in Germany, continuation of KfW 433 is critical to the learning and price falls of micro-CHP systems.

PACE's five developers have fielded a mix of PEM and SOFC systems. Netherland's BDR Thermea has installed its SenerTec Dachs 0.8. This PEM system generates 750 W of power at 38% efficiency (92% including heat). BDR's Remeha Electra 300 uses the same basic technology.

Germany's Viessmann, the market leader, also uses PEM, although in this case based on a Panasonic module under a collaboration which started in 2014. The 750 W Vitovalor PT2 incorporates a boiler and hot water tank, with an electrical efficiency of 37% and 92% overall, delivering a 12-year stack life and a subsidy of up to €11,200 (US\$13,300) per unit available under KfW 433. At the end of 2021, Viessmann announced its 10,000th Vitovalor system sale.

Micro-SOFC systems have also been installed by SOLIDpower, Bosch, and by Sunfire. SOLIDpower, the Italian-based developer with its system production line in Heinsburg, Germany reported in 2021 that 2,500 units have been deployed in 12 countries over the years. The latest version, the BG15, was launched in 2020, with 1.5 kW power output and efficiency of 57%, and 90% overall. Cells and stacks are made at the 25 MW capacity factory in Mezzolombardo, Italy. As with several other fuel cell companies, including AFC Energy, SOLIDpower is now also targeting charger systems for battery-powered electric vehicles.

SOLIDpower's BG15 stack is also at the core of the Bosch Buderus brand of fuel cell micro-CHP systems, with up to 60% electrical efficiency. SOLIDpower and Bosch paired several years ago with a view to replacing Japanese Aisin Seiki modules in the Buderus products. As a system

integrator, however, Bosch also has an agreement with the UK company Ceres to use its SteelCell SOFC technology for commercial-scale end uses.

Bosch is set to become a European leader in larger commercial fuel cell systems. The 2021 plan was to put 100 units using Ceres stacks into operation. Twenty units were operating by March 2021, including a 10 kW system, with 60% electrical efficiency, powering homes in Bamberg, where Bosch's stack production facility is being built. Bosch will start mass manufacture from 2024, with an initial capacity of 200 MW a year (enough to supply 400,000 households with electricity). The stationary play is part of Bosch's €1bn (US\$1.19bn) investment in fuel cells, from Spring 2021, and reflects the view that fuel cells will be part of Europe's Zero Carbon future, with natural gas as a stepping-stone to green hydrogen. Bosch also continues to work with PowerCell to modify the S3 stacks for automotive use by 2022.

Sunfire in Dresden has expanded its solid oxide electrolyser offering. Its micro-CHP product is based on the Sunfire-Home SOFC introduced in early 2020. The 750 W electrical output (1.2 kW thermal) units have an electrical efficiency of just under 40% (89% overall). The Sunfire-Home uses the same Power Core as the Sunfire-Remote systems. The latter are available from 350 to 850 W and have been used as remote power sources for temporary festivals, through oil and gas pipeline sensor systems, microwave radio stations, to railway infrastructure. They can run on propane, for off-grid needs, and operate at temperatures from -20 to +55°C. With an environmental cabinet it can run at temperatures down to -40°C. Sunfire claims its fuel cell units have the longest durability in the market.



Ceres is one of Europe's specialist SOFC Cell and stack developers, the others being Elcogen of Estonia, and mPower of Germany. They licence their SOFC technology and/or sell cells and stacks to system integrators. Ceres has struck development and licence agreements with global engineering businesses that will integrate systems and provide a route to market: Bosch, Weichai in China, Cummins in USA, Doosan Fuel Cell in Korea, and Miura of Japan. Late in 2020, these were joined by AVL in Austria, to help push the technology into European vehicles.

Weichai is focused on using the Ceres stacks as range extenders for vehicles, Cummins on 100 kW stacks for data centres, and Miura its FC-5B CHP unit. Doosan is focused on utility-scale power generation and marine and is building a 50 MW manufacturing volume by 2024 in Korea. In March 2021, Doosan announced a JV with Hyundai Heavy Industries to push the SteelCell technology into marine applications. These developments follow Ceres' £181m (US\$248m) fund raise in summer 2021. Taken together, it is possible that the global production of Ceres SOFC stacks will rival that of Bloom by the mid-2020s, though this will require an upscaling of the core 5 kW modules.

Elcogen is a smaller SOFC player with ambitions to expand. Its technology is mature and claimed competitive with other developers. From a start in 2001, it now supplies several smaller system developers and integrators in Europe, Japan and Korea. In 2021 it announced an agreement with Mainor Ülemiste AS, a property business, to develop a 50 MW cell and stack facility for fuel cells, alongside 200 MW a year of solid oxide electrolysis cells, in Tallinn, Estonia. The facility will enable Elcogen to supply stacks to integrators, including Convion of Finland. Previously, the focus was mainly on cell supply.

Convion has been patiently building its commercial offering with its C60 SOFC unit. Using Elcogen stacks and with 60% electrical efficiency (83% overall), Convion's C60 unit is amongst the best in class. In October 2021, it announced that the C60 CHP system delivered to Finland's LEMENE distributed generation project had achieved 7,000 hours of reliable operation.

Convion, alongside Sunfire and SOLIDpower, has partnered in the EU COMSOS project, designed to demonstrate SOFC systems for the commercial sector. By mid-2021, only Sunfire had deployed a unit, a 25 kW system, in Taiwan. Convion is due to field its C50/60 series and SOLIDpower a 12 kW system. As with other solid oxide actors, Convion is looking to expand its horizons into electrolysis and into electrofuels, in March 2021 announcing a research project with VTT and Neste.

SOLIDpower has also begun to scale its systems outside of COMSOS, using its 6 kW modules to build a 180 kW SOFC stack and a 25 kW reversible solid oxide stack capable of power generation and electrolysis. In December, it announced the start of the Edge Prime Power Project, a European-supported €2.5m project looking at use of fuel cell systems for data centres.

mPower is younger than Elcogen and smaller. It manufactures SOFC stack developed at the Fraunhofer IKTs Ceramics institute, in Dresden and bought the rights to Hexis SOFC from Viessmann in 2020. Stacks are available between 0.3-10 kW. No shipments have yet been reported.

Several other smaller European system developers have some interest in stationary, although their typical main focus is mobility. Boutique actors like Tropical and Helbio ship bespoke units, and emerging companies like Inhouse Engineering are extending their product (in this case, the 4.2 kW inhouse5000+ CHP unit) into renewable ensembles with a fuel cell component. Others, like HDF Energy, also target renewables but at larger scale, as bulk energy storage systems.

2021 has been a busy year for PowerCell, Sweden. Focused previously on road and small stationary, its reach now extends to off-road and marine PEM systems. In February, the PowerCellution brand was created to signal a move towards supplying larger systems rather than individual stacks, using 200 kW modules. In May 2021, an agreement was signed with Hitachi-ABB Power Grids to develop containerised stationary systems of 600 kW, and on module-based solutions for systems of a MW plus. Orders continue for its MS-100 (100 kW) stack, now designated as the 'Power Generation 100'. January saw the such a unit go to the University of Texas to provide power to a computing centre.

In November, Rolls-Royce gave further details of its stationary plant, led by the mtu brand of its Power Systems business unit. Based on cellcentric technology, each module will deliver a net power of ~150 kW, which can be connected to reach the MW scale, used in large data centres. Rolls-Royce commissioned a demonstrator earlier in the year, with plans for a further unit in 2022. Pilot units are expected in 2023, and production systems in 2025.

Germany's Proton Motor has developed several PEM systems that have been placed in stationary applications, the S5/8 with power up to 8 kW and the S25 power up to 25 kW. In November, Proton secured further sales from Deutsche Bahn for modules for critical railway infrastructure sites, with a potential roll-out of 1,800 sites across the network. And in August, Proton recorded sales for eight of its S8 modules to GKN Hydrogen.

GKN's HY2 energy storage systems

Following years of development, GKN Hydrogen was launched as a business unit in March 2021. Its HY2 metal hydride store is scalable, to deliver emergency backup and off-grid energy supply to residential housing, maritime transport, and large-scale industry. The hydride maintains 100% of original capacity after three years. In domestic use, the HY2 facilitates seasonal energy buffering when coupled with green H₂ sources and fuel cells.



In August, GKN Hydrogen got US\$1.7m funding from the US DOE to add two HY2MEGA H₂ storage tanks to the H₂ assets at the ARIES facility on NREL's Flatirons Campus near Boulder, CO. The HY2MEGA storage subsystem will be connected to the MW-scale electrolyser and FC system at the facility and will be evaluated over a range of use cases from September 2022.

Back-up for critical infrastructure is growing fast

Society's critical infrastructure has received growing attention as the impact of 'blackouts', especially those caused by natural events, becomes more apparent in today's connected world. Several countries have identified back-up power for resilience as an investment priority. Not surprisingly, fuel cell developers are attracted to these opportunities, marketing the benefits of fuel cells over diesel gensets and battery systems: longer runtimes, less attractive targets for theft, and cleaner operation. Few developers focus on this market alone, but Taiwan's CHEM Energy and GenCell of Israel are the exceptions.

CHEM Energy has been placing its G3 and G5 ME2 series fuel cells into telecoms towers sites in Africa and Asia for number of years. CHEM's products are built around its 2016 acquisition of Ballard technology, originating from IdaTech. The 2.5 kW and 5 kW systems run on reformed methanol, a 225 litre tank providing up to 100 hours runtime, depending on the power. These systems are manufactured in Taiwan and South Africa.

Vodacom has already installed at least 300 CHEM ME2 units in its network. Sub-Saharan Africa is reported to have potential for a further 300,000, but this must be set alongside similar hopes for other countries in Africa, and Asia, yet to be fully realised.

Like CHEM, GenCell has been focused on the back-up market, offering scalable systems up to 5 kW: the REX (6-8 hrs of backup power), and BOX (runtimes for a full week, for a 1 kW system), fuelled by hydrogen; and the new FOX (with up to a year backup, fuelled by anhydrous ammonia). At the end of 2021, it reported installation of 100 units across 22 countries, with 74 delivered to Mexico alone.

In the USA, Plug Power and Alteryg have provided small systems for many years. Plug's GenSure E series ranges from 200 W to 4.4 kW, with 4,800 units installed across the USA and 36 other countries. Plug has partnered with Canada's Westech Industrial to distribute GenSure across western Canada.



Alteryg's 5 kW Freedom Power System has sold in the very low thousands of units over time, mainly into the US and many with ARRA funding, but few since that ended. Alteryg now also sells into disaster relief, traffic systems and a myriad of uses, as well as telecoms.

Ballard's backup business, based on FCgen-H2PM, accounted for 10% of sales in 2020. The model has outputs of 1.7-60 kW for critical infrastructure. At the end of 2020, an agreement was signed with Eltek Nordic of Norway to work on fuel cell backup power systems for communications networks in the Nordic countries. Ballard's Danish subsidiary will deliver units based on the FCgen-H2PM.

Cummins offers its HyPM-XR systems with outputs of 10, 20, 30 and 120 kW for reliable backup and standby power. It also offers its larger MW Power Plant Platform, up to 20 MW.

PowerCell also has smaller PowerCellution systems for telecoms backup, its 5 kW system fitting into a standard 19" rack.



Taylor Construction Plant, of Maldon, Essex, UK, use BOC HYMERA fuel cells in its Ecolight WH2 and TH200 lighting towers, and in its Genie Eco CCTV tower for surveillance in remote locations. The HYMERA is also integrated into TCP's Eco-CH2 Cabinet, designed for off-grid needs, leased to construction companies, offering up to 2.5 kW standby power (from a battery) and continuous power of 250 W (from the fuel cell). The Cabinet has a capacity of five GENIE cylinders for extended runtime and can also be integrated with solar PV or micro-wind to extend runtimes yet further.

Intelligent Energy has a history of trying to build a telecoms market with its PEM technology, notably in India. 2021 saw a product revamp, the IE-Drive P100 for LDVs, IE-Drive HD for HDVs, IE-flight for aviation, joining the IE-Soar (UAV) and IE-Lift systems. In recent years, it has sold some backup units for Malaysian telecoms operators. In September, Intelligent Energy appointed Singapore's Powerzone Technologies, a builder of power generator sets, to pursue opportunities in Asia. Telecoms has been identified as a key target for the IE-Lift Series, utilising H₂ fuel and outputs of 1, 2 and 4 kW. The units are smaller and lighter, though still higher cost than battery backup.

TCP's Ecolite GH2, developed in 2018, uses an IE-Lift 801 module, to deliver up to 1 kW power off-grid, typically for events and for construction sites.

Intelligent Energy's partner AJC also packages the IE-Lift systems into welfare cabins, to create clean power for the domestic needs of construction workers. A smaller, less mature, system has been demonstrated by the UK SOFC company, Adelan.

EODev continues to expand its activity beyond its starting point of the Energy Observer catamaran. In November 2020, Eneria became a distributor of the GEH2 and REXH2 to greater France, Belgium, Luxembourg, Poland, Romania, and Algeria. In March 2021, LOXAM, the number one equipment rental company across Europe, said it will make the GEH2 available to its clients. In December, Canadian group Aspin Kemp & Associates made an initial order for three GEH2 generators to be used at construction sites and two REXH2 range extenders to be integrated into a ship. Also, in December, Blue Diamond Machinery, a distributor of energy and industrial equipment, acquired three GEH2 units and was appointed as an EODEV agent in Australia, pushing the GEH2 into the mining industry and major sporting and cultural events.

Advent Energy has totally transformed its business, following acquisition of UltraCell early in 2021 and SerEnergy later in the year. Now claiming a broad portfolio, from real 25 W portable units to yet-to-emerge MW-scale systems, it offers its 48 V and high voltage variants in 3rd (H3 5000) and 4th (Serene U-5) generations for backup power, at between 1-15 kW. The systems all use reformed methanol (high energy density and convenience of transportation of fuel) and PBI membranes (tolerant to CO, but high cost).

In May, Blue World Technologies gained EUDP funding, working with Clayton Power to develop a 5-15 kW scale APU (using PBI fuel cells) to power domestic appliances within long distance heavy-duty trucks at stops, and for use as a mobile genset for construction sites, telecoms, remote medical facilities, and other off-grid needs.

Bambili Energy is focused on the beneficiation of South Africa's platinum group metals through the development of an indigenous fuel cell industry. It offers the MRFC5000 i5 kW power system based on a single 2 m tall cabinet. The unit can be scaled out to needs of 100 kW or more, with an option to package systems in shipping containers.

Start-up PowerUP Energy, was awarded €150k from Estonia's Environmental Investment Center (Keskonnainvesteeringute Keskus – KIK), to develop two 12 kW H₂ fuel cell UP12K prototypes and, by early 2023, to validate the units with Mushi Bio Power in Namibia and the National Radio and Telecommunication Corporation in Pakistan.

SFC Energy for many years focused solely on small portable DMFC systems. But following the January 2020 agreement with adKor, SFC now develops and markets the Jupiter series of PEM H₂ systems. The use of H₂ fuel delivers greater resilience to cold climates over diesel or kerosene-fuelled gensets. The platform is scalable from 2.5 kW to 50 kW.

Portable – sales holding, spawning new plays

One route for fuel cell start-ups to enter markets is through an initial focus on small units and the portable power segment. Incrementally, larger markets like ported generators and static telecoms backup are addressed, and some companies aim to bring product to yet larger and higher-power markets, such as automotive. And the prize seems bigger, but along the way a lot of re-engineering effort is needed, with little or no revenue. By now, the company has transitioned from a portable play to a diversified portfolio, possibly losing portable altogether.

But some stay the course, producing products that are mature, reliable, and sell in volume. This is the case for the DMFC company, SFC Energy, now in its 21st year. Along the way it has made acquisitions (not all in fuel cells), and gained access to adKor's PEM platform, with Ballard stacks built into the Jupiter series. SFC has sold over 55,000 units since its inception to end 2021, mostly portable DMFC. In 2021 it sold 6,500 units, an 83% increase over 2020.

The current designs are a result of two decades of market testing, logging data and incremental improvements, and then branching out to PEM once the DMFC units had been optimised for different market segments. These include remote monitoring for civil applications, silent watch (the Emily) and lightweight, high energy, personal power sources (the Jenny) in defence. The PEM play recognises the inherent limitation of DMFC to power ranges peaking around 1-3 kW, due mainly to the inherent high cost of the electrocatalyst in the DMFC stack.

A highly competitive market

Unlike many of its competitors and casualties (NanoDynamics, resurrected as Watt Fuel Cell; Trulite; INI Power; Jadoo; Neah Power), SFC has stayed the course, with 66% of its total €64.3m revenues for 2021 attributed to the Clean Energy segment, most of that being for portable DMFCs.

SFC is now on its 5th-generation EFOY Pro 2800, methanol-fuelled, with an output up to 125 W and a maximum charging capacity of 250 Ah per day. The higher output power is aimed at the sailing community, as an APU/charger to hotel batteries.

Winner Yachts adopted the EFOY as a runtime extender as a customer offering, in July 2021.



Further diversification aimed at sailors is the integration of its DMFC product into the ePropulsion Spirit 1.0 PLUS outboard engine, as a range extender. To do this, and meet other demands, SFC Energy raised money in November 2020. Its sales now extend to Asia, including 48 units for offshore measurement systems via SFC sales partner Beijing Green Century Technology.

In January 2021, 130 EFOY Pro units (the largest single order at the time) were ordered by Toyota Tsusho, to equip temporary LED traffic control lights for a Japanese client. Further diversity has come through partner Jenoptik to use the EFOY systems in mobile traffic speed camera sites, following a similar agreement in March 2021, with Leosphere, to integrate EFOY units into LIDAR technology for wind farms. In May, 100 EFOY Pro 2400 Duo fuel cells were ordered by LiveView Technologies, Utah, to power mounted cameras on trailers, to monitor parking lots, and as power for access control to construction sites, in place of generators. The EFOY units act as battery runtime extenders. LiveView made a follow-on order for a further 600 EFOY units, valued at US\$4m, in September 2021.

Johnson Matthey is a crucial supplier, with a renewed JDA and supply agreement to March 2024.

DMFCs can be part of larger ensembles (24 microgrids for remote villages in India, with local partner FC TecNrgy, were announced in March 2021) but for higher power needs the PEM-based Jupiter systems can offer more than the DMFC.

By February 2021, 40 of an intended 500 Jupiter units had been deployed to network harden the BOSNet public authority radio system in Bavaria. The Jupiter uses FCgen-1020ACS (air-cooled) stacks, from Ballard.

In July, SFC Energy launched a new modular H₂ fuel cell solution, the EFOY Hydrogen Fuel Cell 2.5, for mobile and critical power needs up to 5 kW, with a plan is to extend the offering up to 50 kW. These move into a ported, rather than portable category. Series production was scheduled within Q4 2021.



Like others, SFC is now chasing the wider emerging green H₂ economy. In August, SFC and Nel ASA entered a JDA to deliver the world's first integrated electrolyser and H₂ fuel cell system for industrial markets, replacing diesel generators. SFC and Nel will first address applications up to 50 kW. Next the range will be extended to 500 kW.

A June 2021 order for a Jupiter unit is destined for use in a PV/electrolyser array in Lower Austria. This will require the development of a high power density, liquid cooled stack, likely available from 2025.

HYMERA – old and new

Another of the established fuel cell companies, BOC's HYMERA, has updated its original design, developed with Arcola Energy back in 2013. With a power output of 150 W, the HYMERA II supports a range of commercial and industrial off-grid applications, such as task lighting (for example, for railway maintenance), security cameras, process control systems and environmental monitoring.

The HYMERA II is claimed to have running costs lower than diesel generators, with reduced servicing requirements. It even has its own reusable cylinder, the 54-G20 GENIE, with 5 m³ 300 bar CH₂, (typical, heavier, industrial cylinders are at 175 bar pressure) enough to generate 600 kWh of electricity. The filled cylinders retail at £77 (US\$106).



The actual runtimes depend on the power draw: 2x 50 LED flood lights deplete the cylinder in ~70 hr, a small site office lasts up to 6 days, a 10 W traffic light for 4 weeks and a 4 W alarm for 2 months. While this illustrates the inherent problem with CH₂; unless the storage pressure is very high, the usable power and runtimes are short. But they are fast to recharge, lighter than battery systems, and cleaner and quieter than diesels, so compete perfectly in certain segments.

Many other players – new and old

Imperial College spinout Bramble has pioneered a printed circuit board-based H₂ PEM fuel cell with a claimed low production cost, scalable and recyclable, that can be made at any PCB factory world-wide. Its initial demonstrator has been built into the SDX range of range/runtime extenders, rated at 15 W, 30 W, 45 W and 60 W, also alongside BOC.



Bramble is scaling its technology to larger platforms, for marine, stationary backup, and for light duty vehicles.

Spun-out from EPFL in August 2020, Lausanne-based INERGIO Technologies SA unveiled two prototype portable SOFCs units in 2021: the InoPower 1.0 (50-150 W; 2.5-3 kg) and InoPower 4.0 (200-600 W; 3.5-7.2 kg). INERGIO claims an 80% reduction in mass over its peers. The devices, which can run off propane or H₂, are aimed at delivery drones and other remotely operated vehicles, weather stations, environmental sensors, telecom antenna sites and campsite users.

Adelan's microtubular SOFC has now been going for 30 years, but remains at the demonstrator stage: its flexible designs seeking multiple markets from micro-CHP, UAVs, recreational vehicles, portable uses like battery chargers, to remote power. In February 2020, Adelan trialled its SOFC to power welfare cabins in HS2 construction sites. BioLPG in place of fossil LPG fuel was trialled by Adelan in 2021.

Adaptive Energy has supplied over 2,000 SOFC units since its inception. Most of these have been portable units, for off-grid, and for UAVs or UGVs. It is packaged by resellers such as RedHawk Energy Systems for applications such as border watch, environmental and remote pipeline monitoring, and backup to critical infrastructures, such as SCADA units and railroad switches.

Adaptive's Endurance Series are built for continuous auxiliary or primary power. Its Performer series offers critical backup to batteries in solar and wind ensembles. Both offer units up to 1 kW. These are complemented by its Defender series for unmanned vehicles, including for the military market. They use propane – easy to procure, much more energy dense than hydrogen, and together with the high SOFC efficiency, delivering long unattended runtimes.

In December 2021, Adaptive received an order for 400 Performer Series P250i units from RedHawk, to be delivered over 2022. This suggests the units have achieved high reliability in operation.



Auriga Energy's AurigaGen 1.5 kW PEM fuel cell generator weighs 46 kg, so is definitely in the ported category, but no news has appeared since 2019.

Estonia-based PowerUP offers portable generators rated at 200 W (the UP200), 400 W (the UP400), 1,000 W (UP1K) and 6,000 W (UP6K) for sailing boats, campervans, small vehicles and other outdoor & off-grid applications). The UP200 and UP400 include an internal LFP battery. The UP200 weighs 8 kg and the UP400 10 kg, excluding the Type IV cylinder and CH₂ fuel. The UP400, which offers a lifetime of 5,000 hr, is now priced at €6,500. The company is also working on larger systems.



Time for pastures new

Many former portable players have now moved on. Upstart Power (formerly Protonex, and for a time with Ballard) is now focusing on extended backup power and grid-independent power, in all cases using a SOFC to act as a runtime extender, for a battery. Its 1.25 kW product is designated as the Upgen NXG. As a solar hybrid, it can also feed an EV charger.

Defence developments

Defence applications have taken a similar journey to civil: immature, portable, units as new fuel cell concepts were developed and trialled at small power outputs, leading to larger platforms and to use as UAV power sources.

SFC Energy is the dominant supplier in this space, while UltraCell, now part of Advent, is also targeting portable units for soldier power. SFC's orders include those from armies across the globe, such as September 2021's order for a portable power supply system for the Swiss Defence Forces, in the low single-digit million Euro range. The units will allow the defence forces to operate away from the grid for several weeks during exercises in Switzerland or abroad.

UltraCell's focus is on portable units up to 165 W, packaged as autonomous power sources and in Pelican cases (the Blade for special forces use). In April 2021, UltraCell developed the 'Honey Badger' a 50 W reformed methanol fuel cell on a soldier-worn plate carrier for on-the-move battery charging. UltraCell is working with funding from the DOD to obtain MIL-STD certification for its 70% methanol cartridges.

The future for portable

There was a time when it looked like portable might disappear as category from our charts. But SFC particularly is doing well, with most of the 6,000 units shipped over 2021 – a 147% increase over the numbers shipped in 2020. And new entrants pop up to replace casualties. Prices continue to fall, while the value proposition increases, but the path to profitability in this segment remains elusive.

China – big, and set to get bigger

With their continuous promotion in each region and targets set for demonstrations, FCEVs in China are expected to grow to at least 46,000 units by 2025. Now, the numbers are lower, with unit production dominated by five indigenous suppliers of vehicle fuel cells: SinoHytec, Shanghai Re-Fire, Horizon Fuel Cell, Sinosynergy, and Sunrise Power. Next come Shanghai Hydrogen Propulsion (SAIC), Shanghai Edrive (Broad Ocean), Bing Energy, Wuhan Vision, Edelman, and Weichai, and then over 100 other companies, mostly focused on FCEVs. Light duty cars (the Roewe 950, and the SAIC Maxus FCV80) exist, but in low numbers. Today, the stationary fuel cell count is tiny, but this may change with new provincial policies.

Policy changes and COVID slowed growth

In April, 2020, China's Ministry of Finance, Ministry of Industry and Information Technology, Ministry of Science and Technology, and National Development and Reform Commission jointly released "A Notice on Optimizing Fiscal Subsidies for Promoting New Energy Vehicles". The NEV class includes BPEVs, hybrids, and FCEVs. The Notice was the annual adjustment to China's decade-long national subsidy program for NEVs.

It extended subsidies for two years, to the end of 2022, to continue to stimulate the market, which has been impacted by the COVID pandemic and the global downturn of the auto industry. Overall, the subsidies were phased down to modest levels given the cost differentials with ICE versions. For light-duty fuel cell commercial vehicles (minibuses, vans, and vocational), the base subsidy was set at CNY240k (US\$36k). For medium to heavy-duty commercial vehicles, the base subsidy is CNY400k (US\$60k). The final subsidy is then calculated via a multiplier, increasing to a maximum as the rated power of the fuel cell reaches 50% or more of the overall power output. Simple production subsidies for FCEVs are to be replaced by dedicated promotion packages.

The Chinese central government paused providing purchase subsidies for FCEVs on April 23, 2020. In their place, a new four-year Pilot Cities Programme began, with suitable cities selected to carry out R&D and application demonstrations of FCEVs. The new policy is intended to address local weakness in core technologies, the production of key components, and a lack of refuelling stations.

Funding has moved to a points-based system, based on the plans of the cities, and will be adjusted midway through implementation depending on each cluster's implementation progress.

Applications were invited from cities satisfying basic criteria (>100 FCEVs and two or more >500 kg/day capacity HRS already in place). To get funding, technology breakthroughs in key fuel cell components were needed as part of the submitted plans, alongside routes to reduce H₂ price, to less than CNY35/kg (US\$5.2/kg), a minimum of 1,000 FCEVs and 15 HRS to be fielded, with vehicles running for at least 30,000 km (to avoid vehicles being made, but not used). Cities were quick to submit their plans, but the changes to the policy direction, coupled with COVID, led to a fall in FCEV numbers in China since their peak in 2019. FCEV producers were hesitant to make vehicles in the absence of a clear route by which the subsidies would continue.

Cities were quick to submit their plans, but the policy changes, coupled with COVID, led to a fall in FCEV deployment. FCEV producers were hesitant to make vehicles in the absence of clear subsidies.

The fall in numbers is offset by increasing module sizes, up on average from 38 kW in 2018 to 81 kW in 2020. As capability becomes increasingly established by the module producers and vehicle OEMs, the subsidy is set to taper slowly through to 2023. By then, efforts in cities for adoption of FCEVs and the HRS to support them will come to the fore.

But big plans now exist for cities

Promotion of the FCEV industry is increasing at national level, including the "State Council White Paper on China's Energy Development in the Era" and the recent "Action Plan for Carbon Dioxide Peaking Before 2030", which proposed H₂ use be actively expanded in delivering clean energy in transport.

At regional level, several cities and regional governments have now adopted policy documents, for example, the "Implementation Plan for Hydrogen Industry Development in Beijing (2021-2025)", and the "Development of Hydrogen Fuel Cell Vehicle Industry in Jiangsu".

In **Beijing-Tianjin-Hebei**, CNY100bn (US\$14.9bn) of hydrogen energy value chain investment will be made by 2025 to promote 37 HRS and 10,000 FCEVs in Beijing. There will be also 15 H₂ chain leading enterprises and four international platforms in Beijing by 2025.

Hebei is aiming for 50 HRS and 10,000 FCEVs by 2025; 100 HRS and 50,000 FCEVs by 2030. The whole H₂ energy industry value chain in Zhangjiakou City in Hebei is hoped to be worth CNY26bn (US\$3.8bn) a year by 2025, CNY85bn by 2030 and CNY170bn by 2035.

Shanghai is aiming for 60 HRS and 6,000 FCEVs by 2025. Within Chengdu, there will be 30 HRS, two fuel cell tram demonstration lines (30 km) and 200 FCEVs by 2023. **Jiangsu** is aiming to have 50 HRS and 10,000 FCEVs by 2025. Within Su Zhou, CNY100bn (US\$14.9bn) of revenue from the H₂ and FC industry is targeted, with 10 competitive enterprises. In **Shandong**, 100 HRS and 10,000 FCEVs will be built by 2030. In Henan, 80 HRS and 5,000 FCEVs will be built by 2025. It is estimated that the H₂ value chain will be worth CNY100bn (US\$14.9bn).

Of the regions, Shanghai has the highest target numbers. The plan is supported by policies on "Development Fuel Cell Vehicle in the City", to help to increase the financial funds available. Shanghai is also currently the most active city in fuel cells for vehicles.

Increased presence of international companies

Chinese and overseas companies continue to pair. Ballard supplies Re-Fire, through the Sinosynergy JV. Toyota also provides fuel cell parts to Re-fire, and Re-Fire supplies its FC system to FAW and Higer Bus. Toyota (and SPIC) supply SinoHytec; Ballard and Ceres supply stacks to Weichai.

In January 2021, Hyundai Motor Group signed an investment contract with the government of Guangdong Province to establish a fuel cell system production facility in Guangzhou, with completion by the second half of 2022. This will be Hyundai Motor's first fuel cell production base outside Korea, with an initial capacity of 6,500 units a year.

In March 2021, Toyota a JV with fuel cell specialist SinoHytec. The JV company, called Toyota SinoHytec Fuel Cell (FCTS) based in Beijing, will produce and sell modules for commercial vehicles.

In March, Hexagon Purus and CIMC Enric signed two JV agreements encompassing Type III and Type IV H₂ cylinder production for FCEVs. A new plant with a capacity of 10,000 units will be built to meet the needs of markets in Asia.

In April, Shanghai Re-Fire announced a partnership with Germany's Schaeffler Group. The companies will explore the key areas of fuel cell technology, including thermal management systems, stack end plates and distribution heads. RE-Fire's technologies already power over 2,700 fuel cell vehicles in China and five other countries.

In May 2021, Bosch established a JV with the commercial vehicle manufacturer, Qingling Motors, to develop, assemble and market PEM modules for the Chinese market, aiming to supply systems to all Chinese vehicle OEMs. The BOP components (stack, air compressor, power electronics, and control unit with sensors) will come from Bosch's plant in Wuxi, Jiangsu Province. Small-scale production will start there in 2021, and a test fleet of 70 Qingling trucks with Bosch modules is to be established by the year end. Market launch of the fuel cell system is planned for 2022-2023.

In May, Faurecia acquired CLD, a hydrogen tank manufacturer with two plants in Liaoning. Cummins started operating its first engineering centre in Wuhan. Cummins is also planning an East Asia R&D Centre in 2022.

And In October, Johnson Matthey officially opened its new plant in Shanghai, to produce around 4m MEA components a year, enough for more than 10,000 commercial vehicles. JM's fuel cell technology is already in more than 700 buses and trucks in China.

Stationary potential

Information on numbers of stationary fuel cells in China is limited. Units have been installed for telecom backup and are being developed for CHP and other stationary applications, but at far less intensity than FCEVs.

In March 2020, MOST proposed fuel cell CHP as a key H₂ energy technology, issuing its "Application Guidance for 2020 Key National Specialized Projects of Renewable Energy and Hydrogen Energy Technology", with performance indicators for PEM-CHP/cooling and SOEC-CHP couples.

Provinces and cities have issued policies focusing on CHP, DG and back-up power. But this has yet to translate into significant programmes. Local government plans suggest stationary growing in Foshan, from 2 MW in 2025 to 30 MW in 2035, and in Shandong Province, from 200 MW in 2025 to 1,000 MW in 2035.

Looking to the future

We can't pretend we are not already well into 2022, with all of the upheaval that has brought. But while the global situation is tough, the fuel cell industry, with its strong links to clean air, renewables and hydrogen, could do well. Policies to curb carbon emissions and move from fossil fuels are likely to strengthen, not weaken. Investors still have cash and are continually seeking 'new' industries to support, and supply chain players continue to engage. Pleasingly, the story in 2021 was about growth, opportunity and investment, with no big scandals or damaging company exits. And if the fuel cell product being announced is actually produced and put into service, we could be at the start of a very positive self-sustaining cycle.

Of course much detail and nuance lies behind last year's numbers. We had the same companies dominating as always, but a strong set of players is waiting to join them: Bosch, cellcentric, Ceres, Cummins, EKPO, HDF, Nuvera, Symbio and others are all poised to ship more. Hyzon has a long list of announced orders, and China is poised to revert to growth mode as the revised policy measures kick in. More HRS will support more buses, heavier trucks, and potentially cars – we see increasing announcements for the Chinese light duty sector. And we may even see some progress there in stationary fuel cells.

Like China, Korea is expected to be a growth market as hydrogen policy becomes enshrined in law. More large-scale projects are already in the pipeline, while multiple other end-uses – from shipping to micro-CHP – are gaining traction.

Module standardisation, up to the MW-scale, is being led by HDF/Ballard, PowerCellutions, Toyota, Honda, Plug Power and others. In many cases, they can be used both for mobility and stationary uses. This should further reduce costs and assist developers to pick an 'off-the-shelf' solution for their project, increasing uptake from less specialist buyers.

Standardisation and scale-up are likely to help Hyundai keep its current lead in MW delivered for a while longer. Its 100,000-unit per year factory should be operating at full capacity around mid-2023, so 2022 will see much progress.

Most of the trucks to be delivered into Switzerland are also still to come, which could bring a welcome uptick in Europe's installed fuel cell numbers!

In other regions growth is often linked to a wider and grander interest in hydrogen. Australia and New Zealand have ambitious hydrogen production plans, and are starting to deploy the first small fleets of fuel cell vehicles. The links between hydrogen and the mining of specific materials for the energy sector is an important one. In much of Latin America the main driver is the same, and – like Australia – decarbonisation of mining may lead to substantial fuel cell uptake using locally-produced hydrogen, as it may in South Africa.

North American growth remains hard to predict, though increasing heavy-duty activity, coupled with Californian determination, suggest that transport roll-out will continue to increase, while prime power competitiveness remains strongly dependent on local spark spreads and incentives.

Portable fuel cells may finally be back on a growth path too, across a host of markets and end-uses. Their small size gives them limited impact on the MW installed, or on CO₂ reduced, but definitely helps the industry develop.

While global policy looks something like a patchwork quilt, with different countries adopting different approaches, the overall direction is similar, with opportunity for fuel cells to help deliver. And energy prices are shifting dramatically across the globe, changing the slope of the playing field and moving the goalposts at the same time. Some of this will be beneficial to fuel cell solutions, which will compete where they couldn't before. We hope the industry is ready – and able – to act on those opportunities.

Data tables

Shipments by application					
1,000 Units	2017	2018	2019	2020	2021f
Portable	5.0	5.7	3.9	4.1	6.1
Stationary	54.9	51.9	52.2	56.8	47.9
Transport	10.6	10.9	16.4	20.9	32
Total	70.5	68.5	72.5	81.8	86.0

Shipments by region of adoption					
1,000 Units	2017	2018	2019	2020	2021f
Europe	5.1	7.7	10.7	13.2	14.0
North America	9.4	9.3	8.1	10.8	15.4
Asia	55.3	50.9	53.5	57.6	56.2
RoW	0.8	0.6	0.2	0.2	0.4
Total	70.5	68.5	72.5	81.8	86.0

Shipments by fuel cell type					
1,000 Units	2017	2018	2019	2020	2021f
PEMFC	43.7	39.7	45.7	53.1	55.2
DMFC	2.8	3.7	3.7	3.8	5.3
PAFC	0.2	0.2	0.3	0.3	0.2
SOFC	23.7	24.9	22.8	24.6	25.2
MCFC	0.0	0.0	0.0	0.0	0.0
AFC	0.1	0.0	0.0	0.0	0.1
Total	70.5	68.5	72.5	81.8	86.0

2021f is our forecast for the full year, based on firm data from January to September, and in most cases to as late as December.

We have revised the figures for 2020 in this report, now with firm full year data where previously a final quarter forecast was required.

Data tables

Megawatts by application					
Megawatts	2017	2018	2019	2020	2021f
Portable	0.6	0.7	0.4	0.5	0.7
Stationary	222.3	220.6	274.8	325.1	347.6
Transport	435.7	584.5	921.1	1,012.0	1,964.8
Total	658.6	805.8	1,196.3	1,337.6	2,313.1

Megawatts by region of adoption					
Megawatts	2017	2018	2019	2020	2021f
Europe	38.9	41.2	113.0	150.1	203.0
North America	331.8	425.3	339.2	253.3	613.0
Asia	285.8	337.9	743.9	929.1	1,493.2
RoW	2.1	1.2	0.2	5.1	3.9
Total	658.6	805.8	1,196.3	1,337.6	2,313.1

Megawatts by fuel cell type					
Megawatts	2017	2018	2019	2020	2021f
PEMFC	466.7	609.0	948.0	1,048.2	1,998.3
DMFC	0.3	0.4	0.4	0.5	0.5
PAFC	81.0	86.3	130.9	132.2	95.8
SOFC	85.2	84.1	106.8	147.8	206.9
MCFC	24.7	25.8	10.2	8.8	11.1
AFC	0.6	0.1	0.0	0.1	0.5
Total	658.6	805.8	1,196.3	1,337.6	2,313.1

2021f is our forecast for the full year, based on firm data from January to September, and in most cases to as late as December.

We have revised the figures for 2020 in this report, now with firm full year data where previously a final quarter forecast was required.

Notes

- Data for 2014 to 2021 have been collected directly from fuel cell manufacturers and integrators where they were able to share it. For those who were not able to share primary data, and to sense-check our numbers, we have collected and cross-referenced data from publicly available sources such as company statements and statutory reports, press releases, and demonstration and roll-out programmes, in addition to discussions with other parties in the supply chain.
- Our 2021 figures are a forecast for the full year. The dataset contains firm numbers for the period January to September 2021 (and in many cases as late as December 2021). For any remaining period of the year we use companies' own forecasts, shared with us, or ones we prepare in discussion with industry.
- We will revise data for 2021 in our 2022 edition as appropriate. We have slightly revised the figures for 2020 in this report: Unit numbers were decreased by 0.8% and megawatt numbers increased by 1.4% compared to our published 2020 forecast. Unit numbers are rounded to the nearest 100 units. An entry of zero indicates that fewer than 50 systems were shipped in that year.
- Megawatt numbers are rounded to the nearest 0.1 MW. An entry of zero indicates that less than 50 kW was shipped in that year.
- The reported figures refer to fuel cell system shipments by the final manufacturer, usually the system integrator. In transport we count the vehicle when shipped from the factory.
- We do not count replacement stacks in existing applications, and where possible we also do not count inventory, only systems that are shipped to users.
- Portable fuel cells refer to fuel cells designed to be moved. They include small auxiliary power units (APU), and consumer electronics (e.g. phone chargers). Toys and educational kits are not reported.
- Stationary fuel cells refer to fuel cell units designed to provide power at a 'fixed' location. They include small and large stationary prime power, backup and uninterruptable power supplies, combined heat and power (CHP) and combined cooling and power. On-board APUs 'fixed' to larger vehicles such as trucks and ships are also included.
- Transport fuel cells refer to fuel cell units that provide propulsive power or range extender function to vehicles, including UAVs, cars, buses and material handling vehicles.
- Our geographical regions are broken down into Asia, Europe, North America and the Rest of the World (RoW), including Russia.

Shipments by fuel cell type refer to the electrolyte. Six main electrolyte types are included here. High temperature PEMFC and conventional PEMFC are shown together as PEMFC. Other types of fuel cells currently in an early stage, such as microbial fuel cells and solid acid fuel cells, are not included in the numbers shown.

About E4tech and the authors

Since 1997, E4tech has helped clients to understand and profit from opportunities in sustainable energy, with deep expertise and long experience in many sectors, and in the energy transition. Fuel cells and hydrogen are particular areas of strength, and we have carried out hundreds of projects for early stage companies, SMEs, large companies, financiers and governments worldwide. These projects include:

- market forecasting and competitor analysis
- business plan development and strategy
- technical and commercial due diligence
- support for policy development.

Since June 2021, E4tech (www.e4tech.com) has been part of ERM (www.erm.com), the world's leading pure-play sustainability consultancy. We have also been joined by Element Energy (www.element-energy.co.uk), a specialist low-carbon energy consultancy. Their skills and knowledge strengthen and complement ours in fuel cells, hydrogen and many other areas.

The Review effort is led by those below, and supported by many members of E4tech, in data gathering, drafting and interpretation in different languages, such as Chinese, French, Italian and German.



Prof David Hart is a Director of E4tech, responsible for the Fuel Cell and Hydrogen Practices. In 25 years in the sector he has been an expert adviser, consulted and carried out research for national governments, major industrial companies, start-ups, financial organisations and NGOs. He has been an invited keynote speaker at conferences on six continents.

Dr Stuart Jones is E4tech's Energy Technology Knowledge Manager. He has over 30 years' industry experience with fuel cells, hydrogen and battery technologies, working for large corporates, manufacturing businesses and start-ups.



Dr Tom Houghton is a member of the Fuel Cell & Hydrogen Sector group at E4tech. He is a Consulting Director in E4tech's London office with more than 15 years' experience in the energy sector gained in consultancy, research, banking and industry. He has expertise in both hydrogen energy and power systems.

Xavier Cordobes is a Senior Consultant at E4tech, working on a wide range of projects related to fuel cell and hydrogen technologies. He has over 10 years of experience in the fuel cell industry on three continents, gained in the Honda/GM Fuel Cell Collaboration, several fuel cell system manufacturers and technical consulting.



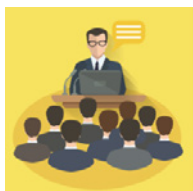
Jonathan Lewis has over twenty years' experience in business development, from strategy and policy through business plans to technology commercialisation. More than 10 years in the fuel cell and hydrogen area, he was with Rolls-Royce Fuel Cell Systems Ltd, and is now an independent adviser. He has extensive experience, including in a variety of roles with the FCH JU.

E4tech, ERM and Element have conducted numerous influential analyses in the fuel cells and hydrogen energy space, in addition to renewable and bio-based fuels and chemicals; batteries and other energy storage; low carbon transport, innovation policy and support and sustainability more broadly. We have also supported technology development, designed and led major funding applications and projects, due diligence of potential acquisitions, and conducted compliance analyses of various kinds.

Can we help?

Would you like to know more about the fuel cell or hydrogen industries? What we think the future looks like? How it affects you? We have supported organisations in the fuel cell and hydrogen sectors globally for 20 years, as well as companies in many other areas who may be touched by these developments. We would be delighted to discuss the Review with you, formally or informally, and any needs you may have.

Our services include:



Bespoke Expert Briefings

– Would you like a focused discussion on the detail of the **fuel cell sector** or the whole breadth of **hydrogen energy** for your **team** or your **Board**?

We can tailor a **presentation** or **workshop**, long or short, to cover the **big picture** or the **fine detail**.

Market and Supply Chain Analyses

– Are you looking for something better than the generic **fuel cell market forecasts** typically available? We can build **bespoke forecasts** for **regions, applications** and **components**

– Do you need to better understand the **supply chain**, the **value pools, global market** opportunities or the **competition**?

– We have carried out detailed analyses for large and small corporations worldwide, feeding into technology and supplier choices, **business development** and **strategy**.



Commercial and Technical Due Diligence Evaluations

– Are you thinking of **investing** in or **acquiring** a technology or company?

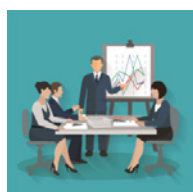
Our many **technical and commercial analyses for due diligence** purposes have helped diverse **investors** to understand risks and opportunities, and we also have a dedicated M&A team for larger opportunities.

Business and Strategy Support

– Could your **business plan** or **strategic approach** be strengthened?

– Are you looking for strategic partners to build a project or business?

We have **data, projections** and a deep understanding of the fuel cell sector, its past and **possible future** to help you develop and stress-test your strategy or accelerate its implementation. We have also built partnerships, secured funding and led major projects.



Objective Review and Expert Resource

– Do you need an **external perspective** or some **extra resource**?

We can evaluate your strategy or your programmes, bring in views you may not have considered, or simply provide expert resource to your team for a specific project or task.

We are always happy to discuss aspects of the sector and questions you may have. Please contact us directly through www.e4tech.com and we'll find the right person for you to talk to.

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9	cellcentric stack	FleetOwner commercial trucks
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13	Latest Toyota Mirai model	Toyota Motor Corporation
15	First Peugeot e-XPRT Hydrogen van	Stellantis
16	Germany's 92nd HRS at Neuruppin, Brandenburg	H2 International Journal
17	Sinopec high pressure HRS with Chengdu electrolyser	Hydrogen Central
19	Solaris Urbino 12 Hydrogen for Arriva Nederland	Solaris Bus & Coach S.A.
19	Hyundai ELEC CITY Fuel Cell bus at OMV HRS	Hyundai Motor Company
19	pepper motion diesel bus conversion	pepper motion GmbH
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