The Fuel Cell Industry Review **2022**

ACKNOWLEDGEMENTS

We gratefully acknowledge the contribution of many individuals and companies within the fuel cell industry in providing information for and assistance with the compilation of the Fuel Cell Industry Review 2022. The Fuel Cell Industry Review 2022 is based on shipment information and news items up to December 2022.

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LIST OF ABBREVIATIONS

ACE	Association of Combustion Engineers of Japan
AFC	Alkaline fuel cell
AGV	Autonomous guided vehicle
AiP	Agreement in principle
APC	Advanced Propulsion Centre UK
APU	Auxiliary power unit
BEV	Battery electric vehicle
BMVI	Federal Ministry of Transport and Digital Infrastructure (Germany)
BPP	Bipolar plate
BTS	Base transceiver station
BVLOS	Beyond visual line of sight
CA	California (US state)
CAAM	China Association of Automobile Manufacturers
CAGR	Compound annual growth rate
CARB	California Air Resources Board
CCS	Carbon capture and storage
CEF	Connecting Europe Facility
CEO	Chief Executive Officer

CH2	Compressed hydrogen
CHP	Combined heat and power
CHPS	Clean Hydrogen Portfolio Standard
CT	Connecticut (US state)
DC	Direct current
DMFC	Direct methanol fuel cell
DOD	Department of Defense (US)
DOE	Department of Energy (US)
DOT	Department of Transportation (US)
DWT	Deadweight tonnage
EU	European Union
FC	Fuel cell
FCEB	Fuel cell electric bus
FCEV	Fuel cell electric vehicle
FCT	Fuel Cell Today
FID	Final investment decision
GHG	Greenhouse gas
GVW	Gross vehicle weight
GW	Gigawatt
HGV	Heavy goods vehicle
HFC	Hydrogen and fuel cell (technologies)
HQ	Headquarters
HRS	Hydrogen refuelling station
HT-PEM	High-temperature PEM (PBI)
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
IAA	Internationale Automobil-Ausstellung (Motor show in Germany)
ICE	Internal combustion engine
IEA	International Energy Association
IMO	International Maritime Organization
IP	Intellectual property
IPCEI	Important Projects of Common European Interest
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IRA	Inflation Reduction Act
ISO	International Organisation for Standardisation
ITC	Investment Tax Credits
JIVE	Joint Initiative for hydrogen Vehicles across Europe
JV	Joint venture
KfW-433	Förderung für das Heizen mit Brennstoffzelle (German national mCHP programme)
kVA	Kilovolt amps
kW	Kilowatt
LA	Los Angeles
LFP	Lithium-iron-phosphate
LH2	Liquid hydrogen
LNG	Liquefied natural gas
LTO	Lithium-titanium-oxide
LT-PEM	Low-temperature PEM
MCFC	Molten carbonate fuel cell
MEA	Membrane electrode assembly
MIT	Massachusetts Institute of Technology
MTIE	South Korean Ministry of Trade, Industry and Energy
MJ	Megajoule
MoU	Memorandum of understanding
MPV	Multiple purpose vehicle
MW	Megawatt
NASDAQ	US Stock Exchange (National Association of Security Dealers Automated Quotations)
NEV	New energy vehicle
NICE	National Institute of Clean and low-carbon Energy (US)

NIP	National Innovation Programme for Hydrogen and Fuel Cell Technology (Germany)
NM	Nautical mile
NOK	Norwegian Krone
NORCE	The Norwegian Research Centre
NOW	National Organisation for Hydrogen and Fuel Cell Technology GmbH
NY	New York (US State)
NYSERDA	New York State Energy Research and Development Authority
OEM	Original equipment manufacturer
PACE	Pathway to Competitive European fuel cell micro-CHP market
PAFC	Phosphoric acid fuel cell
PEM(FC)	Polymer Electrolyte Membrane (Fuel Cell)
PGM	Platinum group metals
PPA	Power purchasing agreement
PRHYDE	Protocol for Heavy-Duty Hydrogen Refuelling
PTC	Production Tax Credit
PV	Photovoltaic
R&D	Research & development
RINA	Registro Italiano Navale
RNV	Rhein-Neckar-Verkehr GmbH
RoW	Rest of the world
RTC	The Regional Transportation Commission of Southern Nevada
RVK	Regionalverkehr Köln GmbH
SAE	Society of Automotive Engineers
SCAQMD	South Coast Air Quality Management District
SEC	The U.S. Securities and Exchange Commission
SEK	Swedish Krona
SOEC	Solid Oxide Electrolyser Cell
SOFC	Solid Oxide Fuel Cell
SRP	Schottel Rudder propellers
SUV	Sports utility vehicle
TEU	Twenty-foot equivalent unit
tpa	Tonnes per annum
tpd	Tonnes per day
UAV	Unmanned aerial vehicle
UK	United Kingdom
UPS	Uninterruptable power supply
US/USA	United States (of America)
ZANZEFF	Zero- and Near Zero-Emission Freight Facilities
ZEP	Zero emission powertrain
ZEV	Zero emission vehicle

CONTENTS

STILL GROWING, BUT THE HEADWINDS ARE STRONG

Despite global challenges, fuel cell shipments of all kinds grew from just over 2.3 GW in 2021 to just under 2.5 GW in 2022. Though lumpy, this is still a CAGR of around 25% since 2018.

As so often, most fuel cell shipments by MW capacity are for mobility, 85% in fact, at just over 2.1 GW. And most of those are for passenger cars, at just over 15,000 units, nearly all from Hyundai and Toyota. Together, cars total just over 1.5 GW - 62% of global shipments by MW. So, while achieving 2.5 GW is definitely a positive sign, it is fragile, as a fall in units from the carmakers would put a substantial dent in the total.

For trucks and buses, China retains its lead, shipping nearly 3,800 units. Outside China, fewer than 400 fuel cell commercial vehicles went to Europe and North America combined. South Korea bus shipments increased to around 175 units, mainly from Hyundai. Other truck shipments were negligible, just over 10 units to South Korea, India and Taiwan together. But an acceleration of vehicle shipments into China is expected, as the country pushes to meet its national target of 50,000 fuel cell vehicles by 2025.

Fuel cell van deployments were subdued, with still limited numbers of Renault's Kagoo ZE Hydrogen, and little evidence of a serious push of last year's demonstrator vehicles from Stellantis. However, Stellantis clearly is committed to the concept, as it pushed for a substantial stake in Symbio.

To support the increasing numbers of vehicle deployments, the hydrogen refuelling station network continues to grow (despite retirements), to over 800 in use (as at the end of 2022). China, behind until now, saw the fastest growth rate.

In other mobility, rail continues to be explored, with growing activity in shipping and in aviation. In shipping, the picture is made more complex by the range of fuels as well as fuel cells being considered. In aviation, interest and growth in drones is now joined by larger aircraft.

Forklift shipments, both globally and into Europe, fell in 2022, to fewer than 10,000 units annually. But the range of supply actors is slowly increasing, with more models available.

As last year, we observe that fuel cell shipments of any kind are driven mainly by the policy context of differing countries, and the surrounding credits or other incentives for sale. Hence South Korea, which has strong incentives, is targeted by Hyundai for vehicles in its home market, and in stationary by Bloom Energy, having partly displaced Doosan Fuel Cell.

Japan has led for many years in residential fuel cells, in fulfilment of the Ene-Farm programme. Ene-Farm shipments increased by nearly 8% from 2021. Sadly, though, after a good year for residential fuel cells in Germany, the closing of the KfW-433 incentive at the end of the year, together with the ending of the PACE programme across Europe, does not bode well for the market.

Large CHP shipments were flat year on year (just over 130 MW for 2021 and 2022), while prime power grew, from 203 MW in 2021 to 231 MW in 2022. Most of the shipments in large CHP and prime power went to South Korea (217 MW) with a reduced number of shipments to the US of 102 MW (148 MW in 2021).

Portable fuel cell shipments continue to grow, led by SFC Energy. Unit numbers were nearly 8,000 units (compared to 6,000 shipments in 2021).

Changes to the paradigm are on the way, and these may drive growth. 2022 saw the beginning of major fuel cell projects in Europe, as national governments and then the European Commission approved 'Important Projects of Common European Interest', or IPCEIs. These transnational projects seek to deliver a competitive edge to Europe, with key aspects like delivering supply chain competencies, manufacturing capacity and demonstrations at scale, a world away from the more modest low unit demonstrators of the past. Funded partly by the national governments (and exempt from State Aid) and partly from private sources, at roughly 70%, these should at least start to deal with many of the obstacles that fuel cells face.

The US has its own plans, with the enactment in 2022 of the Inflation Reduction Act. While the overall budget is vast, much of the attention (and budget) is focused on subsidising green hydrogen, to build capacity, and to reduce costs through the associated learning.

China continues to develop its own policy, with exports of fuel cells a major component, one which is slowly bearing fruit. Another 9 countries set out their own plans for hydrogen and fuel cells in 2022, though none as yet having moved to action. The change of embedded energy systems is slow, but fuel cells are now being disseminated in small numbers to countries beyond Europe, North America and Asia, even if only at the exploratory phase.

And we are, at last, seeing growth in niche but high value markets, notably remote power for events, for power to outside film and television sets, and in backup power to telecoms. This is not just a re-run of the portable power offerings 20 years ago, where the equipment was unrefined and far too expensive for adoption. Now we are seeing plant hire suppliers and resellers in other markets actively placing equipment. In telecoms, the demand often comes from countries with regular blackouts to civil networks, where governments are hardening emergency networks against failure. This attests to the reliability of the fuel cells.

With the huge interest in the sector, yet more fuel cell actors moved into electrolysis in 2022, most, like Plug Power, are now covering both bases rather than switching out of fuel cells.

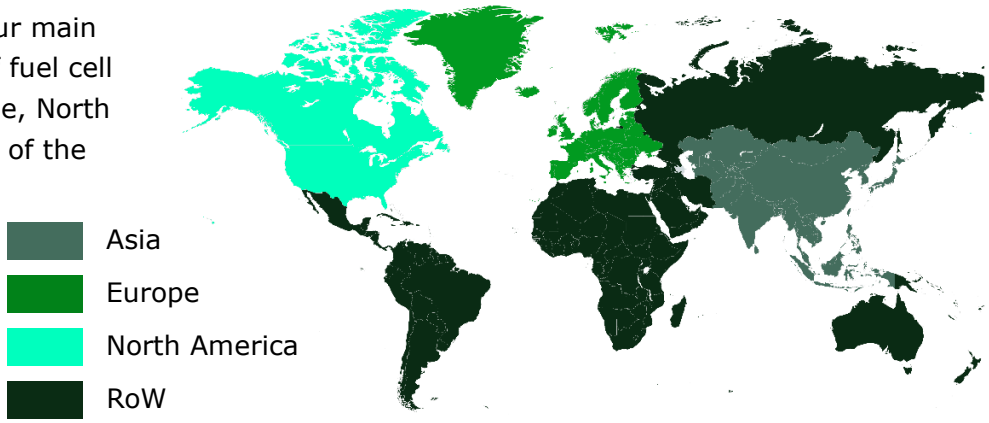
Company activity continues to be vibrant, though investors are not always benefitting. While some of the stalwarts remain, the number of actors, despite some casualties, continues to increase: Blue World Technologies, Bosch, cellcentric, EKPO, Hyvia, Symbio (in new form), TECO 2030, to name a few. Doosan is extending its play to shipping and even now buses, as well as, of course, the Honda, Hyundai and Toyotas of the world, let alone China.

Looking from the outside, the sector is in an odd position. Not growing dramatically, but still with a role to play and with actors and investors engaging. Better supply chains, new opportunities, and a complex and chaotic external environment that means neither conventional nor novel bets are certain. Something may yet click in the geopolitical, technical or environmental environment to change the game.

ABOUT THE REVIEW

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)



APPLICATIONS

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

Application type	Portable	Stationary	Transport
Definition	Units built into, or able to charge up, products 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	1 W to 20 kW	0.5 kW to 2 MW	1 kW to 300 kW
Typical technology	LT-PEMFC HT-PEMFC DMFC SOFC	LT-PEMFC HT-PEMFC SOFC PAFC MCFC AFC	LT-PEMFC HT-PEMFC DMFC
Example	• Portable products • Small 'movable' APUs (campervans, boats) • Semi-stationary power units that are ported (for events, road works, construction) • Military applications (soldier-borne power, skid-mounted gensets)	• Small stationary micro-CHP (domestic and commercial premises) • Large stationary prime power and combined heat and power (CHP) • Uninterruptible power supplies (UPS) • Larger 'permanent' APUs (e.g. trucks and ships, fixed in place)	• Materials handling vehicles • Fuel cell electric vehicles (FCEVs) • Trucks and buses • Rail vehicles • Aircraft • 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 fixed in place, e.g., on 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 types: 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 and low-temperature PEMFC are shown together as PEMFC.

Descriptions of these six main fuel cell types are available on **the archive of FCT's website**.

REPORTED SHIPMENT DATA

E4tech, now ERM, has been publishing this Review for ten years now. Tables of data can be found at the back of this Review going back to 2018. Editions of the review prior to 2018 included historical information 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 of toys and educational kits containing fuel cells.

DATA SOURCES AND METHODOLOGY

We have been in direct contact, either verbally or in writing, with over 30 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. Generally, we do not count replacement stacks in existing applications (with the only exception being FuelCell Energy), 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 calendar year 2022. These comprise direct numbers from shippers or from syntheses, including collation of press releases, where direct numbers were not available. We will revise data for 2022 in our 2023 edition if the shipment estimates need to change. Our final figures for 2021 are revised from our past forecast, with only minor variances in units shipped for grid support, off-grid power and light duty vehicles.

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. We always anonymise data by aggregating published sets, and strictly restrict access to data, to ensure confidentiality is maintained.

LOOKING BACK ON 2022

2022 saw key actors expanding their technology offerings, target regions, and diversifying their business models, reaching for new ways to grow. This is exemplified by Bloom Energy Server shipments into South Korea now being well ahead of the US, Doosan's soft launch of a stationary SOFC demonstrator (using Ceres stacks, as a prelude to larger marine systems yet to come), and Toshiba's push into fuel cell buses in Europe (built on its stationary plays).

Doosan's HyAxiom US subsidiary is broadening its reach into buses (PEM), ships (SOFC), and electrolysers (SOEC). The PAFC business is struggling in the US and facing competition from Bloom in the home market of South Korea. Such is the success of Bloom that Energy Server sales into Korea rose to roughly two thirds of its overall volume in 2022, up from a third in 2021. FuelCell Energy, now with nearly 50 MW of PPA contracts, continues to struggle to profit.

2022 marked the first tranche of fuel cell projects to receive funds as Important Projects of Common European Interest. These aim to transform the competitiveness of the EU overall. Recipients comprise an industry roll call: vehicle OEMs (Daimler, Iveco); JV's (EKPO, Genvia, Hyvia and Symbio); a shipbuilder (Fincantieri); industrials (Alstom, Bosch); fuel cell OEMs (Advent, Nedstack); and supply-chain companies (Arkema, Plastic Omnium). Altogether, nearly €15bn has been allocated in public and private funding, with further rounds to come, bettering supply chains and prospects for the companies. 2022 also marked the passing of the Inflation Reduction Act in the US. The headline US$370bn budget looks impressive, but this is spread over a decade, with much of the credits going to subsidising green hydrogen production.

Aside from IPCEI co-funded developments, 2022 saw fuel cell developers making plans to increase capacity. In July, Johnson Matthey announced it is building an £80 million gigafactory at its Royston, UK, site, capable of making 3 GW of PEM fuel cell components annually for H_2 vehicles. Supported by UK government funds, the site is expected to be in operation by H1, 2024. JM aims for more than £200 million sales in hydrogen technologies in 2025.

Towards the end of 2022, Plug also opened its 2.5 GW fuel cell and electrolyser production site at Rochester, NY. It is worth noting that just because a factory has a given capacity, it may not all be used initially, feeding into shipments. For example, TECO 2030 hopes to reach about 900 MW output by 2027, well below the headline capacity of 1.6 GW due to come online in 2023. Somewhat more modestly Proton Motor increased the area of its fuel cell production site in Puchheim, Germany by seven-times, and Cummins opened its 10 MW capacity site in Herten.

2022 saw a small rise in Ene-Farm shipments, but it was also the year when kfW-433 funding and PACE placements ended. While the objectives of greater volume and reducing cost were met, unit costs remain unattractive, and the lack of subsidy questions the business model.

China's regional and city pilot programmes are now in full swing, with a significant increase in shipments. The Beijing Winter Olympics were a major success, with close to 1,000 fuel cell vehicles deployed. But the national target of 50,000 FCEVs by 2025 looks like it may be missed.

Elsewhere, truck deliveries to Europe were up, while fuel cell bus sales halved. Shipments of fuel cell commercial vehicles in the US more than doubled. And a small and growing volume of fuel cell vehicle shipments is evident to the rest of the world, from Oceania to South America.

Hyzon's claims for vehicle placements in 2021 were rather over-extended, restructuring its European and Chinese operations in the second half of 2022, and finally resuming SEC filings.

Fuel cell car shipments declined from 2021, shipments of the Mirai to California, the main market, falling 20% y/y. Shipments of the NEXO to the home country were up by roughly 1,600 units, with a small increase in shipments elsewhere. In China, cars, mostly negligible to now, were boosted by SAIC, with its Maxus MIFA Hydrogen, though still in small numbers.

In shipping, interest is now extending into several MW of power, including propulsion. Norled's MF Hydra ferry was fitted with its Ballard fuel cells in 2022, with sea trials set for December. For some of the larger ocean-going vessels, still at proof-of-concept stage, fuels cells are often being housed in ISO containers, on-deck. A similar concept is being tested for shore power. The sector is aided by the associated growth in interest of transporting hydrogen by sea and the creation of bunkering facilities, both onshore and offshore. Certainly, the roll call of actors is growing quickly. TECO 2030 is one to watch, with interests spanning maritime, trucks, as well as power for construction. AVL as a partner to TECO 2030 is proving invaluable in its play.

Interest in aviation continued to grow through 2022, extending to propulsion for regional aircraft, with ZeroAvia being particularly active, securing MoU's with key industry actors. Fuel cell drones, with longer flight times than batteries, continue to grow in shipments. Combustion engines using hydrogen are also being explored for his sector, as are turbines for aviation.

Portable fuel cells showed growth, up from roughly 6,000 units in 2021, to nearly 8,000 in 2022, with SFC Energy contributing to most of the shipments. 2022 saw more stationary units aimed at the construction industry, with established genset suppliers like Generac now offering systems from EODev, attesting to the reliability of these units for prime power and emergency stand-by. EODev is now joined by Corvus Energy, Genevos, and others in the use of third-party stacks from vehicle OEMs in stationary systems. The scale-out ability of using multiple fuel cell modules to reach higher powers at lower overall cost is a particular advantage.

NEW AND SHIFTING PARTNERSHIPS

In September, EKPO, the fuel cell JV between ElringKlinger and Plastic Omnium, received a double-digit million Euro order for the new development of a bipolar plate from an unnamed "leading European car maker". As the OEMs are already partnered in their fuel cell supply chain, it is unclear whether this builds on existing relationships or displaces an existing actor.

PROFIT AT LAST

Losses are not unusual in the industry. Only two companies have achieved profitability to date, Doosan Fuel Cell (for many years, an attractive investment target, though trending towards a loss as we go into 2023), and in 2022, SFC Energy, for the first time since its founding in 2002.

ELECTROLYSER PLAYS

Fuel cell actors are increasingly targeting electrolysers, given the emphasis on national policies to H_2, with fuel cells support focused mainly on mobility. Those seeing far ahead and well-funded are leading, others are playing catch-up. Plug and Bloom illustrate this trend perfectly.

The global electrolyser market is growing fast, with 1 GW of production over 2022 (according to IEA figures), set to grow ten times by 2030. At representative capital costs of US$500/kW, the current value of the electrolyser market is around US$500m, so maybe US$5bn by 2030, shared among a growing list of actors. While a significant market, the expected electrolyser volumes fall way short of the economies of scale that solar PV has benefited from, suggesting the road will be bumpy for many of the present market's actors and their investors.

CORPORATE DEVELOPMENTS

Plenty of activity is taking place across the fuel cell space, though with few major corporate events this year. Some of the excitement is yet to come.

PLUG POWER'S TRANSITION

During 2022, Plug Power successfully tested a 3 MW stationary fuel cell with Microsoft. But the main news is in green H_2 supply.

Plug Power is now beginning to exert itself as a H_2 production heavyweight, with a 1 GW electrolyser (100,000 tpa capacity, the world's biggest to date) ordered by H2 Energy Europe for an offshore wind project in Denmark. The electrolyser is set to be supplied out of Plug's gigafactory in Rochester, NY State, with some balance-of-plant parts delivered by European suppliers. Installation at H2 Energy's complex is set for 2024, with green H_2 production from 2025. The electrolyser is set to supply H_2 to HRS in Denmark, Germany and Austria, built on a JV with Phillips 66 to build the HRS, and on a JV with HHM for fuelling fuel cell vehicles.

Over 2022, Plug Power entered into multiple green H_2 supply agreements including Walmart, Amazon and other H_2 forklift customers, for a sales pipeline approaching 200 tpd (73,050 tpa). Plug started construction on multiple green H_2 plants in the US and began work on a 35 tpd H_2 plant at the Port of Antwerp plant in Belgium. Plug Power ended the year with 2 GW of backlog for the electrolyser business and was selected by New Fortress Energy for a 120 MW green H_2 plant on the Gulf Coast.

Plug is a good illustrator of the challenges facing the fuel cell industry. Small companies generally make small losses that are not headline grabbing. Plug is a rapidly growing H_2 and fuel cell company that is also burning through its cash reserves at a rapid pace.

Plug's revenues grew from US$502m in 2021 to US$701m in 2022. Though impressive, the losses were even greater, US$724m in 2022. With cash at hand of US$2.15bn at the end of 2022, it will not be too long before a further capital raise is sought. The cash raises help liquidity, but also unpopularly dilute equity.

Plug Power is experiencing losses from significant investments in R&D, manufacturing plant and production costs, supply chain management and quality control, and from acquisitions. Plug Power has to invest heavily to gain market adoption and build its sustainable growth, for these markets are still at a nascent stage with limited adoption compared to competing and mature renewable technologies. While the company has been successful in securing partnerships with major companies, it takes time for these partnerships to translate into significant revenue growth.

Losses are common for companies in emerging industries, but it is becoming increasingly evident that hydrogen pricing must be attractive for many fuel cell plays to be viable – something at the heart of Plug's business model. But it's becoming evident that the availability of low-cost hydrogen in volume is pushing towards the end of the decade at earliest.

Building a hydrogen infrastructure, including production, storage and distribution will take time. Then there are issues related to supply chain and raw materials, market acceptance and regulatory and environmental aspects – factors the industry still grapples with, despite well over 20 years of effort. All this will require substantial continued investment.

These challenges are not unique to Plug Power. Plug's vision is bold, aiming for US$5bn in sales by 2026, reaching US$20bn by 2030. While the future of fuel cells may be bright, and Plug is a solid leader, investors should fasten their seat belts because the road ahead is full of potholes.

BLOOM GROWING IN FUEL CELLS AND IN ELECTROLYSERS

Plug is not the only company promising GW-scale electrolysis, buoyed by the ambitious green H_2 aspirations of REPowerEU and DOE. Competing US company, Bloom Energy is now targeting sales in Europe. Ferrari may be a glamorous partner but Bloom's work with Italian Cefla, with plans to develop several MW of SOFC for CHP systems, is perhaps more meaningful.

The US remains the largest market for Bloom in term terms of its installed base of Energy Servers but is now second to South Korea in terms of sales. Its success has prompted Bloom to seek expansion of sales into Taiwan, India, Japan, and Australia. In its home territory, Bloom sees the US Inflation Reduction Act as a game-changer for H_2 demand, with up to a US$3/kg production tax credit on H_2 produced via electrolysers using clean electricity, as well the IRA's support to fuel cells directly. Bloom continues to expand in capacity, opening its US$200m multi-GW facility in Fremont, CA, in July 2022. This plant remains focused on production of Energy Servers, showing there is plenty of scope for the fuel cells.

Bloom added a solid oxide electrolyser line to the existing plant in Newark, Delaware, in November 2022, following announcement of its electrolyser product in 2021. In May 2022, Bloom announced it will install, operate and maintain a 10 MW solid oxide electrolyser to supply green H_2 to LSB's 30,000 mtpa ammonia plant at Pryor, Oklahoma, beginning in 2023. Bloom Energy, like most other fuel cell companies, continues to seek profitability. Revenues in 2022 rose to US$1.2bn, but at a net loss of US$301m.

Doosan has found itself hit hard by the delays to fully establishing the Hydrogen Portfolio Standard in South Korea and increasing competition from Bloom. The November deal with ZKRG opens up the Chinese market, with an aggregate 105 MW finished products and part supplies to the end of 2026. Revenues for the year were ₩312bn (US$241m), with a net profit of US$0.3m. The 2022 revenue was a fall of 25% compared to 2021, while the 2021 revenue itself fell by 19% from 2020.

Founded as long ago as 1969, FuelCell Energy is still alive and kicking. Historically, much of the business came from South Korea, and the prospects there continue to act as a pull for the company. By the turn of last year, more details emerged over the settlement between FuelCell Energy and POSCO. The settlement agreement confirms FCE's exclusive rights to market its technology in the critical South Korean and larger Asia markets going forward. Under the agreement, FCE also received a large initial order for fuel cell modules to service existing South Korean operating projects. The agreement further establishes a framework for additional module orders. POSCO Energy agreed to dismiss its claims against FuelCell with prejudice. At the end of 2022, FCE finally announced it is accepting orders for its solid oxide electrolysers.

FuelCell Energy's solid oxide electrolysers will play into an ever-crowded market, where alkaline is still the dominant technology. While the starting point for electrolysers (1 GW in 2022) is similar to fuel cells (2.5 GW shipped in 2022), the emphasis of the overwhelming number of emerging HFC policies focuses on H_2 for mobility and on the decarbonisation of energy-intensive industries supports a much faster pace of growth, underpinning the embrace of electrolysers by some fuel cell actors.

MOBILITY SPREADING ITS WINGS

In April, cellcentric announced its series production would take place in the town of Weilheim an der Teck in Baden-Württemberg. In June, it opened its supporting fuel cell stack making facility in Burnaby, near Vancouver. cellcentric intends to ship fuel cell engines from the second half of the decade. In September, a letter of intent was signed with MAHLE to access a membrane humidifier that will help realise the long cell lifetimes required for long-distance truck applications. And cellcentric continues to supply Rolls Royce MTU in its quest for backup power units for data centres.

Ballard Power Systems was established in 1979 and has the enviable position of being a major supplier of MEAs, with 1.4 GW production capacity for MEAs, 4 GW of stack production capacity, and 3.9 GW module production capacity. As a supplier to third parties, including into China, this gives some stability in revenues, equating to US$83.7m in 2022, a small fall on 2021 revenues of US$105m. The net loss on operations was US$173.5m. Like Plug, the underlying investment falls under the need to "speculate to accumulate" heading.

Much of Ballard's business is focused on mobility, though there remains a significant play in stationary. Segmented revenues over 2022 were US$38.9m for heavy duty motive, US$6.3m for materials handling, and US$10.9m for stationary. The remainder, 'technology solutions', covers engineering services, technology transfer and licensing.

Despite the losses, in September Ballard set out its plans to deepen its manufacturing footprint in Europe, the US and China to support an expected global market demand growth through 2030, with an investment of US$130m into MEA production over the next 3 years. On the stationary front, Ballard noted an increase in shipments to China. Much of 2022's losses stemmed from increased investments in next generation fuel cell stacks, in its A-Drive hybrid powertrain (from Arcola), and activities related to product cost reduction. By 2026, an 80% reduction in stack costs from 2018 costs is forecast, which would markedly help the case for fuel cells. Interestingly, Ballard is losing ground in China, citing challenging vehicle subsidy schemes as throttling fuel cell demand for the company. In 2019, about 45% of sales were into China. Policy support, including zero emissions targets, are cited as the levers to a trend to a near doubling of demand for fuel cells in Europe and in the United States.

Despite signals that Honda would be shifting away from fuel cell vehicles, the end of 2022 saw the company announce its new H_2-fuelled vehicle to be based on the Honda CR-V, with manufacture from as early as 2024 in Ohio. As with Hyundai (with its HTWO brand) and Toyota (starting with its plans for a stationary demonstrator at Torrance, CA by early 2023), all three of the major fuel cell car companies are now seeking to reach larger volume by pushing stationary as well as mobility markets. Honda will combine its car modules into 250 kW 'Quad' units that can be scaled-out to yet larger power requirements.

The push for stationary does not indicate lack of interest in mobility. Toyota plans to bring a fuel cell pickup truck to the light duty mobility market, and 2022 saw a successful demonstration of some of its heavy duty offering as part of the ZANZEFF project in the Port of Los Angeles. And BMW will obtain stacks for its iX5 vehicle from Toyota.

THE WINNERS (FOR NOW)

In July, SFC energy secured a capital raise, with gross proceeds of €56.4m, going to regional and technological expansion, acceleration of R&D activities and inorganic growth opportunities.

Watt Fuel Cell, the US residential SOFC actor, secured US$82.3m investment in November 2022, with generator company Generac as a minority investor. Generac intends to combine Watt units with battery storage in microgrids. Upstart Power, the inheritor of Protonex's fuel cell technology, closed a US$17m Series C round in November. The funds will help accelerate commercialisation of its Upgen systems for on-demand small SOFC backup generators.

In October 2022, Symbio announced it will invest €1bn over 7 years in France through its HyMotive project, supported by France Relance/France 2030, as part of the Hy2Tech wave of the IPCEI hydrogen. HyMotive is expected to help build production capacity from 10,000 systems a year by 2024, to 100,000 systems a year by 2028. In the same month, Symbio and Schaeffler announced the creation of a 50/50 JV, Innoplate. Located in Haguenau, in the French Alsace region, Innoplate will produce fuel cell bipolar plates for global mobility and energy solutions. The preparation of the building and ordering of equipment has started in line with a target to start operations beginning of 2024. This is just one of many IPCEI projects that are set to transform the landscape for fuel cells in Europe, with 17 such projects set to go.

THE STRUGGLERS

Altergy, founded in 2001, and a pioneer of automated stack manufacture, finally succumbed to the effects of years of poor sales in the absence of a strong business case for its telecom systems. In June 2022, myFC, the Swedish developer of micro fuel cells, went bankrupt.

AFC Energy, founded in 2006, remains on the cusp of commercialisation, set for 2023, with demonstrations of its 10 kW 'Power Tower' generators (using air-cooled stacks) to ACCIONA, Keltbray, Mace Dragados, and Kier Group over 2022, and ABB testing its larger liquid-cooled design, targeting e-mobility and backup power. It has been a long wait to turn the corner.

STRETCHING WINGS

Doosan is diversifying to China and long ago FCE pivoted to South Korea. But these companies are not alone in seeking overseas markets for their fuel cell product.

In May 2022, Ballard, having made investments into China over the last decade, co-invested in a Series A round for Wisdom, a technology company based in Hong Kong that designs and manufactures zero emission commercial vehicles (mainly buses and trucks). But the more interesting news is the MoU with Adani (in February) to evaluate a joint investment case for the commercialization of fuel cells in various mobility and industrial applications in India. Fuel cells have been very late in reaching India, but the economic potential is huge.

There was no news over 2022 on the proposed JV of Ceres with Bosch and Weichai. Bosch's own plans are substantial, attesting to confidence in fuel cells as an alternative to combustion plant. In a presentation to NOW in August, Bosch outlined its planned €1bn investment in mobile fuel cells, and €500m in decentralised fuel cells to 2024, and €500m in electrolysis to 2030. The SOFC team now numbers 700 people, with 50 SOFC systems in pilot operation.

With a starting point of its residential PEM units, Toshiba ESS is now pushing for territories and markets, partnering with More Hydrogen Energy Technology in China, and then with Shandong Energy Group, late in 2021. Along with partners Impact Clean Power Technology of Poland and ITOCHU Corp., TESS is also beginning to explore use of its technology by heavy-duty vehicles.

Helion, with its modular FC-Rack PEM system, is now pushing the technology in multiple markets, including marine, for which it has received AiP from Bureau Veritas and from RINA.

CARS AND VANS

MORE NEXOS THAN MIRAIS

Fuel cell passenger car shipments were 15,400 units globally in 2022. While a significant figure, it is less than last year, which contrasts with the growth trend of previous years. Hyundai NEXOs and to a lesser extent Toyota Mirais, dominated shipments, with still limited but potentially upcoming contributions from other OEMs.

North of 11,000 NEXOs were deployed, more than ever before, largely in South Korea. Looking ahead, Hyundai's dominant position in the fuel cell car market could solidify, as Hyundai denied rumours suggesting a delay in the launch of the upgraded NEXO, stating that it would be rolled out 'sooner rather than later'. Moreover, Hyundai is considering producing fuel cell cars under its premium brand Genesis, presenting its N Vision 74 fuel cell concept in the LA Auto Show.

Deliveries of the Toyota Mirai decreased by a third with respect to 2021, with just below 4,000 cars shipped, mostly in California. The reason for the decline is unclear, but it may be related to the boost to sales through 2021, following the launch of the highly anticipated new Mirai.

ASIA CONTINUES TO DOMINATE FUEL CELL CAR SHIPMENTS

Not surprisingly, most fuel cell cars continued to be deployed in Asia. Shipments of the NEXO reached 10,000 units in Korea for the first time, though sales grew more slowly than for previous years. In Japan, shipments were limited to less than 1,000 Mirais, a substantial fall from 2021. Additionally, a few hundred fuel cell cars were deployed in China by both global OEMs and local automobile makers. Significantly, Toyota provided 140 second generation Mirais to the Beijing 2022 Olympic Winter Games, which saw the demonstration of over 1,000 fuel cell vehicles including cars, buses and trucks.

Following the steps of its sibling company Hyundai, Kia Corporation now plans to manufacture fuel cell cars, potentially starting with a fuel cell version of the popular Carnival family car.

CHINA WAKING UP TO FUEL CELL CARS

The Chinese government has now set a target of 50,000 FCEVs on the roads by 2025, with a continued focus on heavy-duty over passenger cars. But China is now slowly beginning to look more seriously at cars, with several OEMs starting to deliver vehicles or announcing plans.

Changan Automobile launched its Deep Blue SL03, including plug-in hybrid, battery electric and fuel cell versions. The latter was marketed as China's first mass-produced fuel cell sedan, but so far sales have been limited. Great Wall Motors reported plans to introduce a high-end brand of fuel cell passenger cars towards the end of 2023, after a pandemic-related delay.

SAIC deployed eighty of its fuel cell multi-purpose vehicle (MPV), the Maxus MIFA Hydrogen, in Shanghai through its mobility service platform. The seven-seater MPV has a 92 kW stack from SHPT, storing 6.4 kg H_2 at 700 bar, to give a range of 605 km. GAC revealed its own fuel cell MPV concept, named Space, exhibiting a futuristic design. Other Chinese OEMs, such as FAW and Grove, with existing or announced fuel cell cars, seem now to be more focused on trucks.

FEWER SHIPMENTS IN NORTH AMERICA

Fuel cell car deployments in California dropped by almost 20% in 2022, with about 2,700 vehicles shipped. This decrease can be mainly attributed to fewer Mirai sales, which continues to be the most sold fuel cell car in the North American market. For example, in January, Southern California Gas Company took delivery of 23 Mirais, with plans to expand its fleet to 50, seeking to support the firm's goal of achieving net zero emissions by 2045.

Honda has been leasing remaining stock of the Clarity Fuel Cell through 2022, after stopping its production in 2021. In an encouraging turn of events, the Japanese automaker intends to begin manufacturing a new fuel cell vehicle in 2024. The car will be based on the Honda CR-V crossover utility vehicle, with a powertrain combining fuel cells and a plug-in feature. The new car will be made in the US, from the next generation systems developed with GM and produced in their Fuel Cell System Manufacturing JV. GM has not yet announced its own fuel cell vehicle programme and, for now, is looking to deploy its HYDROTEC fuel cell power cubes in heavy duty trucks, rail, aerospace and power generation applications.

Further fuel cell cars are being deployed in Canada, Edmonton International Airport having plans to add Mirais to its operations fleet, in line with previous announcements from a few companies in neighbouring British Columbia. And the Vancouver Community College bought a Mirai for education and training purposes, for its Automotive Service Technician programme.

SLOW GROWTH IN EUROPE

Fuel cell car shipments increased slightly in Europe, surpassing the 1,000-vehicle mark, including both Mirais and NEXOs. One of the main trends remains the deployment of fuel cell cars for taxi and mobility services. In France, H_2 mobility operator Hype keeps increasing its fuel cell taxi fleet, with a target of 700 vehicles in Paris by 2023 and plans to expand into the rest of the country and abroad.

Similarly, Danish app-based taxi service DRIVR partnered with Toyota and Everfuel to expand its fleet of 100 Mirais in Copenhagen, aiming for 500 cars by the end of 2025. Further, German urban mobility operator SafeDriver ennoo began Mirai trials on the Uber platform in Berlin. And there are now Mirai taxis in Baden-Baden and Brussels, as well as NEXO taxis in Reykjavik.

But indigenous fuel cell car activity is modest across Europe. Renault unveiled a new Scénic Vision electric SUV, which may use fuel cells to extend the range up to 800 km. The car might become commercially available as early as 2024, building on the activities at Hyvia. In the UK, Jaguar Land Rover displayed its first prototype vehicle at the LCV Cenex conference, based on a Defender model, equipped with a fuel cell system jointly developed with several partners.

BMW started small series production of its iX5 Hydrogen sports activity vehicle in late 2022, seeking to rollout up to 100 units as demonstrators in Germany and beyond through 2023. The fuel cells are sourced from Toyota, capitalising on the partnership between the automakers since 2013, and assembled at BMW's competence centre for hydrogen in Munich. Some reports suggest that the companies may be considering co-developing fuel cell vehicles in the future.

Despite Volkswagen's stated strong preference for battery electric over H_2 cars, the German group registered a patent with microtubular SOFC developer Kraftwerk in February, maybe with a view to using SOFCs in future fuel cell vehicles. In July 2022, luxury brand Aurus Motors of Russia showed a fuel cell prototype of its Senat executive sedan, called NAMI Hydrogen, aiming to produce a limited number of units for testing and demo. The design couples two electric motors totalling 450 kW power, an 85 kW fuel cell, 8 kg H_2 at 700 bar, and a 100 kWh battery to deliver an expected range of 600 km. H_2 fuelling will be a problem, with no hydrogen refuelling stations in the country. And maybe there are other distractions right now.

EXPLORING NEW MARKETS

Deployments of fuel cell cars in other regions are slowly taking off. The Western Australia police force and the South Korean Embassy in Canberra joined the list of governmental entities using fuel cell cars, taking delivery of a Mirai and a NEXO, respectively. In New Zealand, Toyota has partnered with a several local companies to roll out a fuel cell car-sharing scheme, using green H_2 to fuel the cars.

In the Middle East, BMW plans to use its iX5 as a technology demonstrator for clean mobility, while Saudi Aramco reported aspirations to produce hydrogen and fuel cell vehicles locally. Additionally, India has received its first Mirai, as part of a pilot project by Toyota Kirloskar Motor and the country's International Centre for Automotive Technology. And the Government of Chile and Toyota launched South America's first fuel cell car.

PICK-UP TRUCKS GAINING INTEREST

While sedans and SUVs have been the prime focus of fuel cell car developers to now, interest in fuel cell pick-up trucks is growing. In December, Toyota announced £11m funding to develop a fuel cell version of its Hilux pick-up truck. Private and Government backing will help support up to 250 jobs at Toyota's car plant in Derbyshire, UK, where the development will take place. Dates for completion, trialling and delivery are still to be defined.

Australian start-up H2X Global remains committed to the launch of its Warrego 4x4 fuel cell pick-up truck, based on the Ford Ranger, initially with a view to producing a small series of 250 vehicles and beginning sales in Australia and Europe by mid-2023. The plan was to use these in concept proving ahead of a release of a fuel cell van, the H2X Darling in 2024. In December, the company reportedly won a US$98m contract to supply to supply H_2 vehicles in the weight range 3.5-18 t to Gothenburg, Sweden for delivery over 2024 and 2025. These are ambitious plans and how much is real, and how much is hope, remains to be seen.

In the Paris Automotive Week, African-European startup NamX exhibited its HUV, a futuristic fuel cell SUV developed with Italian design house Pininfarina. Innovatively, the car incorporates a fixed tank as well as six removable hydrogen capsules, resulting in a range of up to 800 km. During the same week, French startup Hopium premiered its Machina fuel cell sedan. The firm claims to have received pre-orders for the first 10,000 units and hopes to start production in 2025.

SETTING THE SCENE FOR FUEL CELL RACING

Founded in 2018 by the Automobile Club de l'Ouest and Swiss H_2 fuel cell powertrain developer GreenGT, the MissionH24 programme is going well, with its H24 racing prototype now competing in the Le Mans Cup, a step towards establishing an electric-hydrogen category in the popular 24 Hours of Le Mans race. In another endurance event, the Dakar Rally, GCK Motorsport disclosed a prototype of its e-Blast H2 cross-country racer, expected to hit the tracks in 2024 using a fuel cell powertrain developed with FEV.

For sports cars, UK-based Viritech and Pininfarina intend to produce a limited series of the Apricale hypercar, featuring a fuel cell powertrain and Viritech's energy management system. Alpine revealed its H_2-fuelled Alpenglow concept car, which aims to represent the firm's on-road and racing models of tomorrow. Coincidentally or not, its design somewhat resembles the hydrogen car concept previously co-created by Alpine and the European Institute of Design.

Encouragingly, students continued to participate in fuel cell car racing activities through 2022. In the Netherlands, a student team from Delft University of Technology unveiled the Forze IX race car, with a top speed of 300 km/h. Based in the same university, the Eco-Runner team attempted to reclaim the distance record for a hydrogen vehicle on a single tank. And in Brazil, the Society of Automotive Engineers and Ballard organised a student fuel cell Baja competition.

VANS PLAYING OUT MORE SLOWLY THAN EXPECTED

Despite some expectations for a larger rollout-out of fuel cell vans in 2022, the year saw no further large orders for pre-series production vehicles.

Little has been published on Renault's Kangoo ZE Hydrogen van and its H2-TECH series (using Hyvia systems), and Stellantis' Peugeot, Citroën and Opel branded vans (using Symbio stacks) since their launches in 2021. Hyvia presented a production model of the Renault Master Van H2-TECH at the Paris Motor Show in October, a year after its prototype was unveiled. Its Master City Bus H2-TECH and Master Chassis Cab H2-TECH are now expected from 2023. The production model uses a 30 kW fuel cell as a range extender, coupled a 33 kWh battery pack and 6.4 kg H_2 storage to provide a range of 400 km. Hyvia announced plans for first production vehicle trials to commence in 2023, initially in France, Germany and the Netherlands. By 2030, Hyvia aims to secure 30% of the light commercial H_2 vehicle market. Stellantis' early-stage production vans are already on trial in France and Germany, with plans to bring two left hand drive trial vehicles to the UK in 2023.

While little is happening on the ground right now, much is happening in the background for Hyvia and Stellantis. In September 2022, the hydrogen-facing activities of both companies, alongside Faurecia, as supplier of hydrogen tanks, were approved for significant funding under the HyTech strand of the IPCEI initiative. For Hyvia, IPCEI will support growth of its fuel cell production plant in Flins, France, which opened earlier in the year. For Stellantis, IPCEI funds will be invested in its Hordain plant, to deliver a capacity of 5,000 H_2 vehicles a year by 2024, marking a movement of assembly from the pilot workshop at Rüsselsheim to low-volume pre-series production runs at the Hordain plant.

In December, Stellantis announced it wished to acquire a substantial stake in the Symbio fuel cell JV, alongside existing investors Faurecia and Michelin. Stellantis uses Symbio stacks in its Opel Vivaro-e and sister models. Stellantis is pursuing (alongside significant BEV activity) an expansion of H_2 offerings to larger commercial vehicles – starting with a large van in 2024 in Europe, and from 2025 in the US, with a fuel cell pick-up truck under the RAM brand.

In September, Iveco showcased a prototype of the H_2-powered eDAILY van it developed with Hyundai Motor, a sign of the wider partnership between the two manufacturers. The 7 t van, with a 90 kW fuel cell, can be fully charged in 15 minutes and can drive up to 350 km before refuelling, with a maximum 3 t payload. While an MoU was signed, covering possible activities in developing electric powertrains, it is unclear whether the model will proceed to production.

In December, ABT e-Line GmbH started series development of H_2 fuel cell vans, based on the reception of its two demonstrator vehicles at the IAA Transportation trade fair in Hanover. ABT e-Line adapted the cooling, vehicle control, and electrical systems. Bosch designed the fuel cell system, integrated it into the vehicle together with the 700 bar H_2 storage, and developed the associated control system. Fully loaded, the vehicles can travel 540 km before refuelling.

In September, the UK subsidiary of First Hydrogen Corp. of Canada announced that its two demo vans had obtained road certification. First Hydrogen converts MAN eTGE electric vans to a fuel cell powertrain variant using 55 kW FCgen-LCS stacks from Ballard, fitted out at AVL's facility in Basildon. The fuel cell boosts the range from 115 km to 400-600 km, dependent on payload and speed.

Road trials of the van are expected to start in 2023, facilitated by the UK Aggregated Hydrogen Freight Consortium led by Element Energy (now part of ERM). Fleet operators across telecoms, utilities, infrastructure, delivery, grocery, and healthcare are signed up for trials across the UK. Plans for a bespoke H_2 vehicle design from First Hydrogen was also announced in May 2022.

A TRUE SUPPLY CHAIN BEGINS TO DEVELOP

Beyond the core components of stack and H_2 storage, a wider supporting supply chain is now beginning to be established in Europe. In October, Symbio indicated it will invest €1bn over 7 years in France in its HyMotive project, with IPCEI funding support. Its facility in Saint-Fons, near Lyon, one of the biggest fuel cell sites in Europe, is expected to start production in late 2023, reaching 50,000 systems a year by 2026, and 200,000 systems pa by 2030. Innoplate, Symbio's JV with Schaeffler for the mass production of bipolar plates, was initiated in October. Production is to set start in 2024 in Haguenau, France, reaching 50 million plates pa by 2030. These are impressive expectations that underpin the investment of Stellantis into Symbio.

HYDROGEN REFUELLING

2022 yielded a further 129 HRS deployed, according to H2Stations by LBST. The 18% increase is in line with the 5-year trend, with 814 HRS in use worldwide. We don't track HRS directly, with some sources suggesting 1,000 HRS are in place. The main uncertainty seems to be China, where many HRS are depot-based and not always reported consistently. Depending on the source, China's HRS numbers were at least 250 by the end of the year, and with the fastest growth rate. Europe, Japan and South Korea HRS are increasing, but more slowly.

Over the past 2 years, the evolving hydrogen mobility industry has been increasingly focused on heavy duty and fleet-based applications. This change in use case from private cars, coupled with low utilisation of many early demonstrator car and van HRS, has sparked debate over whether a nationwide public HRS network is the right way to start. South Korea is backing a public network, and commissioned 45 new HRS in 2022, but is also backing FC cars. China is focusing on private bus and HGV stations. In Europe, Germany has the most stations, though they remain under-utilised, while France has looked at building stations near demand clusters.

Regardless of approach, larger and well-utilised HRS will be needed to improve ongoing problems with economics and station reliability. And the increased emphasis on trucks particularly, with a typical refill pressure of 700 bar (as opposed to 350 bar pressure for cars and many buses) means that some of the older car-oriented HRS are becoming obsolete outside of countries like Germany or cities like Paris where significant FCEV car fleets exist.

PRIVATE INFRASTRUCTURE PLAYERS TAKE MATTERS INTO THEIR OWN HANDS…

February 2022 saw Phillips 66 announce an ambitious joint venture with the turnkey provider H2Energy to deploy 250 HRS in Germany, Austria and Denmark by 2026. This would roughly double the number of HRS in Europe. The JV will cover the full supply chain: H_2 supply, logistics and vehicle demand, combining H2Energy's hydrogen learning from Switzerland with Phillips 66's traditional retail fuel network and experience.

To reinforce the initiative, H2Energy announced plans for a 1 GW electrolyser to be built in Denmark in collaboration with Plug Power. The first hydrogen is expected in 2025.

July 2022 saw the first concrete plans emerge from BP and Daimler's 2021 announcement that they would collaborate to develop an infrastructure to support long-haul heavy-duty: initially, two HRS in Germany will supply both liquid and gaseous H_2, at 350 and 700 bar, to meet the preferences of the differing OEMs, much like the unfortunate plethora of charging options for electric vehicles.

In France, the Paris taxi operator Hype remains a leader, with an order for 7 new HRS for the region, from the French company Hydrogen Refuelling Solutions as part of the partnership announced in December 2021. The HRS will dispense from 200 to 1,000 kg H_2 a day, with the Issy-les-Moulineaux station expected to be the first to open.

… BUT GOVERNMENT SUPPORT IS STILL NEEDED

Despite increasing private sector impetus, most HRS don't yet have enough custom to break even, so public funding is still required. In Europe, Connecting Europe Facility (CEF) funds were behind many of the stations announced in 2022, including 12 stations through the GREATER4H project, focused on HGV decarbonisation in Germany, Denmark, Sweden and Norway.

Only 11 new HRS were commissioned (but not yet built) in North America in 2022, but the California Energy Commission's US$2.9bn ZEV Infrastructure Plan includes US$90m for H_2 fuelling stations, and the Inflation Reduction Act, alongside the US$7bn Regional Clean Hydrogen Hubs fund should help.

In South Korea, the private partnership HyNET is in part responsible for rapid station rollout, with funding matched by the Korean Government.

Against the global growth trend, the UK has gone backwards, with very limited support up to now from public funds and little engagement by private industry. Legacy demonstrator stations have been retired, and reduced access to European funds makes new ones harder to build. At the end of 2022, only 9 stations were operating in the UK, some with an uncertain future. The UK operator Motive now plans a shift towards heavy duty uses, supporting private rather than public fleets.

ASIAN NATIONS STILL LAG AMBITIOUS TARGETS

Japan's 165 stations represent a large share of global HRS numbers. But more action will be needed to reach its target of 320 HRS by 2025.

South Korea, despite 50% growth, fell short of its ambitious target of 310 HRS by 2022. Still, in May, Air Liquide and Lotte Chemical announced a joint venture to co-invest in a new generation of large-scale HRS in South Korea. The country plans a 100 tpd hydrogen mobility demand by 2025 under the Hydrogen Economy Roadmap.

China doubled the number of its stations in 2022, or even higher by some accounts. Further growth appears inevitable: in July, Shell and Shenergy signed an agreement to form a JV to build out HRS infrastructure in Shanghai and the Yangtze River delta, with plans for up to 30 stations by 2030. The race is on in Asia, and we will watch it with interest!

Elsewhere, growth is slow, and there are still fewer than 20 hydrogen stations deployed outside the core regions of Europe, Asia and the United States.

Australia has amongst the most ambitious plans: March saw the Eastern state governments of Queensland, New South Wales and Victoria announce a collaboration to build out a station network to service heavy transport and logistics operations. Meanwhile, private players in Western Australia, Fortescue and ATCO, opened the region's first HRS in late December 2022.

Countries are still joining the HRS club, though, with Colombia, Cyprus and Israel each commissioning their first HRS in 2022, bringing the total number of countries worldwide with operational stations to 37. South Africa's Hydrogen Society Roadmap raises hopes for Africa's first hydrogen station to be built sooner rather than later. Ambitious plans are already in place for over 300 more stations, and the overall growth trajectory looks positive.

FUEL CELL BUSES

It has been a mixed year for fuel cell buses. It was a resounding success in Beijing for the 2022 Winter Olympics, with hundreds of fuel cell buses working seamlessly in challenging conditions. In Europe, some planned deployments of hydrogen-fuelled buses were scrapped in favour of fully electric buses. Yet, others retained commitments to fuel cell buses, or even strengthened plans, each city citing cost as a major factor. So, who is right?

The consensus is that it will continue to be a mix of technologies, serving different routes, to realise the relative benefits of each powertrain. That is good news for fuel cell buses, and companies globally have responded with next generation launches, maturing technology and filling the market gaps with short as well as full length buses.

BUSES CLAIM GOLD IN CHINA

At the Winter Olympics in Beijing and Zhangjiakou, around 820 fuel cell buses and 100 minibuses were put into service for visitors across the Olympic villages making it the largest ever demonstration of a hydrogen fuel cell bus fleet, by some margin. The delivery included 30 refuelling stations.

Over half of the buses fielded at the Olympics were already in service, but China bus makers and stack suppliers showed the world how it's done, with hundreds of buses newly built and deployed, seemingly without a hitch. Foton was the stand-out performer, supplying 515 buses (212 of them using stacks and 700 bar tanks from the Toyota-Yihuatong JV). In total, the Foton buses travelled nearly 2 million miles over the event. Next, Yutong provided 185, Geely 80 and Zhongtong 40. Toyota provided 107 Coaster minibuses, alongside 140 of its 2nd Gen Mirai, and there were other logistics and welfare vehicles serving teams and spectators. In contrast, 100 fuel cell buses and 500 Mirais were fielded at the Tokyo Olympics the year before, and only three fuel cell buses were part of Beijing 2008.

Questions were asked about the true greenness of the Olympics, but the buses themselves impressed, 444 returning into regular service in Zhangjiakou, having clocked 27 million km since and serving 81 million passenger trips to the end of 2022. Overall, including the buses for the Winter Olympics, 955 new domestically produced fuel cell buses were shipped within China over the year. China stands out by far as the largest producer and use market.

CHANGING STRATEGIES

Things weren't so rosy in Europe. Just prior to the Winter Olympics, fuel cell buses were dealt a blow from Montpellier, as plans for the city's 51 FCEBs and 800 kg/day H_2 production were scrapped, in favour of battery electric. The city intends to run the buses as a free service for residents, claiming the higher cost of H_2 over electricity for BEVs made it unfeasible, for now.

A further blow came at the end of 2022, Wiesbaden declaring it would retire its 10 CaetanoBus 12 m length H_2. City Gold's after just over a year in service. The change followed ESWE's supervisory board's new focus towards 18 m articulated buses, with their greater passenger capacity, and pressure on space in its workshops catering for 3 different powertrains. They opted for a return to diesel, given limited availability of 18 m buses with electric drivetrains. The escalating H_2 price and breakdown of the HRS serving the buses didn't help the case.

Duisberg, on the other hand, reversed its decision to pursue battery electric buses in favour of fuel cell buses. A report from Emcel, commission by the city and kept private, found FCEBs to be cheaper than battery buses, with lower capital costs for the fleet and infrastructure. The city intends to replace its entire fleet of 100 diesel buses with fuel cell buses by 2030.

What is clear is that each situation is nuanced, and that optimised fleet deployments depend on the specific factors at play at each location. The mixed news didn't deter the industry and 2022 saw a flurry of new product launches, and various short trials took place, in Trieste (Arriva/Caetano), Budapest, Jaworzno, Kraków and Lucerne (Solaris).

NEXT GEN DESIGN AND 18 M PRODUCT LAUNCHES

As is common now in China, many of the newer European bus designs use fuel cell range extenders to batteries rather than relying solely on fuel cells for propulsion. This allows longer runs prior to overnight recharging and is less costly in fuel than a hydrogen-only design. Further, this allows for fewer hydrogen storage tanks, taking less volume, at lower pressure (350 bar). Increasingly, 18 m rather than 12 m long buses are the focus.

In Europe, Mercedes Benz announced it will sell only zero emission buses by 2030, with plans to launch its fuel cell bus in 2023. Partnering with Toyota for its fuel cells, Mercedes Bus chose a range extender design for the eCitaro G with a large battery pack and Type 4 tanks, each containing 5 kg H_2 at 350 bar. Mercedes offers the eCitaro in lengths of 12 m and 18 m. Both are fitted with a 250 kW electric motor. The 12 m bus has three battery packs with a total capacity of 294 kWh, together with five hydrogen tanks. The 18 m bus has four battery packs of 392 kWh capacity with a choice of 6-7 hydrogen tanks. The 60 kW fuel cell is operated at 20 kW load, to maximise efficiency, resulting in a 30-50 km range extension over a pure electric bus, to 350 km for the 12 m variant and 400 km for the 18 m variant. Mercedes's choice of Toyota modules rests on a technology with a 40,000-hour service life. The announcement was clearly popular, with a first order secured from RNV of up to 75 buses for Mannheim, Germany.

Van Hool sees the writing on the wall for internal combustion engine powered buses, launching its new A-series that consist solely of zero emission powertrains. Eagerly anticipated, fuel cell bus orders were placed by French and German customers before the launch. The bus will use the popular Ballard FCmove-HD module, ranging from 70 kW for 12 m buses to 100 kW for 18 m buses. Van Hool was the first to launch an 18 m fuel cell bus in Europe, back in 2019, albeit specifically designed for BRT in Pau, France, but a few years later, more are finally following.

Solaris showed the world its Urbino 18 Hydrogen in early September. Able to carry 138 passengers and using the same 100 kW Ballard fuel cell system as Van Hool, it carries up to 51 kg of hydrogen storage at 350 bar, good for around 350 km. Solaris expects to be able to deliver its buses by mid-2023. The 12 m variant premiered in June 2019.

The 18 m products are clearly sought after and the manufacturers are responding, with a model in the line-up seemingly a must have. GOLDl MOBILITY unveiled its GOLDiON 18 m fuel cell bus, also in September. Supported by the Scottish engineering firm Hy-Hybrid Energy, the bus is equipped with a Horizon Fuel Cell range extender.

Safra introduced its new HYCITY bus (as a replacement to the Businova line) in the Spring of 2022. The 12 m bus uses Symbio 45 kW fuel cells, fed by 35 kg H_2 from 6 tanks supplied by Plastic Omnium, to deliver a competitive 350 km range. Key to Safra's announcement was that the 18 m version is expected to be launched in 2023.

Scottish builder Alexander Dennis, an NFI Group subsidiary, announced development of its second-generation H2.0 bus last year. Now named the Enviro400FCEV, the bus itself was unveiled at the Euro Bus Expo 2022 in Birmingham. Its first customer was set to be Arriva, in Liverpool UK, following the launch. The bus has a peak power of 350 kW. Up to 29.4 kg of H_2 is stored in 350 bar NPROXX composite pressure vessels, feeding a Ballard FCmove-HD module. 45 or 60 kW modules are used according to the operational profile, to optimise efficiency, reduce heat rejection and extend fuel cell life. A 30 kWh LTO battery provides a buffer between fuel cell and motor. The bus can transport up to 88 passengers, with a range up to 300 miles (480 km), without needing any recharge of the battery storage.

In June, Ballymena-based Wrightbus won an order for 20 of its GB Kite Hydroliner single-deck buses for use at Gatwick Airport. The specification is impressive, with lengths 10.9-12.5 m, fitted with a Voith VEDS MD 250 kW drive system, a 54 kWh battery and a Ballard 70 kW fuel cell. When fitted with seven 350 bar tanks, containing a total of 50 kg H_2, a range of 640 miles before refuelling can be achieved. But this is not a lightweight vehicle, at 19,500 kg GVW (compared to the Streetdeck FCEV double-decker at 18,600 kg GVW). Importantly, a 15-year secured H_2 supply from Air Products is part of the plan, supported by £4.3m (€5m) funds from the UK's Ultra-Low Emission Bus programme.

SMALLER BUSES TOO

Bucking the trend of larger buses, in March 2022, Mobility & Innovation of Slovakia launched its 8 m H2Bus, a 21-seater that uses Loop Energy's S300 30 kW stack as a range extender. In October, Rampini of Italy showcased its 8 m, 48 passenger Hydron bus, which also uses a 30 kW Loop Energy stack, citing efficiency as a key factor. Back in November 2019, CaetanoBus and Rampini set out to jointly market their vehicles, but nothing came from the partnership, and now from October 2022, CaetanoBus and Industria Italiana Autobus signed an agreement to start the production and marketing in Italy of city buses built from H_2. City Gold kits based on Toyota fuel cell technology.

Skoda has also got in on the action. Having first demonstrated a fuel cell bus with Proton Motor 10 years ago, a revamped version was launched this year. Following the European market naming trends, it is called the H'CITY. The 12 m bus uses a 160 kW motor and can carry up to 85 passengers (30 seated). Again, a range-extended hybrid (with stacks from Proton Motor), 39 kg of stored H_2 gives a combined range of up to 350 km.

Start-ups now targeting hydrogen include NesoBus in Poland, a 12 m bus with a 450 km range (using a Ballard FCmove-HD stack and 37.5 kg 350 bar H_2) and Arthur Bus in Germany, also aiming towards a 12 m bus, with a 450 km range.

MINIBUSES GOING SLOWLY

In contrast to full-size hydrogen buses, the minibus market has been slow to start. The Master Citybus H2-TECH from Hyvia, the JV between Renault and Plug Power, is now expected on roads by 2023 at the earliest. The range-extended minibus should be able to carry up to 15 passengers, with a 300 km range before refilling.

COACHES CATCHING UP

While most of the industry focus is on buses, Marcopolo, the Brazilian bus maker, has partnered with Feichi (chassis provider), Sinosynergy and Allenbus (integrator) launching the Audace 1050 fuel cell coach at the IAA Transportation 2022 show in Hanover, Germany. The 12 m, 53-passenger coach has a range up to 600 km, with a 143 kW (235 kW peak) motor, two G80-001 stacks fed by four 350 bar hydrogen tanks, and CATL LFP batteries. This marks the first entry of a China sourced coach into Europe.

In October, at the Autocar Expo in Lyon, Green Corp Konnection group signed a multi-year fuel cell supply agreement with Symbio, for use in coaches. At the show, an Iveco Crossway coach was exhibited, with a fuel cell retrofit. Two StackPacks are combined on the vehicle to give a 150 kW output, fed by 34 kg H_2, without compromise to the range (400 km) of the 19 t gross weight vehicle.

LATE BUT NOT NEVER

Not to be left out, Iveco has turned to Hyundai's HTWO, Tata to Cummins and Turkish bus builder Karsan has made hydrogen a key part of its electrification strategy, though it hasn't disclosed its powertrain partner.

In March, Quantron unveiled its Cizaris 12 EV 12 m bus, with a 12 H (hydrogen) bus "to follow soon".

Doosan/HyAxiom expects to launch a bus in South Korea in 2023. Isuzu and Hino are collaborating using Toyota's technology to deploy products in the local Japanese market. And in India, h2e Power Systems alongside Nuvera (60 kW stack supplier), Eka Mobility (bus manufacturer), Ohm Cleantech (integrator) and Oil India (project manager) are now demonstrating a 9 m range-extended bus.

PLENTIFUL SUPPLY, WHAT ABOUT DEMAND?

China still leads, with over 1,000 fuel cell bus sales in 2022 and prices are falling as the beginnings of volume sales emerge. Supportive policies and subsidies remain critical in sustaining the market, however. Europe is the next largest market, but it saw fewer registrations in 2022, 99 compared to 158 in 2021. Trials and tenders continue aplenty.

Hyundai's ELEC CITY fuel cell bus was trialled in the Austrian cities of Vienna, Graz and Salzberg from February. As in Madrid, the buses will be put to the test on inner-city urban routes. Large tenders were launched by the cities of Paris and Bologna. Paris seeks 47 fuel cell bus deliveries for 2023, adding to the existing 7 already in service since 2019. Bologna raised €90m for 127 buses, 34 by 2024 and 93 by 2026.

Solaris leads in Europe, with 42 deliveries in 2022, and has orders for over 100 to be delivered over 2023. The most notable deliveries were of 20, 12 m buses to Heinenoord, Netherlands (with JIVE2 funding); 5, to Hürth, Germany; and the first fuel cell bus deployed in Poland, in Konin, with an option to increase the order to 20. Next year, more are due to arrive in Poznan (25) and Krakow (20). The first of 4 fuel cell buses are expected in Bratislava, Slovakia next year. OBB Post Bus has also ordered 4 buses from Solaris. Other places choosing Solaris include Cologne (20), Upper Bavaria (10), Mallorca (5) and Venice (4). Bolzano, Italy, will take 10 of Solaris's new Urbino 18 m, to join the 12 Urbino 12 m already in service. Frankfurt is to split its new order of 15 fuel cell buses, taking 13 from Solaris and 2 from Van Hool.

Frankfurt and Wuppertal engaged Everfuel to build 350 bar refilling stations. The Frankfurt station was commissioned in 2022. Scaling up the supply is a key consideration Wuppertal, with its ambition for 150 buses in 2030. Everfuel's modular design facilitates scalability for growing fuel demands and augmentation to 700 bar pressure for mixed fleets.

Caetano delivered 4 of its H_2. City Gold 12 m buses to a trial at Bielefeld, Germany, and one in each of Copenhagen, Denmark, Madrid and Barcelona, the first of 8 buses expected in the city.

2022 was a quiet year for Van Hool fuel cell bus registrations. The company has booked orders for 8 in Germany and 32 across France, in Rouen, Pau, Lorient and Belfort, where McPhy is set to supply a 1 MW electrolyser to supply an 800 kg/day HRS able to fuel 7 buses an hour. Like the Everfuel's designs, the planned HRS will be modular and scalable.

The largest European orders of 2022 came from Germany and UK. Mannheim elected for 40 of Mercedes' eCitaro G range-extended articulated buses for delivery in 2023 and 2024, with a further 35 expected by 2027. Separately, RVK, Cologne ordered 40, with an option for more, split between Solaris and Wrightbus for delivery to RVK between 2023 and 2025. And in Crawley (near Gatwick Airport, London), 54 more fuel cell buses from Wrightbus were confirmed for 2023 and 2024 to serve Go-Ahead Group's 24-hour operations of the airport and surrounding area, making it one of the UK's largest fuel cell bus fleets. Birmingham is set for an even larger order, with 124 hydrogen buses, but these are some way off being delivered.

Whilst 2022 was quieter than last year, 2023 is set to boom in orders and deployments.

NORTH AMERICAN DEVELOPMENTS

Over 2022, CALSTART data suggests 82 new fuel cell bus deployments into the US, nearly twice as many as the year before. As with Europe, smaller vehicles are at last gaining attention. In November, US Hybrid (now part of Ideanomics) announced it will develop two shuttle H_2 bus demonstrators, 6 m (based on the Ford E-450 chassis) and 10 m (based on the Ford F-53 chassis), using Luxfer Type 3 tanks, with funding from SoCalGas and the SCAQMD.

The first 18 m (60 ft) fuel cell bus made its debut in North America, back in 2016, from NFI Group subsidiary New Flyer. It too is choosing 2022 as the year to refresh its 2019 model. Available in both 60 ft and 40 ft (12 m) lengths, its Xcelsior CHARGE FC, uses a 100 kW Ballard FCmove-HD+ module. With up to 56 kg H_2 storage alongside up to 1,030 kWh battery storage, the vehicle has a range up to 370 miles before refuelling.

Along with New Flyer, the other significant player in the North American market, ElDorado National California (ENC) has changed tack for its next gen Axess fuel cell bus, the EVO-FC. Plug Power will now supply a much larger 125 kW stack than those of earlier generations. BAE Systems will continue to supply the electric powertrain components.

New Flyer's Xcelsior CHARGE H_2 bus is a popular choice. Three of the 2021 order of 33 buses were delivered to Foothill Transit in LA County, the rest planned for 2023, 9% of its total fleet. Whilst more costly than electric buses, the performance of the battery electric buses in later life is a key concern to the operator. Sunline in San Bernadino County has funding for an additional four fuel cell buses, with the provider yet to be defined. Its existing 21-strong H_2 bus fleet is trialling a mobile HRS from NICE American Research Inc. SamTrans, San Mateo's bus operator, secured funding for 10 fuel cell buses from New Flyer, and 20 battery electric buses, though these are not expected before 2028.

Second only to California, the Northeast of the US is attracting fuel cell investments and deployments, supported by strong regional policy. New York's Metropolitan Transportation Authority received an US$8m grant from NYSERDA to advance its plans for a zero-emission bus fleet for 2040. Two New Flyer buses will be bought for an expected delivery in 2024, along with a refuelling station capable of supporting up to 40 buses. In Rochester, in the north of the State, the regional transport authority secured US$7m for a H_2 fuel cell bus programme. Montgomery County, north of Washington DC, won a US$15m grant to put 13 fuel cell buses into service in 2025, fed by green hydrogen. Elsewhere, in Nevada, the regional transport authority RTC had US$6.7m approved to buy three fuel cell buses.

Regional Clean Hydrogen Hubs are being pushed by the US Department of Energy, similar in vision to the Hydrogen Valleys programme in Europe. Integrating hydrogen production and use, many of the proposed early plans include bus deployments.

North of the border, Edmonton International Airport has selected Quebec-based Latenda to provide a fuel cell bus to demonstrate cold weather performance, operating from 2024. Despite being home to Ballard, there is only one other H_2 bus active in the country at present.

SOUTH KOREA – STILL A GROWTH ENGINE

Another nation relying heavily on national support to increase deployments is South Korea. In January, an MoU was reached between Hyundai, the Ministry of Environment, and the Seoul Metropolitan Government, to promote the supply of more than 100 low-floor H_2 buses annually from 2022 to 2025 to cities in the BuUlGyeong hydrogen economy zone.

The zone is within the Southeastern Maritime Industrial Region, which covers the port cities of Busan and Ulsan. Each bus will receive a subsidy of over US$120,000 (about 24% of the production cost). Hyundai is also offering a discount, albeit only US$10,000 per vehicle. A total of 624 fuel cell bus deployments are expected to arise from the initiative.

INTEREST FROM NEW REGIONS

There are, at last, encouraging signs of growth for fuel cell buses (and for other applications) from regions outside China, Europe and North America.

In Australia, two H_2 buses from China's Foton were delivered to Transit Systems to join its 60-strong electric bus fleet. The buses are equipped with a fuel cell jointly developed by SinoHytec and Toyota. The site of deployment is yet to be stated. The heavy vehicle manufacturer HDrive demonstrated its double-decker hydrogen bus for a day (in November) at the Shellharbour Regional Airport in New South Wales, with the first trial of a hydrogen bus (involving local bus manufacturer ARCC on the Central Coast). More generally, the state allocated AU$25m for trials of fuel cell buses to 2025. The Queensland government is to provide AU$2.7m to the local transport company Emerald Coaches to integrate two hydrogen fuel cell electric buses into the company's existing fleet by mid-2023. In April 2022, H2X, the Australian startup, announced its intention to work with cellcentric to bring fuel cell buses to Trelleborg in Norway.

Elsewhere, Kochi, India is exploring how fuel cell buses can act as a feeder service to encourage more people to use the metro. It launched a tender for 10 fuel cell buses that would join a trial with 18 electric buses. And in Columbia, as part of a US$2.5bn hydrogen strategy, Ecopetrol, the country's largest oil and gas producer, planned to work on two mobility pilots, one in Bogota, where hydrogen generators will supply fuel for a fuel cell bus to be tested alongside the existing bus fleet.

LOOKING AHEAD

Whilst 2022 threw fuel cell buses a few stumbling blocks, the increasing level of activity globally, not least in regions devoid of activity to now, suggests H_2 will have a growing role to play in decarbonising bus fleets. The total cost of ownership is still important (not least the availability of hydrogen at low cost) and range extension is emerging as a winner. This allows for smaller and less costly tanks, with a smaller inventory of hydrogen, for journey profiles where a pure electric bus would be challenged.

European and increasingly US bus builders are now supplying mature and attractive fuel cell buses. But as with electric buses, there are signs the sustained focus on NEVs in China is paying off, as an export opportunity for fuel cell as well as battery buses.

Government support, in yet more regions, remains instrumental in growing the industry, on the quest for scale-up and cost down of products and operations. Large-scale orders are needed to achieve this. But, despite the environmental benefits and some clear technical advantages to fuel cell buses, increasingly it is the hydrogen price that is the barrier to more widespread adoption.

SHIPMENTS BY REGION

2022 showed an increase in overall shipped units, to nearly 89,200 fuel cells in all shapes and sizes, from nearly 86,000 units in 2021. Shipped megawatts increased from 2,316 MW in 2021 to 2,492 MW in 2022. So, fuel cell shipments have continued their growth, still rather slowly.

PEM fuel cell vehicles continue to dominate the shipments, and as with last year, much of the demand is localised to China and Korea. China saw over 4,150 units being shipped, across all modes of mobility (including forklifts, now slowly taking off in the country), while South Korea saw nearly 10,400 deployments, dominated by Hyundai's NEXO. Together with 831 Toyota Mirais going into the home market of Japan, Asia now accounts for around 15,580 units into transportation markets, or 17% of global shipments of fuel cells, and rather more impressively 1,514 MW (nearly 61%) of the shipped megawatt count. Hyundai alone now accounts for 44% of all fuel cell shipments by megawatt capacity (1,092 MW), up from 894 MW (38% of global shipments) the previous year.

Outside the three major automotive OEMs (Honda, Hyundai and Toyota), China continues to be a major hub for fuel cell vehicle deployment. Over 1,000 fuel cell vehicles (buses, trucks, cars, vans) were deployed to the Beijing Winter Olympics, held in February 2022. The fleet included 140 Mirais and 107 Toyota Coaster minibuses. Toyota continues to work actively in China through its partnerships with SinoHytec (BAIC/Foton buses) and Shanghai REFIRE (Higer buses). As in recent years, the focus of China remains bus and truck markets, with a record deployment of 3,789 commercial vehicles over 2022, and an even larger pool (5,009) of newly insured fuel cell vehicles. The unit numbers have been buoyed by the maturing city and provincial demonstration programmes, the adoption of the 14th Five-Year Plan for the energy sector, which highlighted the FCEV and hydrogen sector as one of China's six industries of the future, and the resumption of supply chains following the earlier COVID shutdowns.

Hyundai benefits from the 50% subsidy for fuel cell vehicles in South Korea. South Korea is now also the single largest market for large stationary units, in CHP and prime power modes, with demand driven by the Renewable Portfolio Standard that applies to domestic companies operating large generators. Stationary shipments into the country grew from 147 MW in 2021, to 196 MW in 2022 (8% of the global count, by megawatt capacity). The MW placements would be higher still if FuelCell Energy's POSCO stack replacements were included. Overall, Korea alone accounted for 1,200 MW of fuel cell shipments in 2022, 48% of the global market.

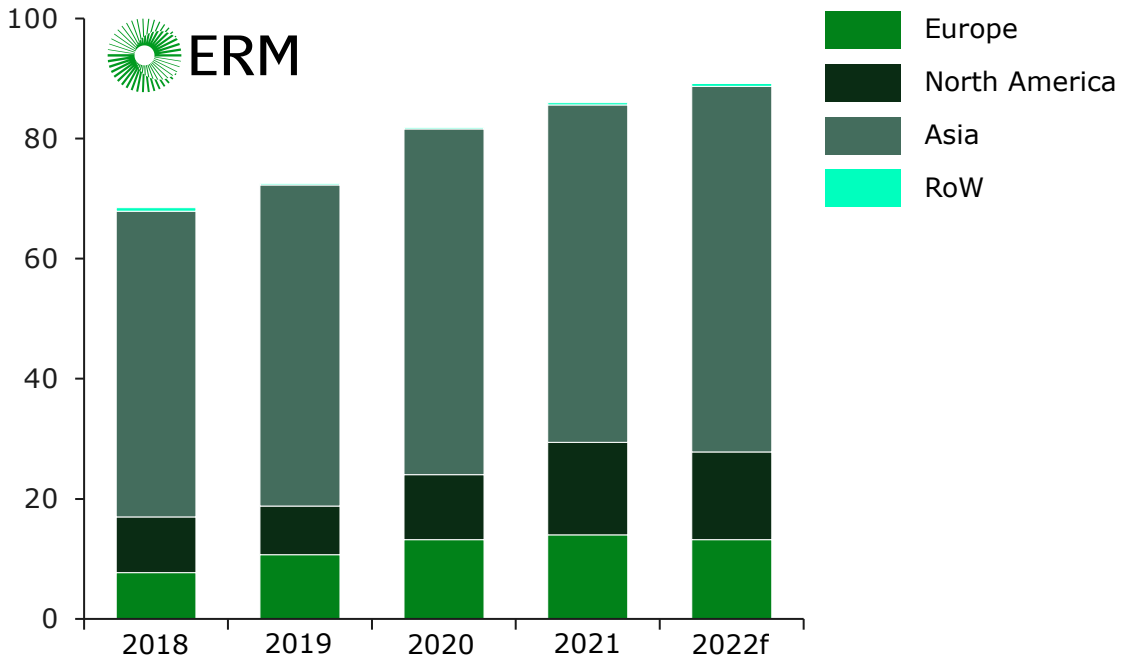
These numbers illustrate the importance of South Korea to fuel cell shipments. The global fuel cell "market" is increasingly made up of very large sub-markets in a few countries that prop up sales but could also create a huge dent in shipments if subsidies were removed. On a positive note, these large volumes are beginning to create an economy of production scale for the three major companies supplying equipment into South Korea (Bloom Energy, Doosan Fuel Cell and Hyundai), which will help reduce costs of fuel cell manufacture and supply.

Allowing for the Ene-Farm programme, with its micro-CHP units to Japan, across all markets (stationary, mobility and portable), Asia accounts for 60,850 units (two-thirds of global shipments) and 1,770 MW (71% of global shipments).

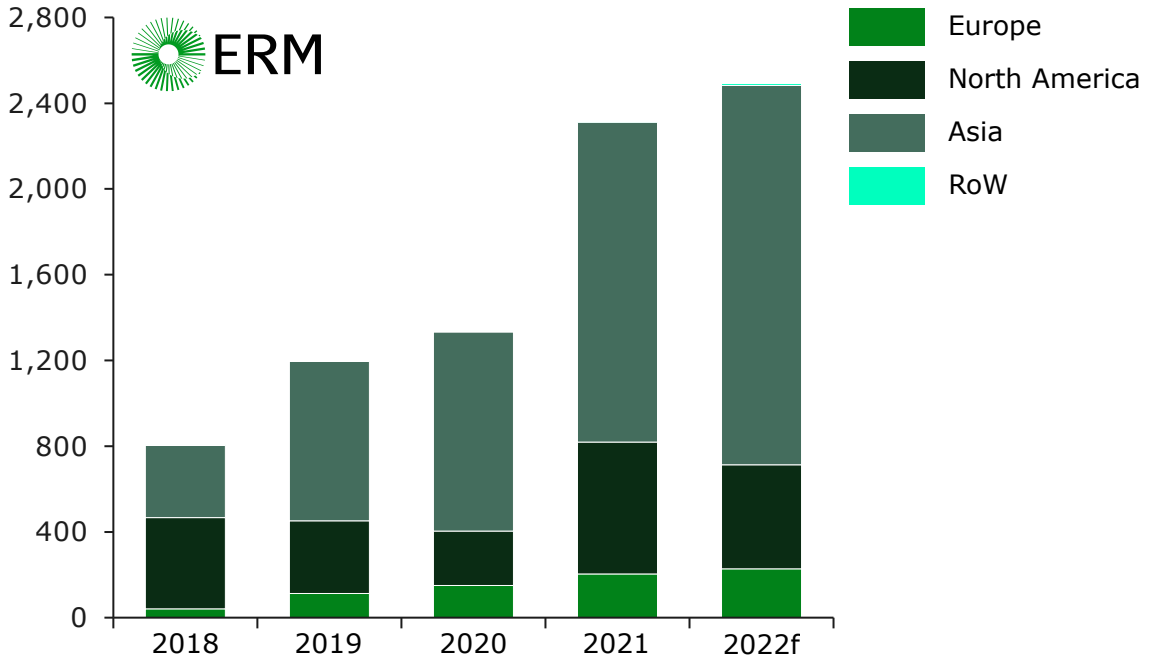
Behind Asia is North America, with around 14,550 fuel cell shipments (nearly 485 MW, 19% of global shipments), dominated by shipments to the United States. Whilst still impressive in volume, the unit shipments to North America fell from a corrected 614 MW in 2021. Much of this fall can be attributed to fewer Toyota shipments into the United States in 2022.

Europe accounted for roughly 13,250 of fuel cell shipments in 2022, down from just over 14,000 units in 2021. The unit shipment fall is attributable to fewer micro-CHP systems being placed as PACE finished and the imminent closure of KfW-433 grant funding for Germany. In megawatts, the count slightly increased, from a corrected 204 MW in 2021, to 228 MW in 2022, about 9% of global shipments. Fuel cell vehicle shipments are lower than for Asia and the US due to the low subsidies that are provided by national governments.

Shipments by region of adoption 2018 - 2022 (1,000 units)



Megawatts by region of adoption 2018 - 2022



MEDIUM- AND HEAVY-DUTY TRUCKS

China continues to lead the way in commercial vehicle deployment – by a large margin. Outside China, Hyundai remains market leader, expanding to new markets with its XCIENT model, though delivery volumes are behind track in Switzerland. European OEMs have begun early stage on-road trialling and look committed to developing commercial H_2 truck variants, although series manufacture will likely remain elusive until the latter part of the decade.

EUROPEAN TRUCK MANUFACTURERS PREPARE FOR SOMETHING BIG…

Daimler unveiled the first prototype of its GenH2 truck at the IAA Hanover Transportation Conference in September 2022, providing some of the first public vehicle specification data from a major European OEM. The 40 t articulated truck is equipped with two liquid hydrogen tanks which combined store up to 80 kg hydrogen, allowing for a range of up to 1,000 km, and is powered by 2 x 150 kW fuel cells. Fully laden, the vehicle will achieve up to 25 t payload in commercial operations, comparable to diesel counterparts.

Over the course of 2022 the GenH2 prototype completed trials on test tracks and public roads, and in November Daimler announced the completion of the first altitude tests over the 120 km highway stretch from Austria to Italy. Despite the progress, Daimler do not look likely to jump to a series launch any time soon. It is expected that the OEM will conduct further on road customer testing over the coming years, prior to a model launch in the second half of the decade.

Daimler's JV partner Volvo has also been progressing its fuel cell model. Like Daimler, Volvo aim to achieve a range of up to 1,000 km and will be powered by a 300 kW fuel cell. In June 2022, Volvo announced it was conducting track testing of its prototype articulated truck model and planned to add hydrogen to its portfolio of offerings also from the second half of the decade. It is expected that the fuel cells will be supplied by cellcentric, Volvo and Daimler's joint venture to develop heavy duty fuel cells. Volvo and Daimler's timelines align with cellcentric's plans to create one of Europe's largest series production fuel cell plants by 2025.

From 2023, Volvo plans to commence on-road testing in collaboration with Everfuel. The trial vehicle models will be tested in Spain and Sweden, to assess the vehicle performance and fuelling in both warm and cold conditions. In September, the company announced that it was on track to begin early-stage customer trials from 2025. For these deployments, Volvo will target selected customers in Northern Europe, followed by additional models to new markets in the immediate years following.

As an aside, in 2022, Volvo became the first truck maker to use fossil-free steel (produced using H_2), sourced from the Swedish company SSAB. Small-scale introduction began in Q3 2022, mainly in Volvo's battery electric cards. SSAB plans to offer fossil-free steel on an industrial scale from 2026. A reminder that the decarbonisation of the supply chain will require hydrogen in many forms.

This year, Accelera (Cummins) announced it will integrate its fourth-generation fuel cell powertrain into Freightliner Cascadia trucks. Work is currently ongoing to validate the model, and selected customers in North America will be able to trial initial units from 2024. However, like many other OEMs selling engines, Cummins is also working on hydrogen combustion, with a new fuel-agnostic platform unveiled, to be applied in its B, L and X-Series engine portfolios, which will be available for commercial vehicles fuelled by diesel, natural gas and hydrogen.

Meanwhile, in April, Cummins announced plans to integrate 20 PEM fuel cells into Scania's BEV platform as part of the HyTrucks initiative. The HyTrucks consortium, with founding partners Air Liquide, DAT 24 and Port of Antwerp, is aiming for at least 1,000 heavy-duty H_2 trucks on the road by 2025, backed up by at least 25 operational HRS. The trucks will be deployed mainly in the triangle between three of the major logistics hotspots in Western Europe – those of Rotterdam, Antwerp and Duisburg.

Later in the year, Scania separately announced plans to deploy fuel cell trucks in Switzerland as early as 2024. These are expected to be Scania's first H_2 vehicles to be sold commercially, cemented by Scania's newly softened position on fuel cells. Iveco has been quiet on H_2 in 2022, with news coming from their partner Nikola. Orders books are at last now open for the fuel cell version of the Nikola Tre truck in the US, an area to watch in 2023.

In January, the Ports of Los Angeles and Long Beach welcomed the first US deployment of Nikola battery-electric trucks and announced plans for the initial two BEVs to be followed by two FCEVs. Following the pilot with four trucks, the respective ports have signed a letter of intent to use up to 100 Nikola zero emission trucks from 2023, of which 70 are expected use fuel cells. In the same month, separately, Nikola signed an MoU with Covenant Logistics Group to supply up to 40 fuel cell trucks from 2023, pending successful trials.

In December 2022, Nikola announced three key partnerships. In the first announcement, Nikola indicated it will work with E.ON to accelerate the rollout of H_2 supply and related infrastructure, to provide an integrated mobility solution. The envisaged JV plans to supply green H_2 to 5,000 Nikola Tre fuel cell trucks across Europe by 2027.

In the second announcement, Nikola will work with Plug Power through a strategic collaboration covering vehicles, equipment and hydrogen supply synergies. An agreement relating to green H_2 supply is expected to provide Nikola with at least 100 tpd H_2, with an option to increase volumes over time. In addition, the partnership anticipates Plug Power purchasing up to 75 Nikola trucks. The vehicles will be deployed over a period of 3 years, starting in 2023, and will be used by Plug to deliver green hydrogen to customers in North America.

Finally, Nikola will work with Plug on a hydrogen hub project in Arizona, US. Plug will supply an initial 30 tpd liquefaction system, to be scaled up to 150 tpd upon hub completion. The hub project has ambitious timelines, aiming to deploy up to 60 H_2 dispensing stations and achieve 300 tonnes of H_2 supply by 2026. Nikola and its partners are in the process of permitting and procurement for a large-scale H_2 supply facility in Buckeye, Arizona, to supply hydrogen to Nikola trucks and third-party demand in regional markets including California.

In the final days of the year, Nikola achieved Zero Emission Powertrain (ZEP) certification from the California Air Resources Board (CARB), allowing for the qualification for the California truck subsidy scheme (HVIP). The incentive is valued at US$240,000 per Nikola truck, making it one of the most attractive subsidies worldwide.

Despite deployment progress, orders and headline projects, Nikola's stock continues to slide going into 2023, risking NASDAQ de-listing if the stock falls to below US$1. In October 2022, disgraced ex-CEO Trevor Milton was found guilty of charges on deceiving investors about the company's progress in developing zero emission vehicles.

…BUT CHINA DOMINATES ORDER VOLUMES

Fuel cell trucks remain a priority in China, making up 59% of total fuel cell commercial vehicle sales between 2017-2022, according to Interact Analyst. In 2022, just over 5,000 commercial FCEVs were registered, 3,744 of which were trucks. Actual shipments to customers in 2022 (as reported by CAAM) were lower, 3,789 vehicles, just over 2,800 of which were trucks.

Commercial FCEV order batches in China typically number in the tens, sometimes hundreds. In one of the largest in date, in September, Sinotruck received orders from three companies for a total of 1,100 fuel cell trucks to be delivered in the next 2-3 years. The models include 4.5 t urban logistic vehicles, 18 t trucks and 49 t tractor units, equipped with fuel cells from Weichai Power, with ratings between 50 and 200 kW. The 49 t truck has been tested in Shandong Province since 2020, with fuelling infrastructure already in place along the provincial highways.

In December, MingZhu Logistics announced a letter of intent to purchase 700 fuel cell vehicles from Shenzhen Kameng, a Dongfeng Motor dealer. Dongfeng is a state-owned Chinese manufacturer that produces several H_2 commercial vehicles, including the Tianlong KL H_2 fuel cell tractor truck. The vehicles are to be delivered between May and October 2023 to the Yantian region for use in port-based and cold chain logistics applications.

China's state-owned multinational construction machinery maker XCMG is also building for scale. Late in December 2022, XCMG delivered 100 fuel cell trucks to the end client Mengxi Zhenghe Group for the construction of a mine near Ordos in the Inner Mongolia autonomous region, just two years after launching its first fuel cell truck. In all, XCMG expects to deliver 1,000 trucks to Mengxi by 2025. The supplied trucks have a range of 450 km before refuelling and are powered by a 110 kW fuel cell.

Outside China, fuel cell truck interest in Asia remains muted. In April 2021, Isuzu, Toyota Motors, and Hino (Toyota's commercial vehicle subsidiary) established the Commercial Japan Partnership Technologies Corporation, to help push cleaner technologies. In July 2022, CJPT announced it would develop a light-duty truck, targeted at supermarket deliveries, for market introduction early in January 2023. However, with Hino expelled from the partnership in August 2022, as a fallout from past falsification of internal combustion engine emissions data, whether this timeline will be retained is open to debate.

HYUNDAI IS EXPANDING TO NEW MARKETS

In 2021, Hyundai reached a landmark of 1 million km driven in Switzerland by their XCIENT trucks. By October this had extended to 5 million km. But in the same month, concern rose over the status of the Hyundai Hydrogen Mobility (HHM) project, with its partner H2 Energy, as press releases emerged suggesting Hyundai was considering withdrawing from the project due to the lack of green H_2 and fluctuating energy costs. Hyundai responded quickly to dispel the rumours, saying it remained committed to H_2 mobility and the HHM project, although vehicle deployment volumes have been paused at 47 throughout the year, and the 1,600 trucks by 2025 looks yet further away.

In the meantime, Hyundai is diversifying markets and this year (in quite small numbers) the XCIENT model entered Germany, South Korea, Israel, Czech Republic and New Zealand. In August, Hyundai announced its next European focus, Germany, with orders placed for 27 XCIENT trucks.

The first German vehicle was delivered in September, when Hyundai handed over an XCIENT truck to Mewa for bodywork. Mewa have already trialled two XCIENT vehicles in Switzerland.

In December, Hyundai launched sales of its XCIENT truck in South Korea, building on verification testing conducted in the Seoul and Yeongnam regions over the past year. Four vehicles will be deployed for year-long trials from 2023 in four different regions.

The XCIENT entry to Israel was in December 2022, partnering Hyundai's agent Colmobil, hydrogen producer Bazan and HRS operator Sonol, seeking to establish a H_2 value chain in line with Israel's commitment to reduce its carbon emissions.

In California, Hyundai presented plans to deploy 30 Class 8 6x4 XCIENT models to the Port of Oakland starting Q2 2023. The articulated model will have an expanded storage system that can hold 67 kg H_2, allowing up to 450 miles per tank. The first 5 trucks will be supported by a US$3.5m grant from the US Environmental Protection Agency and used for testing and commercial demonstration over 5 years by First Element Fuel, the US HRS operator.

CONFIDENCE IN HYZON STALLS

We were rather gushing last year, led by Hyzon statements on deployments, but it turned out these may have been somewhat exaggerated.

Hyzon began 2022 with acquisitions and strategic partnerships to aid deployment of vehicles in the UK and Germany. In the UK, Hyzon signed an MoU with Scottish-based Russell Logistics in March. This partnership would provide Hyzon with the facility to provide vehicle leasing and servicing options to UK clients and facilitate planned customer trials of a UK specification 44 t 6x2 articulated tractor cab. In Germany, Hyzon reached an agreement to acquire Orten, a local manufacturer of truck and trailer bodies with expertise in battery electric trucks, which would provide Hyzon with three new Germany-based production facilities and over 80 new employees.

Germany looked to be a major early European market for Hyzon following the reported sale of 18 fuel cell trucks to Hylane GmbH in April 2022, for use in their vehicle leasing services. The vehicles would be some of the first Hyzon trucks deployed in Europe outside of the Netherlands and would to be trialled on a pay-per-use model facilitated by Hylane. The vehicles were planned for delivery in late 2022, though with no update by the year end.

In May, Hyzon announced the RePower program which would integrate Hyzon's 200 kW fuel cells into existing diesel vehicles for the North American market. The programme planned to accelerate the deployment time for fuel cell trucks by decoupling dependence on long lead items such as vehicle chassis. In June, Hyzon received CARB certification for its RePower vehicles, meaning vehicles sold in California qualify as exempt from emission requirements.

In August 2022, Hyzon announced it would delay filing its 2nd quarter financial performance, failing to meet NASDAQ deadlines for late filings and cutting the companies' stock in half over the coming days. Hyzon gave the reasons of revenue recognition in China, and operational inefficiencies in its European JV with Holthausen. Following the Blue Orca short seller report, and an SEC investigation in January, Hyzon founder Craig Knight was removed as CEO and replaced by Parker Meeks on an interim basis. By November 2022, speculation over allegations of fake customers and exaggerated orders abounded. None of this will have helped investor sentiment. As we enter 2023, we watch in anticipation for events, hoping for a good outcome.

NEWCOMERS MAKE SOME NOISE

Amongst the noisiest in the fuel cell truck space in 2022 was Quantron, a German company aiming to be a technology and platform partner for industry OEMs. Quantron worked with Ballard to develop its hydrogen fuel cell offering, unveiled at the IAA Transportation show in Hanover in September. The Quantron QHM FCEV 4x2 tractor cab incorporates a FCmove-XD 120 kW fuel cell, with up to 116 kg hydrogen, stored in 700 bar tanks, giving the vehicle a range of up to 1,500 km per refuel. The product unveiling was immediately backed up by strategic partnership and a volume order.

In the same month, Ballard and Neuman & Esser announced investment into Quantron AG, as part of a €50m financing round. Ballard's financial investment, in the single-digit million range, included a development cooperation agreement over the next 12 months to accelerate the launch of a first four vehicles. Ballard will be exclusive supplier for these platforms, with a commitment from Quantron to purchase 140 FCmove Ballard modules, totalling approximately 17 MW, with options to buy an additional 50 units. The modules are expected to be delivered in 2023 and 2024.

Early focus markets for Quantron include Germany and North America, with plans for the North American market to generate around 50% of the companies' turnover by 2025. Spearheading Quantron's growth in the US is a framework agreement with US-based logistics group TMP for up to 500 Class 8 fuel cell trucks. Trial vehicles are set to be available from 2024 and will be operated by TMP under Quantron's vehicle leasing scheme (Quantron-as-a-service, QaaS).

In December 2022, California-based Gemini Motor announced a partnership with Ballard to develop fuel cell Class 8 autonomous trucks. Gemini will integrate FCmove modules and Chart Industries' liquid hydrogen on-board storage systems into the vehicle chassis. The consortium plans vehicle demonstrations in real world fleets from 2023, with a commercial offering from 2025, anticipating hundreds of fuel cell trucks. Alongside, Gemini is developing an autonomous driving capability.

Also in the US, Toyota, Kenworth, Shell and the Port of Los Angeles concluded the ZANZEFF Shore to Store project in August. The programme deployed 10 Toyota/Kenworth trucks with customers in California for short term trials operating out of the port. Although the programme concluded in August, some trucks remain with customers as demonstration working models, and Toyota will start manufacturing fuel-cell powertrain modules in Kentucky from 2023.

In November 2022, TECO 2030 signed a letter of intent with AVL, the Austrian development, simulation, and testing company, for delivery of fuel cell stacks to an undisclosed truck customer. AVL will deliver its HyTruck platform to 30 trucks by the end of 2023. Each truck requires two 100 kW stacks and a supply of 120 stacks in total are expected.

In the UK, the start-ups Hydrogen Vehicle Systems (HVS) and Tevva made progress. In September, EG Group announced the investment of £25m into the Scottish based H_2 truck firm HVS, adding to a £5m investment in 2021. HVS plan to develop a 40 t HGV tractor unit using a bespoke chassis design, with a UK specification model to go on sale in 2025. HVS will be supported in vehicle development by the allocation of £15m UK Government funding via the Advanced Propulsion Centre (APC).

Meanwhile, Tevva, the BEV and FCEV commercial vehicle specialist, is focusing on lower weight class vehicles (7.5 t, 12 t and 19 t, for urban/extra-urban duties), unveiling its 19 t H_2 fuel cell truck offering in September. In July, it reached an agreement with Motive, the UK HRS operator, on green H_2 fuelling. Tevva will produce H_2 trucks at its facility in Tilbury, UK, from 2023, in parallel with its BEV offering, and has plans for a second facility in mainland Europe. This would increase Tevva's manufacturing capacity to 6,000 zero emission (BEV and FCEV) trucks per year by 2024.

In December 2022, FAUN, a key player in the European refuse truck market, signed an agreement with Hyundai through FAUN's H_2-facing subsidiary ENGINIUS. Hyundai's fuel cell system brand, HTWO, will provide its 90 kW modules to ENGINIUS, to be integrated into refuse and other trucks, including ENGINIUS' CITYPOWER medium cargo truck model, unveiled at IAA Transportation 2022. The CITYPOWER model, expected to be based on a two-axle Mercedes-Benz Atego, will commence on-road testing from 2024, followed by plans for series production from 2025.

German based company Clean Logistics unveiled its fuel cell truck model "fyuriant" in July 2022, in collaboration with REFIRE, Clean Logistics will integrate two 120 kW REFIRE PRISMA fuel cell systems into articulated tractor units, with a production capacity of 450 vehicles per year targeted from Q4 2023. Following the launch, orders began to fill, headlined by a framework agreement with GP JOULE, the renewables business, for up to 5,000 vehicles, to be delivered between 2023-2027. GP JOULE will make the vehicles available to customers in a rental model, with billing based on kilometres driven.

By October 2022, Clean Logistics announced it had completed the retrofit of seven of its trucks to partners of the H_2 logistics hub in Neumünster, Northern Germany, and an additional three to Bavarian haulage company Hans Wormser AG, with Federal funding, ahead of time.

Perhaps one of the most newsworthy reports relates to PowiDian, and the new multi-purpose vehicle platforms HyRIS H1 and H2, combining a 50 kW stack, 21 kWh battery, and 3.4-5.1 kg H_2 to almost double the ranges of the battery equivalents, HyRIS B1 and B2. These 3 t vehicles cover uses from mobile pressure washers to work platforms and refrigerated goods delivery.

SHIPMENTS BY APPLICATION

Fuel cells for mobility, primarily cars, continue to dominate. Across all modes (including forklifts), 85% of shipments (2,113 MW) fell into this category in 2022, 147 MW more than in 2021. Mobility accounted for 35% of unit shipments in 2022, a slight fall from 2021's share. So, the message is transportation is growing, but other fuel cell markets are growing too.

The major fuel cell car companies are Hyundai and Toyota, achieved shipments of 11,312 (1,058 MW) and 3,683 (471 MW), respectively. These represent an increase for Hyundai, from 8,535 units (814 MW) in 2021, and a fall for Toyota, from 5,910 units (756 MW) in 2021.

The next main contributor to vehicle shipments is China, with a record 3,789 units (buses and trucks) being shipped in 2022. Together, these are estimated as 387 MW of the overall 2022 count. For the first time, this included 80 SAIC Maxus MPVs, alongside Toyota Mirais imported from Japan. Although still small, China's fuel cell car fleet is slowly growing, accompanied by HRS availability to fuel fleets. Such is the success of China's policy, the country is now home to 85% of the global fuel cell bus fleet, and 95% of the global fuel cell truck fleet.

While nearly 1,000 fuel cell buses were shipped into China in 2022, fewer came to Europe (only 99 registrations, compared to 158 in 2021). Outside China, fuel cell truck shipments globally in 2022 remained miniscule. CALSTART, (and our own data) suggests 82 new fuel cell buses were fielded in the US in 2022, mostly in California versus IPHE's records of only 10. Things could change, given the business plans of cellcentric, Plastic Omnium and others.

Fuel cells for ships and for aviation remains exploratory, now with a growing emphasis on propulsion over hotel loads or auxiliary power.

Forklifts (mainly battery box replacements for Class I, electric motor rider trucks, and Class II, electric motor narrow aisle trucks) continue to be a major application for fuel cells, albeit with fewer unit shipments in 2022 (over 9,650 units) compared to 2021 (over 13,400 units). After a big push into Europe in 2021, numbers were lower in 2022.

By number, micro-CHP still dominates shipments, Japan leading with its Ene-Farm programme. ACE shows 42,877 units being installed in 2022, over 3,000 more than in 2021. In Europe the market for micro-CHP is shrinking fast: following the conclusion of PACE and with the imminent closure of KfW-433 as a funding route, numbers fell to just over 3,100 units in 2022, down from over 3,800 units in 2021, and 5,900 units in 2020. Russia's invasion of Ukraine and the dash away from natural gas has not helped the market. Outside Japan and Europe, micro-CHP ships in negligible numbers, further demonstrating the criticality of country-to-country policy in supporting fuel cells.

Larger, fuel cells for prime power and for industrial CHP continue to grow slowly overall, with 325 MW shipped in 2022, compared to 297 MW in 2021. Much of this is dominated by two actors, Bloom Energy and Doosan Fuel Cell, joined by FuelCell Energy building 37 MW stacks in 2022, mainly as refurbishments to POSCO in Korea, following arbitration in December 2021.

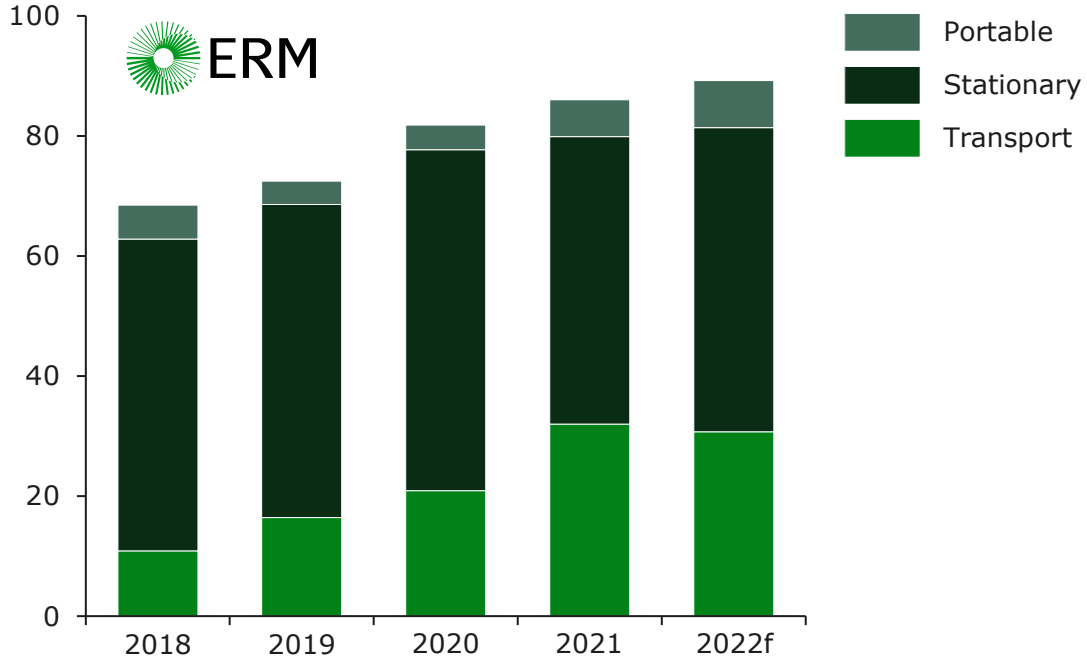
In the middle sit the 5-10 kW fuel cells intended for commercial buildings. These continue to struggle whatever the location and barely count.

Together, prime power and CHP across the power range contributed 364 MW shipments in 2022, up from 335 MW in 2021. While a growing emphasis for developers, fuel cells for grid support and off-grid power remains subdued, at 14 MW (for both years).

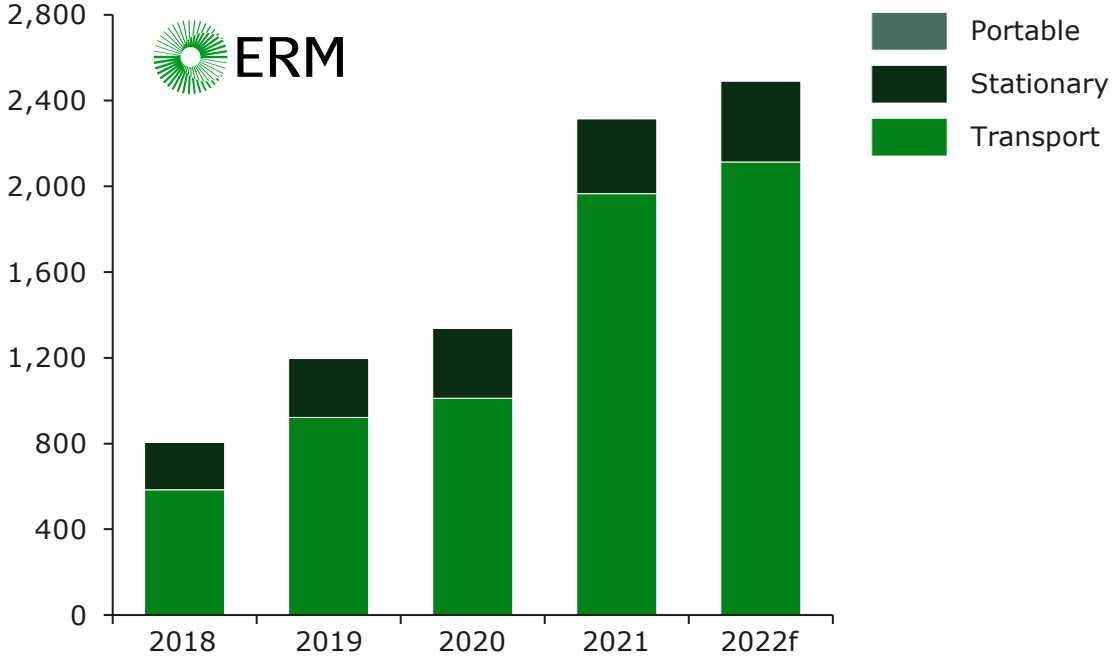
Aside from telecoms backup (the largest historic application), there is now a growing emphasis on large mobile systems for events and for construction works. These are ported systems, not hand portable, requiring wheels or lift hoists. While many actors have produced early (and nicely presented) units for this segment, the focus on hydrogen fuel with its continuing high cost and difficult logistics, make these more a technology push than a market pull though.

Shipments of portable fuel cells (including smaller ported APUs, less than 20 kW) showed an increase, from just over 6,000 units in 2021, to nearly 8,000 units in 2022. These are supplied globally, but most feed into European and North American industrial and consumer markets.

Shipments by application 2018 - 2022 (1,000 units)



Megawatts by application 2018 - 2022



TRAINS AND TRAMS

The first railway line entirely powered by hydrogen trains was inaugurated in 2022 in Europe, which continues to be the main market, though with some teething problems. Other regions are now expanding their interest, with a high-speed H_2 train in China, Stadler Rail's unveiling of its FLIRT H_2 train (the first of its kind for the US), and a H_2 train order in South America.

EUROPE

In the UNIFE World Rail Market Study 2022 conducted by Roland Berger, it was forecast that, by 2035, 20% of regional trains could be H_2-powered, mostly located in Northern Europe. But in October 2022, it was announced that H_2 would no longer be considered as a replacement for diesel Baden-Württemberg, after a study showing a 67-82% higher cost of ownership for a H_2-driven infrastructure over battery electric, over a 30-year period (A catenary-based system came in at a similar cost to a battery electric system). Whilst the study is not helpful towards H_2, it is not the final word. The study assumed a current green H_2 pricing from electrolysis of €7.98/kg (with electricity from the German grid), with next to no allowance for likely falls in H_2 prices over time. The Cuxhaven trains haven't yet stopped but they may have wobbled.

In 2022, Germany became the first country to have a public railway line met solely by fuel cell trains, with a fleet of 14 iLint's, run by Eisenbahnen und Verkehrsbetriebe Elbe-Weser GmbH (EVB) on the route connecting Cuxhaven, Bremervörde and Buxtehude in Lower Saxony. The trains replace the 15 diesel trains previously powering the route, with the state-run LNVG rail authority contributing over €85m to the procurement cost. To meet the fuelling needs, an HRS with a capacity of 1,600 kg H_2 a day was inaugurated by Linde in Bremervörde, the largest H_2 refuelling station in the world for any vehicle type. The iLint is the foremost H_2 train in terms of fielded units, with a top speed of 140 kph and a world record 1,175 km on a single run without refuelling, from Bremervörde to Munich. But it is not without teething problems. Of the 27 trains ordered by the Frankfurt Rhine-Main transport association RMW for 2022, only two were in sporadic operation by December 2022 (though a total of 6 iLint's had arrived by then).

In Germany, Alstom faces competition from Siemens, which unveiled its Mireo Plus H in May, designed as part of the NOW-funded H2goesRail project. There is two-car version of the train that can travel 160 kph and has a range of 600 km, and a three-car unit with a range of 800-1000 km. The hybrid powertrain is rated at 1.7 MW and the train can be fuelled in 15 minutes. The mobile refueller was demonstrated for the first time in September at Siemens' test track at Wegberg-Wildenrath. Over 2002, tests of the train in Bavaria remained on track.

In June 2022, Siemens announced the first serial order for the Mireo Plus H, of seven two-car trains by Niederbarnimer Eisenbahn, a private operator of trains in the Berlin-Brandenburg region. The trains are for the Heidekrautbahn network around Berlin, starting 2024. In September 2022, Siemens ordered 14x 200 kW fuel cells for the trains, with a letter of intent for a further 200 Ballard stacks totalling 40 MW over the next six years.

Also using Ballard fuel cells is the re-tractioned former Class 314 (now reclassified as a Class 614), converted as part of the Scottish H_2 train project. The project consortium is led by the University of St Andrews and received funding from Angel Trains for an on-site electrolyser at Bo'ness that facilitated its first test run in August. This demonstration project is seen as a key milestone towards the Scottish Government achieving a net zero rail system by 2035.

In June 2022, Linsinger Machinenbau of Austria showcased its MG11 Hydrogen milling train. The train was tested in service in November 2022, machining the tracks and repairing track defects on the of the venerable Traunsee Tram line that connects to the Traunseebahn, repairing defects in the rails. The train doesn't need to travel fast, topping out at 50 kph. The hybrid powertrain consists of a 180 kW engine, a 150 kW fuel cell module from Proton Motor fed by conformable H_2 tanks from Hexagon Puris, and a 60 kWh capacity Li-ion battery. The next stop for the train will be demonstration in the US.

Nestlé Waters, in France, plans to be the first company in Europe to use a H_2-powered freight train, transporting mineral water between Nestlé's Vosges factory and its distribution centres from 2025. The train will use a fuel cell delivered by Alstom in collaboration with ENGIE, and will be operate in dual mode, running on electrified lines and H_2 mode on non-electrified lines.

In 2020 Talgo announced the development of the Vittal-One hydrogen trains for suburban and regional transportation. In May 2022, dynamic testing of the train began at its factory at Las Matas near Madrid. Also able to run from a catenary, when the train runs on H_2 it has a top speed of 160 kph and an 800 km range from H_2, similar to that of the Mireo Plus H. The hybrid powertrain design is modular, to facilitate retrofits of existing diesel and electric locomotives.

CAF, in turn, is modernising a three-car Civia 463 train for hybrid traction from both catenary and H_2. As part of the FCH2RAIL project, CAF, alongside consortium members DLR, Toyota, Renfe, ADIF, CNH2, IP, and Stemmann-Technik, began testing on tracks in July. The tests will cover different scenarios (line profile, commercial operations, climatic conditions, etc.) should end in 2024.

Both the Netherlands and Italy saw new tenders for hydrogen trains released at the end of 2022. In November, Arriva Netherlands released a tender for four hydrogen powered trains to traverse the Delfzijl-Groningen-Veendam route from 2027.

Activity also grows in in Eastern Europe. In May, the oil refiner PKN Orlen signed a strategic agreement with Alstom to deliver H_2 trains in Poland in the next 2 years. As part of the deal, PKN Orlen, looking to invest €1.6bn in H_2 by 2030, will provide the refuelling infrastructure. In December, Alstom and Air Products signed an MoU to provide the first H_2 trains and refuelling infrastructure for the Czech Republic to contribute to the country's Fit-for-55 objectives.

ASIA – NOW ON A FAST TRACK

There were announcements in each of the major hydrogen train markets in Asia in 2022, with China, South Korea, Japan, and India all achieving firsts.

At the end of December, CRRC Changchun and Chengdu Railway Group unveiled its H_2 train. Built in Xinjin, and based on the Fuxing electric multiple unit, the train has a top speed of 160 kph and a range of 600 km. The hybrid powertrain uses a supercapacitor rather than a battery, to deal with the inertia associated with moving off from stand.

Also in December, the Korean Railway Research Institute (KRRI) unveiled its prototype H_2 train. Part funded by central government, the project includes Woojin Industrial Systems, a rolling stock maker, and railway operator Korail. Each car is equipped with a 200 kW fuel cell and 14 rooftop tanks, collectively storing 63 kg H_2. The hybrid train has Li-ion batteries underslung between the bogies, to create a 1.2 MW traction system. The two-car set has a top speed of 110 kph. As part of the project, a stationary H_2 refuelling system was also designed and built.

Japan also saw the unveiling of its first H_2 train in February. The Hybari train was developed by Hitachi, Toyota, and JR East, at a cost of ¥4bn (US$31m). The train is powered by Toyota fuel cell modules (like those supplied to CAF in the FCH2RAIL project), and has a top speed of 100 kph and a range of 140 km. As the train is not due to be in commercial operation until 2030, improvements to the speed and range are to be expected. In March, JR East conducted tests of the train on the Nambu line (part of the Tokyo Mega Loop, connecting Tachikawa, Tokyo, and Kawasaki). JR Central, another Japanese railway company, is also showing interest in H_2 trains. Representatives of JR Central toured the HydroFLEX project in Long Marston, in August.

Indian Railways has the fourth largest rail network in the world, with a track length of 128,000 km, 78,000 is non-electrified. Trains account for 4% of India's carbon emissions, equating to a third of the UK's entire carbon emissions. Indian Railways has set an ambitious net zero target for its operations by 2030. Electrification of the broad-gauge network is underway but there is a sizeable opportunity for H_2 trains. In May, Indian Railways commissioned Medha Servo Drives (a rail system integrator) to retrofit at least two diesel-electric commuter trains to run on H_2, from 2024 on the 89 km Sonipat-Jind route on the outskirts of New Delhi. Ballard received an order to for eight 100 kW FCmove-HD+ modules for two of the trains in September 2022.

NORTH AMERICA – "MIND THE GAP"

Progress continues in North America, but still at a slower rate than Europe. Canadian Pacific is leading the way in Canada on H_2 trains as part of its plan reduce the intensity of its locomotive operations by 38.3% by 2030 on 2019 levels. Following its intention last year to convert a SD40-F loco to use H_2, in May an EPC contract was placed with ATCO to build the underpinning HRS at CP's railyards in Calgary and Edmonton. Each will include a 1 MW electrolyser. Build of these facilities is expected to begin later this year, aiming for H_2 supply to locomotives in 2023. The first tests of the retrofitted train took place in November, in Calgary. Elsewhere in Canada, the retrofit of a Southern Railway of British Columbia diesel electric switcher locomotive began, following a statement of intent by Hydrogen In Motion and Loop Energy last year.

The big hydrogen train news from the US in 2022 was the unveiling of Swiss manufacturer Stadler Rail's FLIRT H_2 train at the Berlin InnoTrans 2022 trade fair in September, which is set to be used by San Bernadino County Transit Authority (SBCTA) in its 14.5 km Redlands to San Bernardino connector. A few days after InnoTrans it was announced that Ballard would supply had signed a contract with Stadler to supply six of its 100 kW FCmove-HD+ fuel cell modules, the same modules as to be supplied to Medha Servo Drives in India. When it finally enters service, it will be the first H_2 train in the US, five years after its initial announcement. The FLIRT H_2 vehicle consists of two cars and a middle section referred to as the "PowerPack" which holds the fuel cells and the H_2 tanks and stored the current in a traction battery. The FLIRT H_2 seats 108 passengers (with more standing) and can reach a top speed of 130 kph (79 mph). In September 2022, Sierra Northern Railway of California unveiled the retrofit design for its H_2 powered switching loco first announced in 2021.

Argonne National Laboratory and Oak Ridge National Laboratory announced an exploration of low carbon fuels for rail transport, including hydrogen. As part of the collaboration the laboratories have agreed a programme of research and development activities with Wabtec, a leading rail technology company. The activities include H_2 combustion as an engine technology.

REST OF THE WORLD

As with other end markets, we are now seeing a slow advance of fuel cells in rail outside Europe, Asia and North America. In November, in a breakthrough for South America, Ferrocarril de Antofagasta a Bolivia (FCAB) of Chile placed an order for a H_2-powered locomotive from CRRC. FCAB, a subsidiary of the mining company Antofagasta, plans to begin trials in 2024. The loco will be used to power one of the company's freight trains, as part of an objective to reduce the carbon emissions from mining by 30% by 2025 on 2020 levels.

In Australia, in 2022, a study began on H_2 in rail and one concluded, but there is still little actual on the ground activity, mirroring the huge number of green hydrogen projects in the country, most of which have yet to reach FID. In March 2022, Australia's largest rail freight operator, Aurizon, and global miner Anglo American said they would work together to assess the use of H_2 powered trains for bulk freight. The study will focus on Aurizon's Moura rail corridor that operates between Anglo American's Dawson metallurgical coal mine and the Gladstone Port, and the Mount Isa rail corridor that operates between the North West Minerals Province to Townsville Port, via Aurizon's Stuart Terminal. Anglo American sees the train project as an opportunity to expand its mine truck model to other heavy freight uses.

In May, outline findings of a study between the UK companies Smart Ports and Arcadis were outlined, focused on the potential to decarbonise Australia's rail infrastructure using NH_3 cracking technology. The concept revolves round storing hydrogen to decarbonise long-haul freight trains on the 1,700 km Inland Rail Freight Link. The conclusion of the study was that it would be possible and cheaper to use this technology than diesel powered freight trains from 2024. It would also contribute a large emissions savings of 763,000 tonnes CO_2 on a single journey from Melbourne to Brisbane.

Lastly, in Egypt, a Hyundai-Rotem led consortium with Orascom Construction and Colas Rail, signed an MoU to attempt to build a tram powered by green hydrogen. The consortium had plans to submit a study on the project to the Egyptian Ministry of Transport for approval during 2022 but to now there has been no update on the proposal.

MATERIALS HANDLING AND FORKLIFT TRUCKS

Until a couple of years ago, activity in this sector was all about forklifts. In unit numbers, fuel cell forklift shipments still outweigh any construction, mining or container handling equipment using H_2, but larger heavy-weight products are now (slowly) emerging. And interest is now evident in more countries, for example, at the end of 2022, the HYDRA consortium in Chile demonstrated a stationary fuel cell powertrain for mining vehicles, yet to be vehicle mounted.

GO BIG!

Dump trucks seem popular, as a reasonably large segment of off-road equipment. In May, Anglo American finally showed the world its nuGen prototype dump truck (retrofitted from a diesel vehicle) at Mogalakwena's PGM mine in South Africa. The mine is located at one of the three hubs identified in the country's Hydrogen Valley feasibility study performed in 2021. The truck uses a hybrid powertrain, with a battery pack to facilitate energy recovery from braking. Despite a lightweight design (for a mining truck), at 220 tonnes it is the largest FCEV to date, able to carry 290 t of payload. The vehicle is fitted with 800 kW of Ballard fuel cells and a 1.2 MWh battery pack to deliver 2 MW to the powertrain designed by First Mode. Tanks on and off the vehicle are supplied by NPROXX. ENGIE supplies the H_2 from an on-site 3.5 MW Nel electrolyser, to produce up to 1,000 kg H_2/day in place of up to 3,000 litres of diesel. Anglo says it will retrofit 40 trucks in South Africa before rolling out the nuGen to its global fleet.

By December, Anglo American invested a US$200m equity injection into its development partner First Mode. Upon closing of the transaction, expected in January 2023, Anglo American will enter into a supply agreement with First Mode to decarbonise its global fleet of ultra-class mine haul trucks, of which around 400 are currently in operation, over a period of 15 years.

Back in 2021, the Chinese truck manufacturer SANY delivered a dump truck and a mixer truck, both with H_2 fuel cells. The world's first five fuel cell cement mixer trucks were supplied to its customers in April 2022. All are fitted with 110 kW fuel cells from REFIRE and H_2 tanks facilitating a 310 miles range. SANY aims to be the largest comprehensive fuel cell solution provider in China within 5 years.

In December 2022, Zoomlion's mining division showed its first independently developed fuel cell dump truck, the ZT125FCEV. At 80 t load capacity it is bigger than SANY's dump truck. The truck is equipped with two 120 kW stacks, coupled with a 120 kWh battery, capable of high a rate of charging and discharging. As a hybrid, the Zoomlion truck is 80% more energy-efficient than diesel vehicles under heavy-duty downhill working conditions and 20%-30% more efficient across the full duty cycle.

In June, Cummins said it will provide fuel cells to Komatsu for a future mining dump truck. Also in June, Volvo started testing of the world's first H_2 fuel cell articulated hauler prototype, the HX04, with stacks from PowerCell, in a 4-year publicly funded project in Braås, Sweden.

In October, two years after an MoU was signed to develop equipment using NEXO fuel cell technology, HD Hyundai Construction Equipment and Hyundai Mobis demonstrated its concept HW155H wheeled excavator at Bauma, the world's leading trade fair for construction machinery trade fair, in Munich. The vehicle is fitted with a NEXO-derived 100 kW fuel cell module.

In November, Hyundai Mobis showed its 5 t hybrid forklift, fitted with a 50 kW fuel cell, in Ulsan. A smaller stack than in the NEXO, this opens the door to wider uses in small drones and industrial machinery. Larger variants are also to be developed, to cover large excavators and other industrial equipment. Hyundai plans to pilot H_2-powered forklifts in volume by participating in a government pilot project in 2023.

AND SMALL

Over the past 2 years, Intelligent Energy, FES GmbH and BMW Group have been working to develop a bespoke power solution for the Automated Gliding Vehicles (AGVs) in operation at BMW's factory in Leipzig. Using a 1 kW IE-LFT modules for the pallet lifting, the first of the AGVs has been a success since its operation in January this year, with a plan to convert more of the AGVs to use H_2 fuel cells.

A SECTOR EMBRACING DIVERSITY

2022 has seen prototypes, trials and early production models for off-road use cases from a mix of actors, many new to the area. More fuel cell applications are appearing in construction, such as a mobile elevating work platform from the French equipment maker Haulotte, to be trialled by Bouygues in real world tests at its sites in 2023, using H_2 fuel. Hyzon is seeking wider uses for its fuel cells, complementing its truck activity, supplying generators to Schlumberger in North America. The fuel cells will be used with batteries to replace diesel powered-drilling rigs.

In June 2022, Fortescue and Liebherr announced a partnership to develop and supply a green technology-agnostic platform for T 264 mine haul trucks for use in Australian mining operations, with Williams Advanced Engineering as technology provider. The powertrain covers battery electric and fuel cell options, with an aim for a fully green fleet by 2030. According to the agreement, Fortescue will purchase 120 of the green haul trucks from Liebherr. The initial zero-emission units should be fully operational at Fortescue mine sites by 2025.

Liebherr is not limited to fuel cells for its mining truck. At MINExpo 2021, Liebherr and ENGIE announced a similar partnership, which aims to offer integrated carbon-neutral solutions to the mining industry covering FCEV, BEV and ICE. At the Bauma trade fair, Liebherr unveiled its R 9XX crawler excavator, powered by an H_2 internal combustion engine. Similarly, JCB unveiled its H_2 ICE backhoe loader back in October last year, though H_2 ICE remains JCB's focus.

Manitou unveiled its first H_2 fuel cell telehandler in December, with plans to bring it to market in 2026. But this company too is testing fuel cells alongside BEV and H_2 ICE powertrains to validate duty cycles, reliability and durability for differing customer requirements.

PORT APPLICATIONS CONTINUE TO GROW

Ports are attractive use cases for H_2, supporting the movement of heavy loads with continuous duty cycles. In 2022, Associated British Ports started to trial a Terberg terminal tractor using a fuel cell from zepp at Immingham, the UK's largest port, one of many trials now underway in many countries. There is still hesitation though. In a white paper from port equipment maker Kalmar exploring the use of H_2 for container handling equipment, concluding fuel cells only as best for 24/7 operations, and where the infrastructure costs of hydrogen are low.

Claiming an autonomous operation of 15 hours, carrying up to 65 tonnes, Gaussin launched the world's first H_2 AGV for large containers at seaports, powered by a 45 kW fuel cell, with 20 kg H_2 storage. The fuel cells for the container tractors will initially be Symbio StackPack units following the signing of an MoU between the companies this year.

The Hyster-Yale shipping container handler for Fenix Marine Services at the Port of Los Angeles is finally in service. Two 45 kW fuel cells from subsidiary Nuvera, are coupled with H_2 storage and batteries to capture energy when braking and lowering heavy containers. Able to provide power for 8-10 hour shifts, the technology will be tested in Los Angeles ahead of trials at the ports if Valencia, Spain and Hamburg, Germany in 2023.

Policy support in Japan has led to strategies being defined, target setting, and now, slowly, actions are being taken. NYK Line and UNI-X NCT have adopted four new container transfer cranes in the NYK Tokyo Container Terminal, with a retrofit capability for fuel cells. NYK will work with Mitsubishi Logistics at the NYK Kobe Container Terminal with similar aims.

Not limited to seaports, Hyundai showcased a 30 kW M-Vision airport tug for baggage handling at the H2 MEET in Korea, the first since Plug last demonstrated fuel cell airport tugs in 2019.

WHERE IT ALL STARTED, WITH FORKLIFTS

One of the earliest applications for H_2 fuel cells was in forklifts, given the small stack size (which equates to low cost and low required hydrogen volumes). Shipments from all suppliers grew have grown to over 9,650 units (in 2022, a fall from 2021 though). Most continue to be from Plug Power, which over the years has driven an expansion of the business to cover green

H_2 production and supply. Most of the news comes from Plug. Its major customers include Amazon, Walmart and Home Depot.

Plug Power's GenKey offering and acquisitions such as Applied Cryo Technologies in 2021 helps drive its dominance, as the green H_2 label eclipses simple use of (mostly grey) H_2. Walmart has worked with Plug to adopt and expand H_2 fuel cells at its facilities for over a decade, starting with a 50-fleet pilot in 2012, expanding to a fleet of 9,500 and growing. In April 2022, Plug agreed to supply up 20 tpd liquid H_2 to Walmart 's facilities, one of the first contracts of its kind for Plug. Plug is targeting 70 tpd green H_2 by the end of 2022 and remains on track for 500 tpd production in North America by 2025 and 1,000 tpd globally by 2028. Plug's industrial-scale electrolyser capability, built originally from its PEM fuel cell play, now encompasses 5 and 10 MW PEM electrolysers, claimed as the most efficient on the market today. The electrolyser customers include Amazon, retail companies owned by the private equity business Apex Group, and UK-based Ardagh Group, a global supplier of sustainable packaging.

In October, Plug announced an agreement with FreezPak Logistics, a third-party food logistics company, to provide fuel cells for lift trucks and H_2 fuelling infrastructure to four sites in 2022 and five more in 2023. The order for battery box replacements covers nearly 400 lift trucks.

Around 98 forklifts (80% of the fleet) at Lidl's logistics centre in Carquefou, Western France, already use fuel cell drives from Plug Power, with the rest to follow by the year end. The centre will be supplied with 75 kg/day green H_2, generated 75 km away by Lhyfe using wind energy. For Lidl, refuelling times were decisive in opting for fuel cells, 3 minutes' filling (and 97% availability), as compared to hours (and only 50% availability) for lead-acid battery lift trucks. Lidl intends now to switch its entire fleet in France to fuel cells based on its experience.

In April 2022, Plug Power and its South Korean JV partner SK E&S signed an MoU with Doosan Bobcat to provide fuel cells into the South Korean market, starting with a pilot supported by MTIE, focusing on forklifts below 5 t. By September 2022, the SK Plug Hyverse JV indicated it will provide forklifts, charge stations and fuel to Coupang Fulfilment Services and to Kendall Square Asset Management, two major logistics companies, in furtherance of the project.

According to its regulatory filings, shipments of Nuvera's fuel cell forklifts is drying up, despite being owned by Hyster-Yale. But the work on forklifts has opened the door to application to larger mobility for the company, which could be a bigger prize.

Meanwhile, Hangcha shipments within China reached nearly 500 H_2 forklifts. After a long wait, this market is now growing steadily.

Overall, fuel cell forklifts, fuelled mainly by grey H_2 to now, are making dents in battery electric forklifts, but the argument is not yet fully persuasive for many. The availability of green H_2 at an affordable cost will play heavily into the choice for many.

BICYCLES AND MOTORCYLES

It seems e-Bikes, e-Scooters and battery mopeds are everywhere. But H_2 fuel cell bikes have supporters, with a range, fast charging and safety benefits over the batteries in electric bikes.

FUEL CELL E-BIKES ARE MOVING TO LARGER PLATFORMS

Pragma is now taking orders for its Alpha Neo second gen e-bike, launched in 2021. The bike has a 480 W motor, a 150 km range from 67 g H_2 at 300 bar and can reach 25 kph (the legal limit in Europe). The high up-front cost of €5,690 is mitigated by a long-term lease. Pragma partners with e-bike makers to access motors, wider uses, and sales outlets. Four prototype 3-wheeler cargo bikes were co-developed with VUF Bikes in France in 2022, and a 4-wheeler cargo bike (the HeFlow) was announced with e-Flow in South Korea.

An electric cargo bike carrying heavy loads might deliver only 40-50 km range, with the 3-4 hour recharge for batteries an obstacle, even with spares. In January, Oxford-based Electric Assisted Vehicles announced the build of six cargo e-bikes for trial in Aberdeen later in the year. The EVAH2Cubed bikes target parcel and supermarket urban deliveries, in place of small vans. The bikes will make use of existing infrastructure investments, such as the H_2 bus HRS and cycle lanes in the city.

Yong'anhang, the largest public bicycle contractor in China, put its fuel cell bicycle on sale in September, targeting high utilisation in urban centres. The bike, with a price tag of CNY12,800 (€1,650), weighs 27 kg, with a range up to 80 km, from a 0.7 litre swap-out H_2 cartridge.

In May 2022, Pragma said it will collaborate with the electric moped manufacturer, Mob-ion, to create ScootHy, a H_2 version of its AM1. Mob-ion is ditching the canister it was exploring with STOR-H last year, opting for conventional refillable tanks.

Triton EV, an alliance between Triton Solar in the US and Ushva Clean Technology in India, set out an initial focus on mopeds but then moved to 2- and 3-wheel fuel cell bikes and tuk-tuks, for local sales and export. By the end of 2022, plans were set to establish a manufacturing plant at its Bhuj facility in Gujarat.

THE FUTURE FOR MOTORCYCLES IS STILL UNCLEAR…

Weight is also a key concern of motorcycle OEMs. Clever designs can save 10s of kilogrammes, critical to packing in enough battery capacity to achieve a reasonable range, but retaining the handling dynamics of engines remains a challenge. Consequently, Ducati, Toyota and Kawasaki are focusing on the conversion of internal combustion engines to run on H_2. But a common obstacle to fuel cells is the space needed for storing H_2. In terms of tight packaging, with the Hydra fuel cell concept motorbike (announced in September, from a design trio), and H2Motronics' Moto 3 (targeting a trial next year) both see significant compromises to performance over conventional ICEV designs.

MARITIME

There was a time, not so long ago, when the focus of fuel cells was on small boats to prove concepts. As the technology improved, larger units, first for hotel loads, then for auxiliary power, and now for primary propulsion, have risen on the agenda, as has shoreside power (whether for cold-ironing or for cargo handling, at ports). Activity is growing fast in this area.

The drivers for change include strengthening policies on CO_2 emissions from shipping (driven by IMO), pressure in shipping companies and cargo owners (to reduce costs), and investor pressure, responding to public and corporate sustainability concerns. IMO aims to reduce the carbon emissions associated with international shipping by 40% by 2030, and 70% by 2050. Green fuels, slower speeds and new designs all have a role, but the targets are ambitious. As ships typically have 20-40 year lives, change is slow. To meet IMO targets, new build vessels are increasingly the focus, particularly for ships covering distances where battery charging is impractical. While H_2 has a potential role, the logistics are challenging. Bunkered supplies are years away and cost is a key driver. Fuel choice, range, prime mover, location and use case all play into the case, resulting in a variety of plays. It is definitely not a case of one size fits all.

MAIDEN VOYAGES

The world's first fuel cell powered push boat, the ELEKTRA, launched in April 2022, following a long development process that started in 2016, from a team comprising TU Berlin, Berlin's port logistics operator BEHALA, ship builder Hermann Barthel and Ballard. Testing of ELEKTRA will initially take place in the Berlin area. Starting in 2023, the tests will be continued on long-distance routes towards Hamburg, pushing a heavy barge, the Ursus.

ELKTRA has a length of 20 m, with a service speed of 10 kph and a maximum thrust load of 1,400 t, with a range up to 215 NM (398 km) when pushing its companion barge. This is facilitated by two Schottel Rudder propellers, type SRP 100 with nozzles (200 kW each). In battery-electric mode, the tug will cover 65 km (40 miles) over an 8-hour period before recharging is required.

The boat carries 750 kg CH2, in swappable stores, feeding three 100 kW peak power PEM fuel cells, alongside a 2.1 MWh battery system. Although the power of the battery and the fuel cells both power the electric motors, for full redundancy the two powertrains are entirely independent systems. The vessel efficiency is further enhanced using waste heat from the fuel cell system, heat pumps and by installed PV on the roof. The first stations for the changeover of the push boat's H_2 tanks and electric charging stations will be operational in Westhafen and Lüneburg in 2023. The tanks can be swapped with the onboard crane, and the shore power cables are mechanically handled to save time.

ELEKTRA was built under a €13m (US$15.7m) project funded mainly by the German Federal Ministry of Transport and Digital Infrastructure. The project team expects to use ELEKTRA as a proving platform for a wide range of inland and coastal vessels.

OCEAN-GOING VESSELS STRUGGLE WITH HYDROGEN

Generally, given the size, complexity, and cost of the larger fuel cells for ocean-going vessels, much of the work now is at the concept phase, with few demos. Hydrogen is not easy for this market. The low volumetric energy of H_2 limits range, entailing regular replenishment. Longer-distance shipping is looking to more nuanced solutions, including the use of LNG at sea, and H_2 at shore. For LNG and hydrogen bulk carriers, adding a SOFC generator is a no brainer.

In February, ABB, working with Ballard, announced it had received an approval in principle (AiP) for its high-power PEM concept for ships, the independent assessment confirming that the design is feasible, with no significant obstacles to prevent the concept from being realised. The concept envisages 3 MW power blocks applied to a range of larger vessels. A cruise vessel in coastal areas could either run entirely on fuel cell power or switch to it when operating in environmentally sensitive areas or emission control zones, while a ferry with a regular schedule and frequent bunkering opportunities could operate solely on fuel cell power. For ocean going vessels, the fuel cell power would support auxiliary needs. The concept of the solution also envisions the integration with an energy storage system.

In March, another world first saw shipbuilder Chantiers de l'Atlantique fit two 75 kW Bloom Energy LNG-fuelled SOFCs to the 6,700 passenger MSC World Europa cruise ship (albeit rather obtrusively housed in a 40 ft ISO container). The SOFC delivers 60% efficiency, while comparable diesel gensets deliver 35% efficiency (and natural gas 25%). The MSC installation is configured for power when docked, but the fuel cells, which passed rigorous tilt-table testing, also achieved full power output during the maiden voyage between Saint-Nazaire and Qatar. Bloom is working on an architecture that will operate in parallel to the engine.

In July, the Italian shipbuilder Fincantieri signed a memorandum with MSC Group's Cruise Division, the luxury travel brand Explora Journeys, to construct two cruise ships with similar fuelling to the MSC World Europa – but with a much larger fuel cell. The ships, Explora V and VI, each capacity for 1,473 passengers, will each incorporate a 6 MW fuel cell, fuelled from LH2, to ensure smokeless port operation and to deliver slow steaming navigation. Delivery of the ships is scheduled in 2027 and 2028. But lest we get too excited, a Senior Vice President of MSC noted the volumes and absence of a supporting H_2 supply chain could well undermine the concept. The fuel cell type was not disclosed in press releases, but the use mode would play into the always-on preference of SOFCs.

In November, Fincantieri delivered the Viking Neptune to the Ancona shipyard for the smaller cruise operator Viking. The unit is in the small cruise ship segment, at 47,800 tons, with 465 cabins to accommodate up to 930 passengers. A 100 kW PEM fuel cell will be used to help determine how H_2 fuel could be developed at a larger scale in future builds of this class of ship. Again, the ultimate target scale is for a 6 MW fuel cell. Four of the Viking cruise ships, optimised for use with H_2 fuel cells, are scheduled for builds, with a delivery window between 2026–2028.

In August, HAV launched its series of deck-based fuel cells concept, based on 200 kW H_2 fuel cell modules, with up to 1,000 kW output from a standard 20 ft shipping container (which can be multiplied for larger power outputs), developed under the FreeCO_2ast project. The project is currently developing a high-capacity LH2 based storage system that can be retrofitted onboard two coastal cruise vessels owned by the Norwegian operator Havila Kystruten. A preliminary design approval was obtained from DNV in June.

In September, Northern Xplorer signed a letter of intent with Portuguese shipbuilder West Sea for a 250-passenger cruise ship, fitted with a hybrid fuel cell/battery propulsion system from ABB (with the fuel cells sourced from Ballard). Assuming the build takes place, delivery is expected for the start of the 2025/2026 cruise season, in the Norwegian fjords.

Following a statement of intent back in 2021, in October 2022 it was announced that Doosan Fuel Cell and HyAxiom (its sister company in the US) had joined forces with Korean ship builder KSOE, part of Hyundai Heavy Industries, to develop a new deep-sea LNG carrier for Shell to use from 2025. Two 300 kW SOFCs, manufactured by Doosan Fuel Cell (using Ceres' IP) will be integrated into an APU by HyAxiom with assistance from KSOE. DNV is helping with safety expertise. When launched, the vessel will operate for year, where data will be collected to inform how future vessels can be powered by SOFC technology at scale.

CONTAINER SHIPS FOR INLAND WATERS

In February, Future Proof Shipping (FPS) joined the Clean Hydrogen Partnership's FLAGSHIPS consortium, to bring the shipping company's second zero-emissions inland container vessel, FPS Waal, to Europe's waterways. FPS's first vessel, the 110 m long retrofitted FPS Maas, used 3x 275 kW fuel cells from Nedstack, with funding from Interreg, the Netherlands Enterprise Agency, and the Port of Rotterdam. This hybrid vessel began its retrofit in August and remains on track for a launch in 2023. The second vessel will operate from Rotterdam to Duisburg, with heavier loads (with a cargo capacity of 200 TEU) and will use six 200 kW FCwave fuel cells from Ballard coupled to a 675 kWh battery array. VTT is the project coordinator, with LMG Marin as the ship design company. This vessel is also expected to launch in 2023.

FLAGSHIPS is also contributing funds to the Zulu06 H_2 push boat being developed for owner/operator Compagnie Fluvial de Transport (CFT), which will sail between Gennevilliers and Bonneuil-sur-Marne on the river Seine in Q3 2023. The vessel is fitted with two Ballard 200 kW FCwave modules and will operate on green CH2. Design is from LMG Marine, with ABB overseeing the power architecture.

CONTAINER SHIPS FOR COASTAL WATERS

In June 2022, logistics group Samskip and marine robotics company Ocean Infinity secured NOK150m (US$14.4m) funds from ENOVA to progress the development of two H_2-fuelled SeaShuttle container ships. The remotely controlled ships, each powered by a 3.2 MW fuel cell, will operate between Oslo Fjord and Rotterdam by 2025.

FERRIES

Fuel cell activity in ferries is gathering in pace, particularly in Norway where the logistics of short sea shipping, coupled with significant hydropower to make green H_2 by electrolysis, favours deployment. The eagerly awaited Norled MF Hydra ferry is expected to begin operation in 2023. In November, the LH2-fuelled ferry was fitted with two of DNV type-approved 200 kW FCwave modules from Ballard. The Norled ferry trials also benefit from FLAGSHIPS funding.

In August, Lloyd's Register awarded AiP to the Norwegian ship owner Torghatten Nord for two H_2 ferries operating on Norway's longest ferry route, Vestfjordstrekninga, connecting Bodø, Røst, Værøy and Moskenes. The vessels will use a minimum of 85% green H_2 based fuel, with hotel loads and propulsion from fuel cells. The ferries are scheduled to enter operation in October 2025.

In July, TECO 2030 announced it will lead a project with shipbuilder Umoe Mandal and marine power engineering company BLOM Maritime to develop a H_2-powered high-speed zero emissions catamaran. The partners will receive up to NOK5m (US$440k) in funding support from four counties in Norway. Phase one comprises a development and approval activity, set to conclude in 2023. Phase two is for build and demonstration. The design basis is for a vessel transporting 200-300 passengers at speeds above 35 knots, over "long distances". Assuming success, the vessel will be in pilot operation from 2025. In December, TECO completed production of its first 100 kW stack, with support from AVL, which will be combined into scalable 400 kW modules during the summer of 2023.

In June, Toshiba ESS and Echandia, a Swedish developer of energy storage solutions for heavy duty marine applications focusing on ferries, announced their collaboration to develop long life fuel cell systems for continuous operation on ships, aiming for a commercial solution around 2024. The fuel cells are expected to last twice as long as competing systems, resulting in lower costs. The move is quite "out of the box" for Toshiba ESS.

Despite having dipped its toe in the water, in April, there have been no updates for project Water-Go-Round, in the US. The 21 m ferry, Sea Change, should carry 94 passengers at up to 22 knots, from an ensemble comprising 2x 300 kW shaft motors, 360 kW of PEM fuel cells (from Hydrogenics), 242 kg H_2 at 250 bar, and 100 kWh lithium-ion batteries to give up to 2 days operation. Fuelling is from a truck, but in a related project, part funded by DoE, a land-based barge will be facilitated. The CARB-funded project, delayed by the COVID pandemic, now expects to see passengers from 2023, and will be used as a proving bed to support rollout of further systems by its developer Zero Emission Industries. In September 2022, ZEI, the project coordinator, received Series A funding for its activity in an investment round led by Chevron New Energies.

Meanwhile, in another project underway in the Bay, Project Nautilus, funded by the US DOT, continues in its exploration of H_2 retrofits to diesel ferries. Phase 1 of the project, due to end in 2023, is evaluating Hydrogenics and PowerCell systems for the Discovery Zero ferry.

RESEARCH VESSELS

Fincantieri, in collaboration with Italian universities is also working on a smaller ship, ZEUS, intended to serve as a research vessel for green technology, utilising two fully redundant HyShip 72 (71 kW) units (each containing two PM 400-120 modules) from Proton Motor, delivered in February 2022. Alongside a metal hydride hydrogen storage system and batteries, a 6-hour window of zero emission propulsion is targeted from 2023.

In August, UC San Diego's Scripps Institution of Oceanography announced it will partner with naval architect Glosten to build a coastal research vessel, supported by US$35m funding from the state of California. The design will integrate fuel cells with a conventional diesel-electric power plant. The intention is to operate 75% of its missions on H_2, with the diesel engine used for longer missions.

SUPERYACHTS

In October 2022, Nuvera signed an MoU for supply of its E-45 (45 kW) engine to H2Boat for marine type approval certification, ahead of integration of H2Boat's forthcoming HP Energy Pack. H2Boat, part of Bluenergy Revolution, a spin-out of the University of Genoa, equips private luxury boats with zero emission power packs, for the more conscientious boat owners.

DREDGERS

In August, Helion received AiP from Bureau Veritas for its FC-RACK Marine H_2-fuelled powered generator. The unit is designed for inside or on-deck installation, for propulsion and shore-to-ship power supplies. A 200 kW fuel cell is currently being installed on a dredger, which will be operational in the Occitania region by the end of 2023. The fuel cell will supply hotel loads to the vessel and the smaller propulsion power levels needed during dredging activities.

BULK CARRIERS

In November, Samsung Heavy Industry announced it had received AiP from DNV for a fuel cell propelled bulk H_2 carrier. Domestic partners Bumhan Fuel Cell delivered the PEMFC design for the system, with the design for the H_2 tank, and S&S the power management system.

In November, TECO 2030 and its partners Shell, Ektank AB, Blom Maritime AS, Umoe Advanced Composites AS, FKAB Marine Design, Neste Oyj, and The Arctic University of Norway, announced an award of €5m in funding from HORIZON EUROPE for a H_2-powered tanker concept, HyEkoTank. The project will retrofit a 18,600 DWT product tanker with a 2.4 MW fuel cell system by TECO 2030 and 4,000 kg CH2 for demonstration in 2024. The tanker is expected to deliver a 60% reduction of GHG emissions during its voyages.

HYDROGEN BUNKERING

Alongside fuel cells for waterborne craft, there is significant activity in ports, from concept studies of landing hydrogen (many yet to reach the FID stage), to early trials of container handing, to shoreside power for ships at berth. If fuel cells are to grow significantly, the supporting infrastructure must be in place.

In May, the Norwegian H_2 bunkering actor HYON announced it will conduct a feasibility study in the second half of 2022, with Mitsui funding, for the potential for development of H_2 bunkering at scale, and joint exploitation globally. In September, TECO 2030 launched its concept for containerized fuel cells, the 'Power Barge', comprising fuel cell, batteries, power electronics, safety, automation systems, H_2 storage, and a refuelling solution. The concept forms a scalable floating multimegawatt solution for electricity production for shore power from hydrogen.

In November 2022, the innovation cluster 'Clean Port & Logistics' was established, supported by the Federal Ministry of Transport and Digital Infrastructure (BMVI), centred on the HHLA Container Terminal Tollerort in Hamburg. HHLA has commissioned Linde to build a filling station to support H_2-powered heavy goods vehicles and terminal equipment demonstrations at the port.

In August, Netherlands' first H_2 bunker permit was granted to Windcat Workboats to allow the H_2 ICE Hydrocat 48 crew transfer vessel to be fuelled in the port of IJmuiden. In September, plans were outlined to establish a H_2 fuelling station at Stockholm Norvik Port, covering land and sea uses.

METHANOL IS PROVING POPULAR FOR SOME

Methanol has many advantages as fuel, as a liquid with a higher volumetric energy density than H_2, greater availability at low cost, and with easy handing. For all its benefits, the focus for methanol is on smaller boats and short sea shipping given it has about 43% of the energy content of marine gas oil.

Methanol is also easy to reform, though the need for low CO levels reaching the PEM anode adds to system complexity. But there are workarounds. One is to replace the conventional shift and selective oxidation train with a membrane separator, as has been applied to backup power systems for telecoms for years by H2 PowerTech, and now exploited more widely by e1.

Maritime Partners, the US-based ship leasing company, is developing the methanol-fuelled MV Hydrogen One hybrid tow boat. When built, the boat is expected to have a range of 550 miles. ABB is delivering the propulsion plant including integration of fuel cell and battery. The design incorporates a reformer from e1 Marine. In June, Maritime Partners made a SEK37m (US$3.6m) order to PowerCell for multiple PowerCellution MS 200 units and services, including installation, class approval and commissioning support. The fuel cells will be delivered during 2023.

Another approach to processing methanol is to use a HT-PEM, which is more tolerant to CO, as pushed by Advent Technologies (formerly SerEnergy), with its SereneU units. Methanol is an ideal fuel for a HT-PEM, excess heat from the stack heating the fuel and driving the reformer.

This concept has been proven in the river cruise RiverCell project, funded by NIP. The project, which began in 2015 and closed in 2021, was led by luxury cruise ship builder Meyer Werft, with partners including Neptun Werft, Viking River Technical Cruises, and Advent Technologies. The activity in RiverCell has attracted interest. In February 2022, Advent signed an MoU with Electric Ship Facilities for distribution of SereneU units for maritime and land uses in Europe. Also in 2022, Advent joined a feasibility study on bunkering arrangements for methanol, and the potential use in the engines and fuel cells for ferries from the island on Læsø in Denmark.

In June, Advent signed an MoU with Laskaridis Shipping, a Greek company with a fleet of 90 vessels. Under the MoU, Laskaridis will install Advent units on selected dry bulk vessels to assess their overall performance as auxiliary, backup, or emergency power sources up to 90 kW. In the same month, Advent signed an MoU with Neptune Lines, a vehicle logistics provider with a fleet of 18 car and truck carrying vessels, focusing on application to ship APUs.

In the Pa-X-ell2 demonstration project, also led by Meyer Werft, Freudenberg demonstrated its own methanol reformer/HT-PEM couple (originally from its Elcore acquisition), also with NIP funding, in another strand of the e4 ships innovation cluster. Since 2016, Meyer Werft has been testing of the fuel cells on board the Baltic Sea ferry Mariella. AiP was received from DNV in 2020 encompassing safety, modularisation, and standardisation. Since 2021, the fuel cells have been tested on Carnival's cruise ship AIDAnova, with a focus on prime propulsion.

In September 2022, Freudenberg received "Type Approval" with the installation of the first two 100 kW systems on the cruise ship by the international classification society RINA, indicating the system meets the minimum set of regulatory, technical and safety requirements before it can be sold. In the future, system units with a respective nominal output of 500 kW are to be combined into total capacities in the double-digit MW range.

Blue World Technology, backed by Bill Gate's Breakthrough Energy Ventures, was still readying itself for production in 2022. Its 200 kW methanol-fuelled HT-PEM modules are also designed to be assembled into MW-scale systems, for auxiliary or propulsion power. Blue World hopes to be able to produce 500 MW fuel cells a year by 2025.

In December, Ørsted took its final investment decision and full control of the e-methanol production plant, FlagshipONE, with Haldor Topsøe as its partner. Captured CO_2 and H_2 from renewable energy will produce up to 50,000 tonnes of net-zero carbon e-methanol, for supply to the shipping industry. Construction of the plant is to begin in early 2023. Ørsted is also developing the 300,000 tonne 'Project Star' in the US Gulf Coast area and the 'Green Fuels for Denmark' project in Copenhagen, which will both produce significant volumes of e-methanol to enable the decarbonisation of shipping.

AMMONIA AS A FUEL

Ammonia is (alongside LNG, biofuels and e-fuels) a focus for ICE OEMs, seeking to extend their product lifetime. As a combustion fuel, the energy density, 12 MJ/L, is higher than liquid hydrogen (8.5 MJ/L). When thermally cracked for fuel cells, the resultant H_2 constitutes 17.65% by mass of the ammonia.

Ammonia is shipped globally in tankers, with about 10% of global production shipped by sea. Orders for very large ammonia carriers are on the increase. But ammonia is also highly toxic as well as combustible, so its use as a fuel is generally confined to deep sea vessels away from population centres, to limit hazards.

Ammonia is also an effective poison to PEM fuel cells, even when an NH_3 getter (sorbent) is used to capture residual NH_3 from the cracking process. Consequently, it is unusual when coupling with PEM fuel cells is suggested, with SOFCs and AFCs generally being the direction.

Founded by four MIT PhD alumni in 2020, Amogy aims to accelerate the decarbonisation of the global transportation industry using its ammonia cracking technology. During 2021, Amogy received Series A funding from investors including Amazon and AP Ventures. Amogy is targeting commercial shipping, where ammonia is already transported at scale, with established safety protocols in place. Amogy placed an order for fuel cell systems and supporting services with PowerCell in September 2022. A further order was made in December to Ballard for 3x 200 kW FCwave engines for delivery in 2023, with an option for seven more. Amogy plans to install the fuel cell engines into workboats. Previously, Amogy had demonstrated a 5 kW fuel cell drone and an NH_3-fuelled 100 kW fuel cell powerpack in a tractor.

In April 2022, PowerCell received an order for a 100 kW fuel cell module from Siemens Energy, building on their MoU signed in 2018. Siemens will test the module as part of its R&D on fuel cell based marine systems for propulsion and power generation, leveraging its BlueDrive play.

GOVERNMENT SUPPORT

Particularly in Northwest Europe, with significant shipping activity, national governments are increasingly investing in maritime hydrogen applications. At the end of 2021, a 26-partner Dutch consortium, including Nedstack, was awarded €24.2m for SH2IPDRIVE, (Sustainable Hydrogen Integrated Propulsion Drives) to develop reliable, safe, standardised, scalable and cost-effective solutions for H_2-based ship propulsion and energy systems. The project is researching a variety of H_2 carriers (CH2, LH2, hydrides) for vessels relevant to the Dutch economy (inland, short sea, passenger, and workboats). Based on the work in SH2IPDRIVE, the project aims to see more than 30 emission-free ships in service by 2030.

In September 2022, Corvus Energy announced it will lead the OptHyMob (Optimised Hydrogen Powered Maritime Mobility) project, alongside research institute NORCE and others, to reduce costs and extend the lifetime of hydrogen fuel cells and batteries in hybrid configurations, with NOK13.9m (€1.2m) of funding from the Research Council of Norway. The project builds on the ongoing H2NOR project, part funded by Innovation Norway (in a €5.9m grant), where Corvus, shipowners Norled and Wilhelmsen, and ship design company LMG Marin, are developing a modularised maritime system using Toyota modules. The new project is set to end in 2023.

WIDER DEVELOPMENTS

Fuel cells are not alone in targeting hydrogen as a fuel, with companies such as MAN seeking to preserve their longstanding market in combustion engines. Anglo Belgian Corporation (ABC) located in Gent, Belgium, is a leading European manufacturer of medium-speed engines in the power range 600-10,400 kW. The port of Antwerp-Bruges ordered a H_2-fuelled tug (Hydrotug) from ABC in 2019. The tugboat hit the water in May 2022, at Armón Shipyards in Navia, Spain. In October 2022, the vessel arrived in Ostend, where it was fitted with a H_2 system. Trials are due in 2023. CMB.TECH is the technology provider to the boat, using modified MAN engines.

CMB owns and operates 139 seagoing vessels in dry bulk, containers, chemical tankers, and crew transfer vessels (under the Windcat Workboats brand name). Windcat owns and operates a fleet of over 50 offshore crew transfer vessels, mainly serving the European offshore wind market. The CMB.TECH business unit focuses on hydrogen and ammonia fuelling of vessels. CMB.TECH unveiled its dual-fuel diesel/H_2 crew transfer vessel (the Hydrocat 48) in May 2022. The engines are rated at 1,498 kW, the vessel being 25 m LOA, with capacity for 10 t of cargo. In October, CMB.TECH announced a partnership with the marine engine maker Volvo Penta. For this business, hydrogen is the future, with a strong synergy between production and use.

More generally, activities relating to port hubs are proliferating, from production to distribution, storage, and use. These will assist in the development of fuel cell markets. Some of the initiatives will not get off the ground, but as there are now tens (if not hundreds) of prospects, some will. To cite just a few instances, in 2022, new initiatives were announced for the Port of Newcastle, New South Wales, led by Macquarie (in May); for the Ports of Tallinn and Gdynia (in June); for the Sines project with Shell, covering green LH2 transportation from Portugal to the Netherlands (in July); and by South Africa’s Transet National Ports Authority (in August).

Methanol is also a competing vector to bulk transportation of hydrogen. However, just as with grey hydrogen, moving to a fully green route is also essential if the emissions associated with fossil methanol (conventionally sourced from natural gas) are to be avoided.

AVIATION

The aviation sector has seen another busy year, with announcements of joint development agreements, partnerships, and demonstrations, and continued developments in powertrains. The growth seen last year, from ZeroAvia and Universal Hydrogen, is still very much ongoing.

The near-term focus is on the smallest planes and shortest flights. But even if the technology were proven and shown to be reliable in tests, prudent risk aversion and regulatory oversight means these are some way off, maybe 2030. Nearly all the demos to now have been limited to minutes in the flight phase. But that is changing. In April, a first flight between commercial airports took place, the 4-seater aircraft HY4 completing a 125 km journey between Stuttgart and Friedrichshafen, building on 30+ test flights previously completed. The aircraft, developed by Stuttgart-based H2FLY, uses a 65 kW PEM plus a Li-ion battery for supplementary power during take-off and ascent. On the way an altitude record was set, the plane reaching around 2,200 m. The aim is to power a 40-seater Dornier 328 regional aircraft in test flights by 2025.

Longer haul, larger planes are more challenging, given the low energy even of LH2, Boeing looking at 2040 at earliest and realistically 2050. In the meantime, synthetic aviation fuels (in some cases, with a green H_2 feedstock) will fill the gap. And drones continue to benefit from the high power density of PEM fuel cells and the longer range facilitated by H_2 over batteries.

ZEROAVIA

ZeroAvia continues to develop its ambitious plans for hydrogen fuel cell technology, developments in 2022 suggesting momentum is growing, with announcements concerning further investment funding, supply agreements and collaborative partnerships on fuel cell components, powertrains and whole aircraft, as well as the acquisition of a fuel cell technology development company.

In early 2022, news came of a MoU signed at the very end of 2021 with De Havilland Canada (DHC), manufacturer of short-haul regional aircraft with 10-20 seats, a key early target market application for fuel cell powered flights. The MoU gives DHC an option to purchase up to 50 powertrains but there was no specific commitment on timings. By July 2022, RAVN Alaska signed a MoU with ZeroAvia to purchase thirty ZA-2000 2 MW powertrains. This envisages a retrofit to their De Havilland Dash planes which are used for short haul flights with up to 20 passengers.

In June 2022, a MoU was signed with MONTE, a company which finances and leases aircraft. This involves the purchase of up to 100 of ZeroAvia's 600 kW ZA-600 powertrains, either for retrofit or for new installs in small regional aircraft. The powertrain will be proven in the HyFlyer II project, targeting a 300-mile flight from 2024. The deal sees ZeroAvia becoming the sole supplier of fuel cell powertrains to MONTE.

In October 2022, ZeroAvia signed an agreement with PowerCell for serial supply of stacks. This is on top of an initial order in 2021 and will eventually see 5,000 fuel cell stacks delivered by PowerCell. Each is 100 kW, to now combined by ZeroAvia into the ZA-600 modules.

In July, ZeroAvia received a US$30m investment from a consortium of Barclays Sustainable Impact Capital, NEOM in Saudi Arabia, and venture capitalists AENU. This funding will be used to support the development of the 2-5 MW fuel cell powertrain aimed at 40 to 80 seat aircraft, and to further develop the underlying airport H_2 refuelling infrastructure. In August, ZeroAvia received US$35m investment funding from American Airlines, a MoU giving AA the opportunity to purchase up to 100 powertrains, likely to be the ZA-2000 unit. Series B funding now totals US$150m, and marks a point where development is transitioning to commercialisation.

HYPOINT

Stacks from US-based HyPoint were evaluated by ZeroAvia over 2021, HyPoint aiming to complete a 150 kW, full-scale system for a demonstration flight for ZeroAvia by the end of 2022. HyPoint expects its compressed air-cooled HT-PEM stack technology to be commercialised from 2023, at an indicative price point of US$100-500/kW (when mass-produced). In October 2022, HyPoint was acquired by ZeroAvia for an undisclosed sum. HyPoint's technology represents a next generation technology that could supplant the LT-PEM stacks currently supplied by PowerCell. HyPoint claims 2 kW/kg specific power for its stacks (including cooling subsystem, in all 61% lighter than an equivalent LT-PEM system), by using lightweight bipolar plates, and from the higher stack temperature (with easier heat rejection).

UNIVERSAL HYDROGEN

Universal Hydrogen (UH), which is scaling up a H_2 fuel cell powertrain conversion kit aimed at small and regional aircraft, signed several agreements for supply of their technology in 2022, with ambitious plans for deployment. In February 2022, a letter of intent for three ATR 72-600 hydrogen conversion kits was secured from Amerila, the brand name for Paris-based airline Regourd Aviation. The target aircraft carry between 44 to 78 passengers and the intention is to have a plane in the sky by the end of 2023. In June, UH received a firm order from Connect Airlines, targeting routes from Midwest and Northeastern cities to Toronto, to convert 75 ATR 72-600 aircraft using UH's fuel cell technology. The order follows a letter of intent in 2021, with deliveries scheduled from 2025. In Jul 2022, UH received an order for 20 conversion kits from Avmax, a Canadian airline leasing company, again aimed at small and regional jets including the ATR 72-600 and the De Havilland Dash 8-300, which carries between 50-56 passengers.

ACTIVITY INCREASING ELSEWHERE

In February 2022, Aerostack GmbH, the JV of Airbus and ElringKlinger, made another "large" order for EKPO stacks. Over the next two years, EKPO will deliver development support and stacks optimised for aerospace applications. As liquid-cooled bare stacks, the NM12 stacks will deliver an impressive 6 kW/L power density, but this is much reduced when the cooling loop is included. EKPO has an initial production capacity of 10,000 stacks pa, which is capable of being expanded as orders increase. In July 2022, Germany's NIP awarded Aerostack and its partners, including Airbus, €26.5m in funding (geared by a further €18m from the project partners) for H2Sky, to develop and pre-industrialise the 100-200 kW fuel cell stacks that will be used in the main propulsion system of future aircraft. The award was the highest ever granted by the NIP.

In November 2022, Airbus outlined its ZEROe project, which aims to bring to market the world's first hydrogen-powered commercial aircraft by 2035. The project covers hydrogen combustion in turbines as one approach, and fuel cells as the other, across four concept aircraft with ranges up to 2,000 NM. All use liquid hydrogen fuelling.

In January 2022, the Electric Aviation Group, which has targeted 90-seater zero emissions aircraft, announced a spin-off company focused on fuel cells in the MW range, aimed at larger aircraft and other uses, such as maritime and rail. No timeframe was stated for the availability of a commercial offering. MagniX, which is working on zero emissions solutions for aviation using batteries, announced in October 2022 that they will also work on H_2 fuel cell solutions, asserting a mix of solutions is likely to be required. Avio Aero, a division of General Electric, announced in December 2022 it will lead a demonstration project for H_2 fuel cell aircraft, in a 4-year project, with 21 partners, part-funded by the Clean Aviation Joint Undertaking.

The Brazilian plane maker Embraer unveiled designs for 4 jets with 19-30 seat capacity, to be powered by fuel cells. These are not expected to come into service until the mid-2030s. The design basis assumes flights at altitudes of over 9 km, entailing operation down to –60 °C.

In November, Airbus said it is developing a H_2 fuel cell engine, also targeting the mid-2030s. Fuel cell modules will be installed on an A380 jet in the mid-2020s, with tests to run in parallel with conventional engines. Airbus also announced that Ariane group will provide H_2 refuelling facilities at Airbus' Toulouse base from 2025, serving ground and test flight demonstrators to serve the groups' H_2 R&D programmes into the future. This adds to previous announcements on a H_2 infrastructure build at Lyon-Saint-Exupery airport in collaboration with Vinci airports.

Air New Zealand announced a partnership with four companies as part of its ambition to have a zero-emission flight demonstrator. In a "statement of intent to order", an initial commitment to three aircraft is in sight, with an aim of expanding that to 20. The project, known as "Mission NextGen Aircraft", will see ANZ work with Hiringa Energy on H_2 fuelling and infrastructure, and with aircraft developers Eviation, VoltAero, and BETA. The target model has yet to be defined.

As with gensets, while fuel cells are a definite plus in emissions, they compete with engines. In April, Pratt & Whitney won a US$3.8m ARPA-E award towards the development of HySIITE, a Hydrogen Steam Injected and Intercooled Turbine Engine, aimed at lower NOx emissions.

DRONES

Doosan Mobility Innovation (DMI) continues to grow its drone business, built on increased flight times over batteries. In January, DMI signed an MoU with 42air to provide fuel cell powered delivery drones. 42air has pioneered delivery to ships in the Mississippi River and envisages expanded operations beyond visual line of sight (BVLOS), to ships at anchorages around the Port of Los Angeles, and to oil platforms in the Gulf of Mexico. In March 2022, DMI received ₩27bn (US$21 M; 13% of the stock) investment from IDG Capital, Korea Investment Partners, and DS Asset Management, which will be invested mainly in developing logistics cargo drones with hydrogen fuel cell technology. In June, DMI signed a supply contract with Hover UAV, an Australian drone company, for use in shark detection and drone deliveries.

In December 2022, the Australian UAV manufacturer Carbonix said it will work with H3 Dynamics, the Horizon Fuel Cell subsidiary, to apply H3 Dynamics' in-nacelle systems to deliver BVLOS applications such as pipeline inspection or mining industry mapping drones. Other companies, such as Intelligent Energy, continue to sell growing numbers of fuel cells into drone markets, both fixed-wing and rotor-driven. In October 2022, Shell trialled an Intelligent Energy IE-SOAR 2.4 kW fuel cell power unit on a Harris Aerial H6 airframe for its pipeline inspection operations in the Northeastern United States, benchmarking the unit performance against a competing ICE hybrid.

SHIPMENTS BY FUEL CELL TYPE

PEM continues to outweigh other fuel cell types in shipments, both in volume and in MW capacity. Of the nearly 90,500 fuel cells shipped in 2022, over 55,000 were PEM (similar in number to last year, now at 61% of all shipments by number). By MW, PEM fuel cells recorded 2,151 MW, 86% of the overall volume of shipments, again a similar share to 2022.

Many of the PEM shipments relate (in number) to vehicle markets (cars, buses and trucks, mainly). By MW capacity, cars (led especially by South Korea), then trucks, and then buses (led by China) factor mainly into the numbers. Micro-CHP remains a significant contributor to the PEM fuel cell count, which, given the fall in shipments into Europe, looks like Japan may be the last man standing in any meaningful sense.

HT-PEM, generally utilising methanol rather than hydrogen as a fuel, continues to grow, led by Advent and its acquisition of both SerEnergy and UltraCell. While still a fraction of overall PEM units (in which we include this type of fuel cell) at present, the shipment numbers are set to grow more aggressively given the improved logistics and increased runtimes enabled by the methanol fuel. We are still waiting for Blue World Technologies to ramp up from plant building to fuel cell production. Its product launch is now expected early in 2023.

SOFC grew, from just over 25,000 units in 2021 to nearly 27,000 units in 2022. The MW count grew from 207 MW in 2021, to 249 MW in 2022. Much of this is attributable to stronger sales from Bloom Energy. As with last year, other potential suppliers, such as Ceres/Bosch continue to develop product, with few if any units fielded directly in the market. SOFC is gaining more interest as a prime mover for ships, so is expected to grow, but unlikely that will be quickly.

PAFC units actually fell in shipment terms, from an estimated 95 MW in 2021, to just 56 MW in 2022. Dominated by Doosan Fuel Cell's play in South Korea, issues like plant reliability, spark spread differentials and the slowness for policy to kick in have dogged sales. So too has SOFC as a competing technology, given the higher efficiency and the focus of Bloom Energy to secure an ever-higher share of the South Korean prime power market.

Doosan Fuel Cell's prospects may improve with the signing of a large-scale (105 MW) supply contract for its PAFC fuel cells to China's ZKRG, but this will only really kick in from 2024. Otherwise, Doosan's order book is bulging.

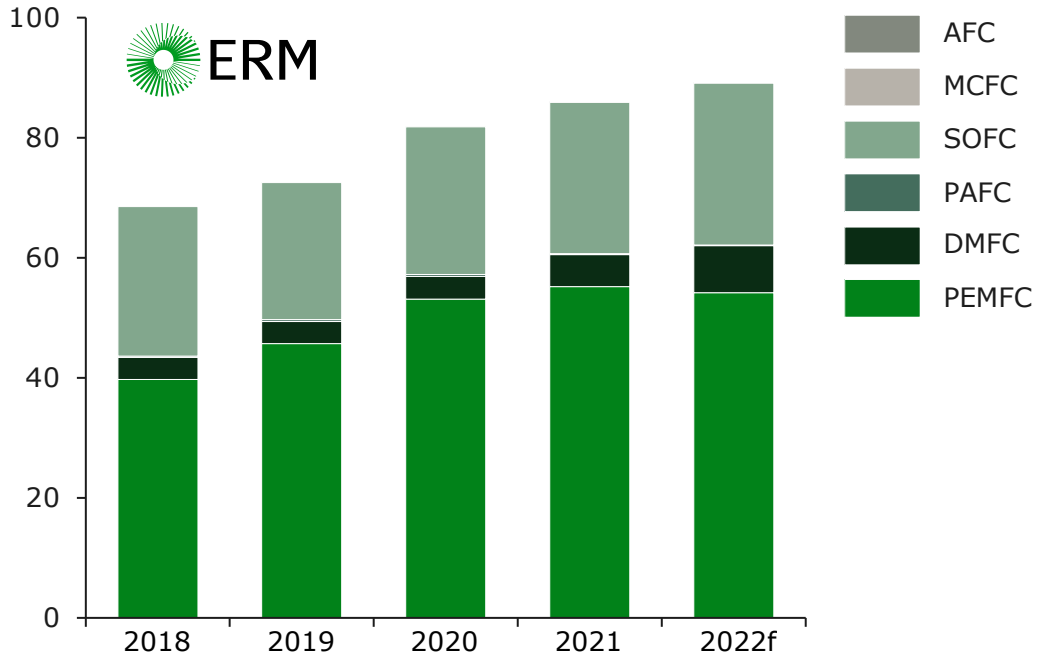
Both LNG (gasified) and hydrogen (white, sourced as an industrial by-product, and grey, with blue in sight) are used as fuels in Korea's fuel cell plants. The flexibility extends to the type of fuel cell stack, with MCFC also a contributor to the South Korean generating market.

Normally, we report only on new fuel cell shipments and excluding stack replacements. This year, for **MCFC**, we have had to make an exception. FuelCell Energy, the sole actor in this market (alongside its partner POSCO) posted no new shipments in 2022 (though it did get its 7.4 MW capacity uplift to the Groton, CT, submarine base in place – which we recorded in 2021). Consequently, for this year, we include in our overall figure of 2,492 MW global shipments a contribution of 37.4 MW for molten carbonate fuel cells, representing the annualised production capacity of the company over 2022.

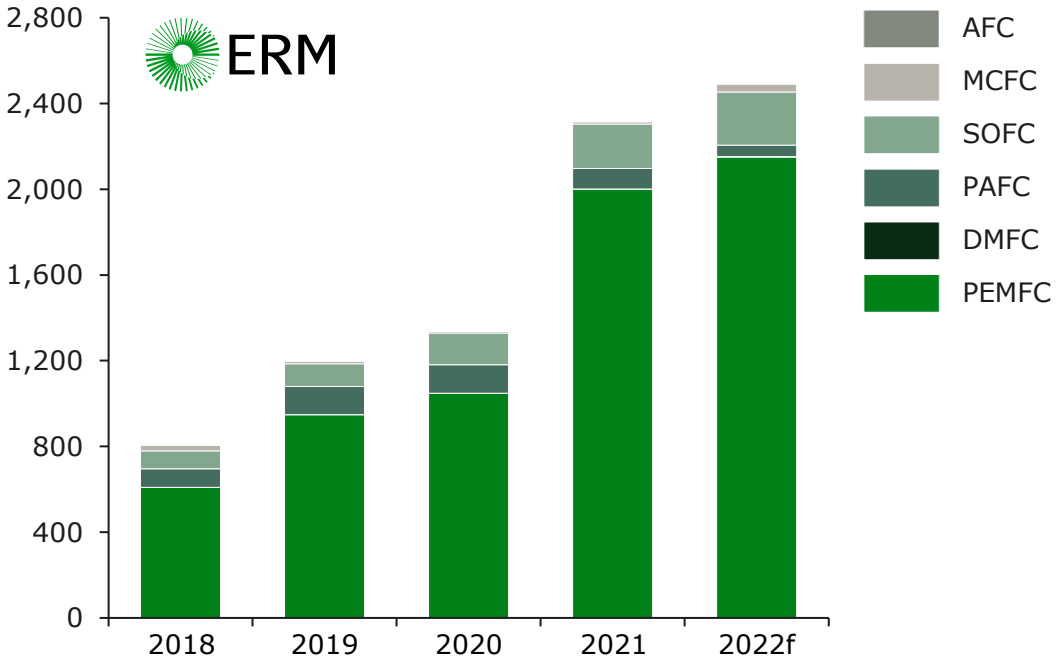
DMFC had a good year. From over 5,000 units in 2021, shipment numbers increased to nearly 8,000 units over 2022. Most of these are from SFC Energy, which continued its slow progress towards profitability, now with well over 60,000 units sold.

AFC continues its advance from near obscurity, with over 100 shipments globally through 2022. Most of these are from GenCell, mainly for remote telecoms backup to renewable energy ensembles. The company, AFC Energy, which began in 2006, has at last started to ship units to early adopters, believed to be less than 10 units sold over 2022.

Shipments by fuel cell type 2018 - 2022 (1,000 units)



Megawatts by fuel cell type 2018 - 2022



STATIONARY FUEL CELLS

The commercialisation of stationary fuel cells continues to be uneven, forging ahead in the US and Korea, yet hesitant in Europe and Japan. The themes this year are the continued lead of Bloom Energy and Doosan, their search for new markets (Bloom in Europe, Doosan in China); the embrace by integrators of H_2-fuelled PEMFC for temporary events, such as construction; a sustained focus on the potential of units for data centres; and the risk to micro-CHP in Europe.

JAPAN, LOSING MOMENTUM?

Japan has the world's largest fleet of stationary fuel cells with an estimate of 440,000 PEM and SOFC residential CHP units deployed in Japan's homes by 2022. The 2030 target of 5.3 million units will likely be missed, as was the 2021 target, despite consistent (though arguably insufficient) policy support since 2009. Subsidies, mainly discontinued, have been insufficient to push sales from the 10,000s to the target of 100,000s a year.

Despite missed targets, units of shipped Ene-Farm increased in 2022. But the enthusiasm of OEMs may wane as the potential of H_2-powered fuel cells gains traction in a world where natural gas fuel is not as secure as it once was. The main suppliers into the Japanese market are Panasonic (also selling to Viessmann in Europe), with PEM units, and Aisin, with SOFCs.

COMMERCIALISING HYDROGEN PEM SYSTEMS…

Both Panasonic and former supplier Toshiba have built on their Ene-Farm PEM units to develop larger systems with electrical outputs of several kW, together with operation on hydrogen.

Panasonic's 5 kW unit, dubbed the H2 KIBOU, can be combined in multiples to deliver higher powers. In the spring, 99 H2 KIBOU units, totalling 495 kW, were deployed with 570 kW of solar PV and 1.1 MW of lithium-ion batteries to provide power to Panasonic's Kusatsu fuel cell factory near Kyoto. The objective was to show a mix of systems can meet the demand of factories, even if the H_2 used is grey.

In autumn 2022, an agreement was signed with Environmental Clean Technologies of Australia to trial the H2 KIBOU at the Bacchus Marsh chemical and gases site near Melbourne, fuelled by H_2 produced on site.

Toshiba used its Ene-Farm experience to develop first a renewable ensemble concept with its small fuel cell, and then to upscale it into larger modular systems, H2Rex (fuel cell) and H2One (electrolyser combination).

The H2Rex uses hydrogen, usually trucked-in, to produce power at 50% efficiency. The grey H_2 isn't sustainable, but at least it is procurable. Several units have been installed at commercial and manufacturing sites across Japan over the past few years, including Toyota's Honsha plant at the end of 2021, and (in July 2022) at the HQ of the U Group Company, in Ningano City.

The H2One ensemble has proven to be popular, with a range of end users including the Port of Yokohama, which had installed a system for emergency power backup and, more recently, in July 2022 at Tokyo Metropolitan University as part of a renewable ensemble to extend time horizons.

The H2One may also be configured as an H_2 generator for refuelling fuel cell vehicles. As with many of the Japanese innovations, there does not appear to be a rush for product anytime soon, however.

Toyota is now making a serious stationary play, in 2021 announcing it intended to offer its Mirai module into applications with powers of 8-24 kW and up to 80 kW. Its biggest success has been its collaboration with EODev, which is actively developing – and selling – bespoke units to the construction and marine industries, at ever-large power outputs and increasing product volumes.

In August, Toyota itself announced it would deliver a 1 MW fuel cell, with a build based on multiple Mirai modules, to the Flatirons, Colorado based ARIES (Advanced Research on Integrated Energy Systems) project, in a three-year DOE-funded collaboration with NREL.

Separately, Toyota is performing R&D in both PEM and solid oxide electrolysis, committing itself to the developing H_2 society. For hydrogen, the message is mixed; it is undoubtedly green but is costly and not yet available easily. As renewables grow, and the need for bulk energy storage grows, this will likely change. But this will take time some years.

…BUT NEAR THE END OF THE ROAD FOR NATURAL GAS?

Japan has long supported development of natural gas fuelled stationary units for commercial premises but few if any have translated into significant shipments. Japan's IPHE submission notes only of 10 commercial-scale SOFC systems installed at mid-2022, with no update since.

Fuji Electric is one of Japan's oldest fuel cell actors, with its FP100i, a 100 kW PAFC. The electrical efficiency when using natural gas is 42% (and 48% with H_2, still higher in CHP mode). A respectable 60,000-hour stack life is reported. But sales are few, even in Japan.

The largest stationary fuel cell system available in Japan is from Mitsubishi Hitachi, with its 250 kW MEGAMIE hybrid pressurised SOFC/microturbine. When operating on natural gas, MEGAMIE has an electrical efficiency of 53% (70% in CHP mode). Sales have been slow, mostly to supply chain partners, such as Toyota, from which MHI sources its microturbine. The last reported demonstrator went to the Gas- und Wärme-Insitut in Essen, which began operating in June.

A take home from Japan is that even when mature systems are available, with good metrics, using a relatively affordable infrastructure fuel, fuel cells struggle to make headway.

SOUTH KOREA, FULL SPEED AHEAD?

For many years now, South Korea has been one of the best places in the world to do business for a stationary fuel cell OEM. A government with an eye to economic development, focused on realising lower carbon emissions, has worked actively with domestic conglomerates to create a viable market. South Korea also has a concentration of heavy industry, with high energy demands and a surfeit of waste hydrogen from its industry.

According to the Korea Power Exchange, 859 MW of capacity of mostly industrial fuel cells systems were reported to be installed throughout South Korea, the largest volume in the world by far. South Korea also has the largest fuel cell facilities, exemplified by Incheon's 79 MW installation at the Shinincheon Bitdream HQ, in December 2021.

Strong growth over the past five plus years has been driven by the Renewable Portfolio Standard (RPS) imposed by the Government on Korea's energy generators, which includes support for fuel cells. Policies have also promoted on-site generation for larger building developments, and the mandatory use of distributed energy systems where appropriate.

South Korea's Hydrogen Economy Law of June 2022 set out a raft of measures and targets that specifically aim to stimulate development of the country's hydrogen economy. The Act targets generation of 2.1% of the country's power needs from clean H_2 by 2030 and 7.1% by 2035. The RPS for fuel cells will be replaced by a Clean Hydrogen Portfolio Standard, with details due to be published in 2023. The country's Hydrogen Road Map targets a domestic base of 8 GW stationary fuel cell capacity by 2040, exports of a further 7 GW, plus 2.1 GW for building CHP systems. CHPS aims to propel Korea into a major fuel cell exporter, much like China's plans.

Two of the world's largest stationary fuel cell OEMs are based in South Korea: Doosan Fuel Cell (spun out of Doosan Corp. in 2019) and Bloom SK Fuel Cell, a JV of SK Group. FuelCell Energy (FCE) is also a major actor, albeit experiencing a hiccup as it fell out with its partner POSCO.

Doosan offers the PureCell Model 400, a 440 kW PAFC unit with an electrical efficiency at 42% using natural gas (higher using H_2, and 90% in CHP mode). After buying the technology from ClearEdge in 2014, unit costs had reportedly fallen by 48% by 2019. Together with the 10-year stack life, and its early availability, the PureCell is popular, leading Doosan to have around 59% of the installed base of industrial-scale fuel cells in South Korea. Orders in 2022 were 168 MW (vs. 131 in 2021), and a stepping stone to the target of 248 MW for 2023. While the order pipeline impressive, it takes time for orders to convert to sales, and there was a drop in shipments in 2022. Delays to the CHPS and increasing competition from Bloom Energy played a part. Next year, the shipments are expected to improve in line with order placements.

The majority of Doosan's PureCell systems appear are now sold as part of PPA deals (like FCE's business model). In 2022, Doosan announced intended orders for 20 MW of PAFCs at South Gyeonsang Province as part of a Future Food, Fuel Cell and Energy facility, that uses the cold from vaporising LNG to freeze food, and 15 MW of H_2-fuelled units for a facility in Yecheon.

Doosan has long harboured ambitions to become the Hydrogen Energy Global Number One player, seeking to export the PureCell to Asia and further afield, to reach higher volume. In autumn 2021, Doosan announced the sale of a few units to a Chinese property development, but 2022 saw Doosan step up several gears. A 4.8 MW order for H_2-fuelled PureCell units for Zhejiang was announced in April, followed in November by a deal with ZKRG of Guandong to set up a venture for supply into China. An initial 50 MW of units will be supplied from South Korea, followed by components for another 55 MW to be assembled at a facility at Foshan.

Volume is needed to reduce PAFC supply costs. Doosan increased the capacity of its Iksan facility to 275 MW per year in 2022. Higher efficiency SOFCs offer another pathway to profit. By 2023 Doosan expects to open its 50 MW SOFC factory at Gunsan Saemangeum Industrial Complex, following the agreement with Ceres to licence and produce SteelCell modules for marine and stationary markets. A soft launch of a 10 kW SOFC module took place this year.

Doosan's main competitor in the Korean Market is Bloom SK Fuel Cell. The JV is reported to have sold 381 MW of Servers into Korea in the five years to 2022. These were originally sourced from the USA, but in 2021 the JV started manufacturing units at its 50 MW capacity Gumi factory.

In 2022, completed Bloom installations included 15 MW at Iksan for Korea Western Power, 19.8 MW at Daewon, and the RE 100 Energy Infrastructure system at Changwon-Si, comprising 1.8 MW of H_2-fuelled Energy Servers coupled with H_2 storage and vehicle refuelling.

Meanwhile, POSCO, with MCFC stacks licenced from FCE, and once the leading stationary OEM in Korea, has faded from the picture. Late in 2021, an agreement was struck with FCE enabling existing systems to be supported, but the POSCO's Korean stack production plant is moribund. The agreement anticipates FCE developing new prospects for its technology in Korea, separate to POSCO. In May 2022, POSCO signed up with Korea Electric Power Corporation to cooperate on H_2 supply and relevant technologies. A month later, KEPCO emerged as FCE's new partner in South Korea, with plans to build a 50 MW powerplant at an Iksan industrial complex. A KEPCO subsidiary, Eugene Fuel Cell Power, has been set up to manage delivery. Waste heat from the plant will be used for industrial needs, with electricity supplying 150,000 households.

Korea's ambitions continue to encompass residential fuel cells. The main actors are S-Fuelcell and the Fuel Cell Business Unit of Doosan Corp., which retained the business when the PAFC side was split off. As well as its Cellville PEM systems, the Business Unit was used for the soft launch of a 10 kW commercial SOFC developed with Ceres. Despite the synergies, as a much smaller business, (with less potential), in June 2022, Doosan Corp. said it was looking for a buyer for its residential fuel cell business. S-Fuelcell has long marketed its PEM range, with powers of 1-50 kW, and acts as an agent in South Korea of Fuji Electric for its 100 kW PAFC. The third actor at the lower power end is Bumhan, leveraging its agreement with Sweden's PowerCell to distribute PEM systems into stationary markets in South Korea. Between the three actors, just less than a thousand small fuel cell systems are sold into the country each year.

NORTH AMERICA, NO LONGER FIRST

In 2020, North America – more particularly the US – lost its number one spot in the size of its stationary fleet. Since then, Korea has surged ahead. The IPHE summary indicates 550 MW large stationary units to be active in the US by the end of 2022, 289 MW rated at a MW or less, for distributed generation rather than utility-scale (which is increasingly the driver in Korea). A further 131 MW capacity has been approved across the US, yet to be installed or operational.

The US benefitted from its first mover status for PAFC, MCFC and SOFC systems. In recent years, Bloom has provided the biggest expansions of the stationary fleet, with slowing MCFC and PAFC installations. Stationary PEM systems have yet to take-off. The Inflation Reduction Act of August 2022 includes provision a for a mixture of billions of dollars of incentives and credits for all things H_2-related but is double-edged. The 30% ITC will remain in place to 2024, and then replaced by a technology-neutral Clean Energy Investment Credit. This is pushing developers to add H_2-fuelling to their fuel cell systems and to deliver electrolysis capability.

HARD GOING FOR SOME IN CONNECTICUT….

Connecticut has been a solid supporter of its two OEMs, FCE in Danbury and HyAxiom located in South Windsor. The State is one of the few places that class natural gas fuelled systems as renewable, on a par with wind and PV. It is ironic, then, that FCE and HyAxiom have struggled in recent years, whilst out of state Bloom has succeeded in increasing its market share. Of the 183 MW installed and approved capacity to 2022 across Connecticut, Bloom secured 81 MW of SOFC Energy Server orders, against 87 MW of FCE units and HyAxiom's 15 MW PAFC units.

FCE's revenues for the fiscal year were US$130.5m, an 88% y/y increase. FCE now generates most of its revenue from PPAs. But 2022 saw improved sales arising from the delivery of 20 replacement modules to Korea Fuel Cell, the former POSCO subsidiary. Most of the 37.4 MW annualised production at FCE's Torrington plant is now dedicated to stack refurbishments.

FCE's 7.4 MW slow installation at the US Navy base at Groton, CT, finally started operation in December 2022, but at a reduced output of 6 MW. The 2.8 MW tri-generation unit, Hydrogen, Water, and Energy at Toyota's Long Beach, CA, is now expected to be operational by July 2023. The Derby, CT, 14 MW installation is expected to be operational by the end of 2023.

FCE and ExxonMobil, continues to push carbonate technology into greening otherwise quite dirty operations. In February, FCE won US$6.8m from Canada's Clean Resource Innovation Network competition. A MW-scale carbonate plant will capture carbon from a process heater at the Scotford Upgrader, owned by the Athabasca Oil Sands Project, near Edmonton, Alberta.

But for a truly green play, FCE announced availability of a solid oxide product from December. Trinity College in Hartford, an existing SureSource customer, was the first to receive a 250 kW SOFC at the end of 2022. The unit has a 66-67% electrical efficiency (higher than Bloom). The SOFC stack plant in Calgary is being expanded to provide an annualised production of 40 MW, with a 400 MW capacity facility opined in the US at some date in the future. The same platform is configurable for electrolysis mode, and even as a reversible system, an advance on most competing systems. The company stated it is now "accepting orders" for the technology, though by the end of the year, a specification for the electrolyser had yet to be made available.

HyAxiom's latest system to start operation was at the University of Connecticut, in August. But HyAxiom is involved in more diverse tie-ups with Doosan Korea and others for future projects, notably signing up with Ballard in April 2022 to pursue mobility related fuel cell applications.

.. WHILST THE SUN SHINES IN CALIFORNIA

Since going public in 2018, Bloom has gone from strength to strength, achieving US$1bn in revenues in 2022. A total of 1 GW of installations now operate over 1,000 locations, across six countries. Shipments over 2022 amounted to 228 MW, up by 22% y/y. By the end of 2022, Bloom claimed 80% of the US market in large stationary fuel cells, and 80% of Korean market. However, as with FCE, each fuel cell system sold incurs a loss. Bloom went back to the markets for another US$388m in August 2022, and makes extensive use of project financing to fund customer product purchases and to prime power purchase agreements. It is heavily reliant upon two businesses (including the JV with SK Ecoplant) for as much as 75% of its SOFC sales.

Bloom Energy sells systems upwards of 150 kW, built on multiples of its standard 50 kW power module. The Servers can operate reliably on natural gas, biogas, or H_2. In December, Bloom facilitated an optional CHP mode to its Servers. While overall 90% efficient, the electrical efficiency drops from 60% to 54% when operated in this mode. The largest Energy Servers supplied are to South Korea, units sold into the US generally being much smaller in power output. In May, Bloom reported an agreement to supply 1.5 MW of Energy Servers for Fayetteville Public works waste treatment plant utilising multiple bio-gas streams. In September, Bloom won an order from Taylor Farms, for 6 MW of Servers for a micro-grid, including 2 MW of Solar PV and 2 MW/4MWhr of batteries to allow the business to move off-grid, save costs and improve reliability. These are just a couple examples of many installations.

Dominant in the US and South Korea, Bloom is now targeting more countries. As an early indicator, Bloom received an order for 1 MW of Energy Servers for Ferrari's manufacturing plant and headquarters in Italy, in July 2022, and an order for multi-MW of systems in November 2022, to be delivered by 2025 from Cefla, an engineering company in Italy that sells co-generation systems.

PEM GAINING TRACTION IN STATIONARY MARKETS

PAFC, MCFC and SOFC fuel cells are largely suited to stationary applications using natural gas, while PEM fuel cells operate best on H_2, have high power density, and are more flexible in end use. North America has always had globally significant PEM OEMs: Ballard of Canada, Plug and Accelera (the Cummins brand name for the former Hydrogenics business). While each has long offered stationary plays, to now these been second place to mobility. But this is changing, with stationary now a part of longer-term strategies. Moreover, vehicle OEMs are seeing scale-out potential in selling their auto modules to stationary packagers. And, as green H_2 rises on the agenda, so too does the prospect of lower-cost, more ubiquitous H_2. This potential is helping the growth of H_2 PEMFC in ported units up to 100 kW and containerised units above that.

Ballard's containerised MW-scale ClearGen II product is based on its FCgen-LCS H_2 stack technology, originally designed for heavy duty motive. This is being sold to HDF Energy for use in microgrids in French overseas territories. Plug Power's GenSure high-power H_2 PEM product suite is based on arrays of 125 kW ProGen modules and designed for scalability, up to 1 MW. Its new production facility at Slingerlands in New York State opened in December. Accelera is targeting 1 MW-scale stationary but with no specific news or detailed specification as yet. Nuvera (Hyster-Yale) is developing its H_2-fuelled G-Series of 360 kW and 470 kW generators, a modular platform targeting microgrids, data centres, backup power and electric vehicles.

FOR EUROPE, CLOUDS GATHER OVER MICRO-CHP

Europe has not lacked technical capability or enthusiasm for stationary fuel cell systems. But the deployment has never reached the scale of Japan's Ene-Farm programme for micro-CHP, or the size of the commercial and utility programmes in the US and South Korea. This reflects a raft of issues, from high grid reliability, weaker, less consistent, policy and financial support compared to South Korea, to the small size of many developers, lacking the cash available to established OEMs making profit.

Over its lifetime, PACE deployed 2,601 micro-CHP units, from five European manufacturers across ten countries. KfW-433 supported the installation of 20,814 units of 750 W to 4.2 kW (more than the target of 15,000 units) across Germany from a mix of grants and tariffs, at €28,800 (US$30,500) a unit. Most of the units fielded came from Viessman. None of the micro-CHP units have reached true profitability, able to sell without subsidy.

European stationary deployments are now at a crossroads. By the end of 2022, the two main programmes supporting smaller stationary fuel cell deployments closed, in a region no longer awash with gas, and with no direct follow-on to the PACE and KfW-433 programmes. From 2023, the German Federal Fund for Efficient Buildings will only support fully green systems, operating on biofuels or on green H_2, which will have minimal penetration in residential markets. The tax reductions of up to 20% for these are unlikely to shift the dial. What all this means for Viessmann's micro-CHP business going forwards, and for its competitors, is unclear.

On a positive front, the EU has established a raft of measures in response to global warming, the US Inflation Reduction Act, and the Russian invasion of Ukraine, that directly or indirectly blend to create a more supportive environment to fuel cells. These include the Fit-for-55 initiative, the RePowerEU plan and its Connecting Europe facility, and the IPCEI initiative, which is facilitating Member State investment directly into competitive fuel cell companies across Europe. Moreover, these policy measures are shifting towards hydrogen as a fuel rather than natural gas.

Hydrogen, for all its drawbacks (and benefits) is though, slowly, becoming more acceptable to consumers. Home Power Solutions (HPS) of Germany is now selling around 200 of its Picea (1.5 kW) systems a year, and the sales rate is growing. Picea is a self-contained system pitched at remote residential and small business power needs, with a built-in electrolyser and compressor (to facilitate refilling of the H_2 storage cylinders), coupled to a PV array. Picea smooths diurnal and longer periods of renewable unavailability to give reliable and uninterrupted power, a growing theme, pioneered by Toshiba and GKN Hydrogen.

When daisy-chained into a Multi-Picea system, higher powers and longer periods of autonomy can be facilitated, particularly when bundled with PV and battery storage. In October, HPS inaugurated its first Multi-Picea, a 9-unit system, at a site in Bad Kissingen, Bavaria.

Over in China, there is less activity in stationary, the focus being on mobility. But this does not mean stationary is altogether neglected. An example is the CarNeu series of CHP systems, of Jiangsu HuaDe Hydrogen Energy, rated between 5-500 kW in output, intended for use mainly where by-product (white) H_2 is available. In July 2022, Hydrogen Energy Era (HEE), domiciled in Guizhou Province, launched its H_2-fuelled CH2p-100 (100 kW) demonstrator in Germany.

LARGER SYSTEMS ARE AGAIN RISING ON THE AGENDA

For many years in Europe, interest in large-scale units has been limited, with few deployments. This is changing, Germany's Bosch making a strategic investment in SOFCs (and Ceres stacks), and Rolls Royce Power Systems business, using cellcentric PEM modules for data centres.

Bosch is developing SOFC systems for use in cities, factories, data centres, and as a power supply to EV charge points. Multiple modules of 10 kW can be deployed in arrays to deliver up to 100 kW power at 60% efficiency. The activity is supported by 700 staff and a €500m investment to the end of 2024, by which time a 200 MW capacity will be established, marking the start of series production.

As an integrator, Bosch brings its system and balance of plant capabilities and market access. Over the past two years the business has installed over fifty modules, across ten sites, mainly at Bosch factories.

The SOFC system work at Bosch complements its work with PowerCell on PEM units for trucks. In a further sign of its realignment to the H_2 economy, in May 2022, Bosch allocated a further €500m to the end of the decade, to apply its expertise to PEM electrolyser components.

Rolls Royce has been rather quieter about its fuel cell development, which again targets data centres, displaying its first demonstrator unit in 2022. A field test is expected for 2023.

DATA CENTRES ARE OF PARTICULAR INTEREST

In December 2022, ground was broken at the New Britain Data and Fuel Cell Project, in Hartford, CT, with US$55m in tax breaks. Originally, HyAxiom PureCell units were to be used. But Phase 1 will now deploy 19.8 MW of Bloom Energy Servers. In August 2022, Bloom SK Fuel Cell won an order from GDS, China's largest data centre operator, to supply systems for centres in China. In September 2022, Bharti Airtel announced that its subsidiary Nxtra Data has partnered with Bloom Energy to deploy fuel cells at its data centre in Karnataka, a first for Inda. Bloom's Always On (24/7) model, with high reliability, fits the prime power model. And natural gas has been for years relatively low cost and accessible, geopolitics aside.

At the other extreme, fuel cells can be used for backup, rather than prime power, which is especially relevant where H_2 is to be used as the fuel. Large data centres consume several MW of power, so a backup mode, with less H_2, reduces storage and supply logistics. But this means the fuel cell may hardly be used – a difficult payback argument. In September, NorthC, the largest regional data centre company in the Netherlands, opened its Groningen data centre, equipped with a Nedstack 700 kW PemGen, fuelled by green H_2 stored for backup duties.

OUTSIDE BLOOM, SOLID OXIDE STRUGGLES FOR SCALE

Europe has several specialist SOFC cell and stack developers that have built a business around selling stacks or power modules, exemplified by Elcogen, or by licensing IP to channel partners, as with Ceres. Given the time and cost to develop large systems, where until now customers have been few, many of the actors that started with kW scale systems have only begun to transition to much larger platforms over the last 2-3 years.

Elcogen has two stacks, the E1000 (1 kW) and E3000 (3 kW). The business also supplies cells to 60 customers, and larger stacks to integrators, like Convion. In January 2022, Elcogen announced a supply contract from WattAnyWhere of Switzerland to power a charging station demonstrator for battery electric vehicles. Also in January, Elcogen signed an MoU to provide a 200 MW electrolyser cell and stack factory in Uljin-County, South Korea. In May 2022, Elcogen won a €24m investment from the HydrogenOne Capital Growth fund to expand its play in the production of green H_2 using its reversible solid oxide cell technology.

In 2022, Convion announced the installation of two C60 units, one running on biogas, and another in China as part of a micro-grid development. In the COMSOS project, funded by the Clean Hydrogen JU, business cases have been developed, including 50-60 kW SOFC based systems, running off biogas at wastewater plants.

Ceres continues to progress its 10 kW SOFC stack through its partners Bosch, Doosan and Weichai. Doosan expects to open its 50 MW capacity SOFC plant in Saemangeum, South Korea in 2024, for marine, power and utility-scale applications. Ceres's JVs in China are running slow, with 120 kW power systems with partner Weichai now progressing through testing and certification. As with other solid oxide actors, electrolysis continues to rise on Ceres agenda, targeting MW-scale systems.

SolydEra is a participant in the Eco Edge Prime Power project, focused on power for data centres, with €2.5m Clean Hydrogen JU funding. SolydEra is also a participant in COMSOS as the project heads to its conclusion in 2023. 15 units of 12 kW each were to be tested. These small power units are a world away from the multi-MW power needs of most data centres, implying use as distributed nodes.

WHILE PEM CONTINUES TO GROW

Sometimes, things just take time. Helion, now owned by Alstom, launched its SYSPAC stationary line way back in 2005. H_2-fuelled, aimed as a 20 kW diesel genset substitute, the unit was demonstrated for backup at a data centre in 2012. Now in 2022, with the impacts of climate change being yet more evident, and with more policy support for H_2, perhaps the time has come, with a re-launch of its modular FC-Rack system, from 160 kW and scalable to 2 MW, for stationary and marine.

From its inception, PowerCell has supplied units for stationary as well as mobility, establishing the PowerCellution brand for MW-scale power in 2021. The market isn't huge for MW-scale systems yet. Revenues across its range (including mobility) grew from SEK 160m (US$15.3m) in 2021, to SEK 245m (US$23.4m) in 2022, with an SEK 58m (US$5.5m) net loss. In May, an order was made by Kaizen Clean Energy of the US for a PowerCellution Power Generation 200 module (rated at 200 kW), housed in an ISO container, and fuelled by methanol. The unit will be used to create a mobile microgrid for EV charging, H_2 fuelling and critical backup power.

Proton Motor offers its PM400 module, with up to 75 kW output, 52% electrically efficient when run on H_2 fuel. Its HyScale product supports pooling to MW-scale. In October, Proton expanded its production facility to meet increased orders across its portfolio. Also in October, TECO 2030 gained an order from the infrastructure contractor Implenia for two FCM400 modules (800 kW in all), as part of the HydroPilot project, funded by ENOVA in Norway. TECO is being supported by AVL as a development partner, with MEA for the modules supplied by SinoHyKey. Housed in a 20ft ISO container, the generator will power equipment on an Implenia construction site. In December 2022, TECO 2030 produced its first stack at AVL's premises in Vancouver, Canada.

THE SWEET SPOT FOR PEM SYSTEMS

Much activity is taking place at the 50-150 kW range. The accessible market in this range is over 4,000 semi-stationary units pa across Europe, for short-term events, outdoor markets, roadworks and construction. Some units are wheeled, others require a hoist or crane for lifting.

The packagers help the OEMs to reach volume and indigenise the systems to the specific market need. The list of fuel cell OEMs offering modules is now long: Cummins, GM (with its HYDROTEC Power Cube), Honda (testing a prototype at its campus in Torrance, California), Hyundai (with its 85 kW HTWO module), and Toyota (also with 80 kW modules).

The integrators include EODev (using Toyota modules), GeoPura (Ballard), H2SYS (Ballard, in THYTAN 50 and 150 systems), PowiDian (Ballard, in M30 and M110 systems), and zepp (EKPO stacks, in Y50 and X150 systems). Companies like H2 Generators in the UK now sell packaged units from multiple suppliers. The units all use H_2 fuel. All the integrators are European. For all its worth, the US IRA is limited in its support for stationary fuel cell plays. We expect sales of the larger units to increase, influenced by H_2 pricing. The integrators have not been slow to see the need for a green H_2 supply. In November, PowiDian indicated it would deliver a 100 kW fuel cell, two storage tanks carrying 100 kg H_2, and an EL20N electrolyser from H2B2, with a PV array, to a hospital in Elst (Netherlands), providing 60% of the hospital's energy needs.

CRITICAL INFRASTRUCTURE BACK-UP AND OFF-GRID POWER

Beyond 'traditional' grid-connected units and the larger stationary units, there is an ongoing play for smaller fuel cells for off-grid and micro-grid markets at fixed sites. These markets have been tested with enthusiasm and little real success for at least two decades, fuel cells long being fielded in telecoms towers, remote health centres, buildings in environmentally sensitive areas and construction sites. With diesel perceived as polluting and inefficient, the push by fuel cell companies into these markets is getting a little easier. But not by much.

Intelligent Energy had ambition for the India telecom BTS market, with a near death outcome. Happily, its IE-POWER series is finding new niches now, as part of a PV based micro-grid alongside an electrolyser, powering a small hospital in Namatanai, Papua New Guinea. A similar grid exists in Thailand. PowiDian also uses Intelligent Energy stacks in its low power products.

CHEM Energy of Taiwan has had more success, with its methanol LT-PEM systems, using Ballard (originally IdaTech) technology. Its 2.5 and 5 kW systems provide back-up to towers across South Africa. CHEM's G5 system is now manufactured in Durban, South Africa, a sign of the proliferation of fuel cells beyond Europe, the US and Asia.

Ballard has a long history of supplying off-grid, especially back-up power for critical infrastructure. Its FCgen-H2PM series provides power from 1.7 to 10 kW, fuelled by H_2. The sector sees a reliable, if small, source of sales for Ballard, with over 400 units under extended warranty service contracts. Helion also seeks to exploit its small fuel cells for telecoms backup.

Plug provides off-grid and back-up markets with its GenSure Low Power (LP) series of systems. Three variants provide powers between 200 W and 10 kW, again H_2-fuelled. Installed across the world, the installed base exceeds that of Ballard, with units added each year.

Altergy of California for many years marketed its Freedom Power series of fuel cell systems of 1-5 kW, operating on H_2, for off-grid applications. In August 2022, Phoenix Motor, an electric vehicle business, bought Altergy's assets, a sad end to a pioneer of automated stack assembly.

In December 2021, Toshiba ESS announced it had established an agreement with Shandong Energy Group to manufacture and supply TESS systems for stationary uses in China. Also in December 2021, TESS revealed it had formed a partnership with More Hydrogen Energy Technology, of Guangzhou, China, in 2019, and had provided technical support to two 5 kW reformed methanol fuel cell systems, used in mobile towers. Toshiba also signed an MoU to start a discussion on a potential partnership to use the systems on boats and trains.

Blue World Technologies began series production of its HT-PEM based units in December 2022, but we are still waiting for these to be translated into systems. The wait may not be long.

ALKALINE FUEL CELLS EMERGING

Cleantech Power, formerly Alkaline Fuel Cell Power, of Canada, is reported to be developing two off-grid products, rated at 4- and 10 kW, with demonstrations set for 2024 and 2025. A micro-CHP unit is also reported to be available. AFC Energy of the UK continues to develop and market its product, but with shipments limited presently to single demonstrator units.

Israel's GenCell has been rather more successful, with over 100 placements at BTS and other sites over the year (remarkable such a young company). Available up to 5 kW, these can operate on H_2 or ammonia (with a cracker in place).

REMOTE, PORTABLE AND MILITARY OPTIONS

While we report on hand-carried portable shipments, we also include ported units up to 20 kW in the same category. Originally, the units were mostly truly portable, but increasingly the line is being blurred, with even the smallest of units left in place for days to years. In terms of new product releases, portable has been outpaced this year by remote power sources from a few kW to as much as a MW. These range from static backup systems to mobile telecoms, to short term semi-stationary power for events, outdoor markets, roadworks and construction sites.

SFC Energy through its DMFC range continues to dominate the portable fuel cell market having produced over 60,000 units over the last 23 years. While some units continue to be sold to camping enthusiasts (the COMFORT series), many are now pitched at off-grid and grid backup needs (the Pro series). In March 2022, SFC reported a 300-unit order from LiveView Technologies, a mobile surveillance provider in the US, then in May a further 300, followed by a US$15m order for a yet another 2,300 units in late 2022 – the largest single order in SFC's history.

In August, the company announced a further order from Oneberry Technologies, at the opening of the surveillance company's new HQ in Singapore. As a long-time partner of SFC, Oneberry Technologies has purchased more than 1,800 EFOY fuel cells to date for use in numerous applications such as flood early warning systems, high-rise waste disposal, ad-hoc and mobile monitoring.

In August, Edge Autonomy acquired Adaptive Energy (previously Adaptive Materials Inc.) – a developer and manufacturer of SOFCs for UAVs, backup, and off grid power. Edge Autonomy had previously used Adaptive Energy's fuel cells for its own range of UAVs for over ten years. Edge Autonomy aims to further Adaptive Energy's research to extend the duration and improve the performance of fuel cell-powered UAVs. Redhawk Energy continues to actively push Edge's P250i SOFC units into a range of applications, from trackside rail, to oil and gas, telecoms and other critical infrastructure, buoyed by the low cost and easy logistics of propane fuel. Over 2,000 Edge units have been deployed to date over all uses, with annual sales in the hundreds.

In early 2022, the Japanese start-up, Scitem, announced it was to launch a 30 W portable hydrogen generator the size of a briefcase for emergency energy supplies. This is one of the few new units at this scale of power output for many years and overlaps with SFC's DMFC range. It seems more a demonstrator than a product.

The generator builds on Scitem's existing business of producing canisters for hydrogen research. Scitem states a system price of about JP¥500,000 (US$4,400) at mass production. The company plans to market generators with varying electrical outputs based on the orders.

In February, the fund HydrogenOne Capital Growth invested £10m in Bramble Energy as part of a Series B round. Bramble intends to use the cash injection to roll-out its portable, printed circuit board PEMFC products, and to certify its mobility products for key sectors. Bramble's stacks are now being fitted into portable power units, with a claimed run time of up to 30 days.

The portable H_2 fuel cell maker, PowerUP, has continued to develop partnerships in its home country. In June, it partnered with the Estonian branch of Telia, the telecoms giant, to explore alternatives to diesel gensets for backup power. An initial test focused on 2 kW generators (2x UP1K units, and 2x 9-litre H_2 cylinders) to cover a 2-hour backup period, with a view to roll out to all its telecoms towers. This has potential to lift sales from tens to hundreds a year. Later in the year, PowerUP partnered with the Greek technology developer, Meraki Green Development, for the deployment of systems to decarbonise the energy and hospitality sectors. PowerUP intends to begin scaling up to 6-, 12- and 24 kW liquid-cooled systems by the end of 2025.

Over 2022, Intelligent Energy rebranded its IE-LIFT series as the IE-POWER range. At up to 4 kW output, the fuel cells are aimed at telecoms, micro-grids, APUs and critical infrastructure. IE has long sold small fuel cells for drones, but in October 2022, it won a 10 MW order from its distribution partner Hogreen Air to supply 100x 100 kW output IE-DRIVE HD units for larger drones, for mobility and for medium-sized gensets in South Korea and Southeast Asia. In October, the Japanese materials developer Teijin said it will trial a portable generator powered by an IE-Lift fuel cell at the Shibuya Station redevelopment in Tokyo. Trials are set for 2023.

PORTED SYSTEMS ARE BECOMING MORE COMMON

2022 saw a big increase in shipments of larger packaged fuel cell gensets for remote power, with offerings from EODev and others. Even the smallest units are sometimes integrated into trailers for ease of deployment (as with the Eco-H2 generators and Ecolite-GH2 mobile lighting systems of Taylor Construction Plant). Larger, heavier, units often have lifting rings for ease of porting and require a crane. Units marketed as clean H_2 semi-stationary power sources are positioned for hours to weeks of supply, rarely longer. These really need a low-cost green H_2 supply to be viable. This, together with the awkward logistics of H_2 supply (needed in volume for the higher power units), mean most of the units are going to enthusiastic early adopters.

In April, SFC joined with Test-Fuchs from Austria and Auto AG from Switzerland to develop a mobile generator using H_2 fuel, aiming for a prototype of its H_2Genset by H1 2022. The product is aimed at outdoor festivals and construction sites up to 100 kW. By July, a 5 kW prototype was used to power a Red Bull booth at the Formula 1 Grand Prix, in Austria. By September, pre-series units at up to 25 kW were available.

In January, General Motors said it would apply its automotive fuel cell technology to stationary generators. GM is planning multiple generators, built on GM's Generation 2 HYDROTEC fuel cell power cubes, including a mobile unit to fast charge EVs, and a palletised to quietly and power military camps. GM joins Toyota and Hyundai in gearing its automotive modules to generators.

EODev had a good year. LOXAM, the European rental company, took delivery of a GEH2 unit in January. The GEH2 provided continuity of supply to 16 homes during a planned grid outage up to June. Lower fine particles and noise were seen as key benefits. In July, a GEH2 was used to power a portable 5G BTS, to increase bandwidth and signal reliability, to Bouygues Telecom at a horse racing event at Longchamp, Paris. Over 2022, distributor agreements were made with Generac and United Rentals (US), Kennards (Australia), and Nilsson Energy (Scandinavia).

EODev's 80 kW GEH2 can be daisy-chained for higher powers, but in December, EODev committed to develop bespoke generators from 10 to 1,750 kVA output. The 10 kVA "Mini GEH2" model targets telecoms and grid support and was used to charge BEVs back in August. The 350 kVA model will come in a 20 ft ISO container, and the 1,050 kVA in a 40 ft ISO container. These target energy security for a wide range of commercial applications. Customer demand for the 350 kVA unit is said to be strong, with production set for 2024. Development of 280-1,400 kW models for the marine industry, based on the REXH2, is also underway.

MILITARY – MULTIPLE SMALL-SCALE DEPLOYMENTS

Military orders tend to be sporadic, some years with large shipments and others with none. DMFCs and SOFCs at less than 3 kW are the only technologies mature enough to attract sales at present. SFC leads this market with their Jenny (up to 50 W power) and the Emily 3000 charger (rated 125 W, consuming 3,000 Wh per day). SFC's results for defence are now rolled into the Clean Energy segment and no longer reported separately. But across all suppliers, sales are modest, with single orders of tens of units. Significant sales are hampered by the modest power outputs, high costs, and the logistics of methanol compared to JP-8 or diesel.

Larger DMFCs struggle with high electrocatalyst costs (which feeds into equipment costs). But in September, SFC, in partnership with defence developer VINCORION, created a prototype genset for military applications, dubbed the "PPM modular^{V}". The 12 kW genset, which includes batteries and can take a range of power inputs (including an engine), was modified to accept banks of EFOY Pro 12000 Duo DMFCs (each supplying 500 W continuous power). The unit is heavy, and more suited to a truck mounting, for disaster relief, rather than ported into place.

UltraCell (owned by Advent), secured moderate sales of its portable units to militaries around Europe. Built around reformed methanol (HT-PEM) technology, UltraCell delivered its "Honey Badger 50" (50 W) soldier power source to DOD in August. Two weeks later, it secured sales to the Hellenic Army. Most of Advent's sales are of larger HT-PEM units, mainly for civil backup.

DRONES

Edge Autonomy, Doosan Mobility Innovation, and Intelligent Energy continue to provide fuel cells to civil and militaries seeking enhanced flight times for drones. Horizon also supplies its technology in this area. As with the ground fuel cells, the numbers are low, though growing more quickly.

CHINA ON THE RISE

China continues to dominate fuel cell shipments in heavy duty mobility, in line with policy. Other areas, where policy is weaker, such as stationary, are growing, but more slowly.

2022 was a bumper year, with 3,789 commercial vehicles powered or range-extended by fuel cells (compared to 1,787 units in 2021) and a small increase in shipments of light duty vehicles (from around 20 in 2021, to nearly 100 in 2022). Rather larger numbers of commercial vehicles were registered (yet to be sold) in 2022, just over 5,000. The increase is driven by the gathering momentum of regional and city H_2 projects in China. The Beijing Winter Olympics, with over 1,000 H_2 fuel cell vehicles fielded, also helped grow numbers.

Some major NEV manufacturers saw strong sales growth, but some missed their annual targets due to disrupted supply chains and dented consumer confidence from COVID-induced curbs to economic activity. In September, tax exemption for NEVs (including FCEVs) was extended to the end of 2023.

2022 marks the second most installed HRS in a year, about 90 units, a small fall on 2021, when just over 100 new HRS were installed.

NATIONAL POLICY

In March 2022, China released the 14th Five-Year Plan for the energy sector, which highlighted the FCEV and hydrogen segment as one of China's six industries of the future.

In March 2022, the National Development and Reform Commission and the National Energy Administration jointly released a plan on the development of the H_2 industry in China over the 2021-2035 period, focusing on carbon neutrality.

The policy promotes the application of H_2 fuel cells in heavy vehicles and their use in heavy industrial sectors, with near continuous use, such as mining, ports, and industrial parks, and seeks to help build an underlying HFC support base, from supply chain companies (with an eye on future exports) to H_2 networks and storage, and HRS builders. The policy also supports adoption of 700 bar H_2 for vehicles.

If the plan's goals are realised, China would see 100,000 to 200,000 tons of green H_2 produced annually and a fleet of 50,000 FCEVs by 2025, with an associated CO_2 emissions fall by 1-2 mtpa.

To help advance H_2 technology research and supply chain development, the national government has selected five city groups – the Beijing-Tianjin-Hebei cluster, Guangdong and Henan Provinces, and Shanghai – for demonstration projects. Before the release of the roadmap, provincial governments had already started to support the development of the hydrogen and fuel cells sector, but the release of the national policies has spurred specific policy supports for FCEVs from across 13 regions.

PROVINCIAL SUPPORT

Since September 2022, several provinces, including Shandong, Shaanxi, Sichuan, and Hubei released fuel cell vehicle roadmaps, many with subsidies for the vehicles, which have a direct impact on sales. Some of the more ambitious plans are summarised below.

Beijing's 2020-2025 FCEV roadmap aims to realise 3,000 vehicles and an industry valued at US$12bn by 2023. By 2025, it looks to have a cumulative number of 10,000 FCEVs on the

road and increase the industry value to US$34bn. It also plans to have 5-8 globally influential energy enterprises in the hydrogen sector.

Shanghai aims to have 10,000 FCEVs on the road and 100 HRS by 2025. Jiading Hydrogen Park, Shanghai's first H_2 energy and fuel cell industrial park, has attracted more than 50 H_2 energy and intelligent automobile projects, with a combined investment of more than CNY10bn (US$1.5bn).

Guangdong aims to have 10,000 FCEVs on the road by 2025. It's also promoting large-scale application of H_2 FCEVs and is speeding up efforts to build HRS with 300 planned for the Pearl River Delta and its coastal economic belt.

Sichuan's plan aims to build a H_2 energy industry worth CNY100bn (US$13.90bn), put 8,000 FCEVs on the roads, powered by 80 HRS, and to have a H_2 energy and FCEV industry cluster built around the provincial capital Chengdu, which will utilise renewable energy from western Sichuan and transmit energy through a H_2 corridor to Chongqing, 200 miles away.

Henan Province issued its plans in September for construction of a Zheng-Bian-Luo-Pu H_2 corridor, which is expected to be completed by 2025, part of its wider H_2 industry plans in the province to 2035. The plans also aim for the creation of a H_2 industry worth over CNY100bn, to promote and field over 5,000 FCEV, for 3-5 large green H_2 demonstration projects to be built, and for the terminal price of H_2 to fall below CNY30/kg (US$4/kg).

Together, the plans for these provinces alone add up to at least 38,000 FCEVs fielded by 2025. Against this must be measured the cumulative 12,000 FCEVs fielded in China to the end of 2022. Therefore, a big expansion in activity will be needed to reach the ambitions of the regional plans.

FUEL CELL VEHICLE DELIVERIES

Well over two-thirds of the vehicles shipped were fuel cell trucks, with buses making up most of the remainder. In 2022, the highest number of FCEVs were delivered to Beijing, Henan and Shanghai at 887, 721 and 588 respectively.

The top 10 providers make up 87% of the overall market, led by SinoHytec (25% market share), then REFIRE (17%), SHPT (15%), and Sinosynergy (13%). Only SHPT supplies fuel cells to the smaller passenger car segment in meaningful volumes.

Of the OEMs using fuel cells, the top five vehicle manufacturers are responsible for 55% of the market, led by Yutong (16%), then Foton (13%, Feichi (12%), SAIC Maxus (the electric vehicle business of SAIC, at 7%), and Higher Bus (7%).

TRUCKS

The fuel cell truck market is fuelled by policy providing higher incentives for larger systems, with fuel cells pushing now to 120 kW power and more.

In 2022, truck tractors units represented the largest share (54%), followed by dump trucks (20%), and lorries (16%). Smaller shares of refrigerated trucks, cleaning trucks and mixing trucks made up most of the remainder. Most of the fuel cell heavy goods vehicles were licenced in Henan (18%), Shanxi (14%) and Shanghai (14%).

In 2021, Hyundai broke ground for its first overseas FCEV system manufacturing facility, in Guangzhou, Guangdong province. The plant, with an annual capacity expected to reach 6,500 units is yet to be completed.

Hongyan Truck's fuel cell truck line in Ordos City started production in January 2022. It uses SHPT's PROME P3X FC system (117 kW) and has an annual production capacity of 3,000 zero emission vehicles.

Notable deliveries over 2022 included FAW Jiefang, with 300 trucks to Shanghai, Beijing, and Shanxi (in June), 300 trucks to Jinna Steel Group (in August), and 100 trucks to the mining company XCMG (in December, part of an order of 1,000 H_2-powered units by 2025, with modules from Sinosynergy).

In January, the vehicle OEM Dongfeng and the State Power Investment Corporation Hydrogen Energy Technology Development company agreed to deliver 1,000 trucks over the next two years.

In August, FAW Jiefang delivered 100x 18 t HGVs to the logistics company BESTPATH. The trucks use modules from REFIRE. The three actors have a strategic agreement to deliver a total of 1,000 trucks over the next 3 years.

For fuel cell trucks to be viable, the supporting infrastructure must be in place. Truck maker Yutong is providing services along the H_2 supply chain, including production, distribution, refuelling, in addition to fuel cell electric vehicle making. It is also located in Henan, where there is strong policy support for the HFC industry.

BUSES

Many provinces, including Shanghai, Jiangsu, Zhejiang, An'hui, Sichuan, Chongqing, Hubei, Shandong, and Henan have expanded their fuel cell bus fleets. The Beijing Winter Olympics utilised over 800 fuel cell buses, retained as city buses in Beijing and Zhangjiakou. 515 (63%) of the buses fielded at the Olympics were from Foton AUV, 185 (23%) from Yutong. With larger deployments, fuel cell bus prices have fallen significantly over the past few years, down by 30-40% on 2019 prices.

Weifang, in Shandong has implemented an incentive specific to fuel cell buses, with a reward of CNY15k (approx. US$2,000) per 10 thousand kilometres travelled, capped at a total of CNY200k over a three-year period. The city also provides a direct financial subsidy for HRS and fuelling costs.

The provincial roadmap for Shandong's H_2 industry aimed to have 3,000 fuel cell vehicles and 20 HRS across the province by 2022, and 10,000 FCEVs and 100 HRS across the province by 2025.

In September, Weichai delivered 200 buses to the National Centre of Technology Innovation of Fuel Cell in Shandong. Following the handover, the company received an order from customers totalling 1,100 commercial vehicles, in the weight classes 4.5 t, 18 t, and 49 t, which will require fuel cell stacks in the 50-200 kW power range.

Other notable deliveries in 2022 include Yutong's delivery of 50 fuel cell buses to a bus operator in Beijing (in July), DR Power's delivery of 10 buses to Chongqing Bus (in May), Sunwin Bus' delivery of 13 units to Shanghai (using SHPT P390 92 kW modules, in July), and Hydra Visions' supply of 6 buses (and 5 cleaning trucks) to Wuhan (in May).

Earlier in 2022, Hydra Vision received an order for 30 buses from the Jinshan City Public Transport Company, in Hubei province. An order for 100 fuel cell buses from Yutong was also expected by the end of 2002, for Henan province.

PASSENGER VEHICLES

Passenger cars are overshadowed by other industry activity. In exception, last year, China's largest SUV and pickup truck maker, Great Wall Motors, said it would invest CNY3bn (US$450m) over three years in H_2-related R&D. It plans to expand production and sales of core components and systems, aiming to become a top three company in FCEV powertrain solutions within China 2025.

By late 2022, Toyota planned to begin exporting its second-generation Mirai to China, primarily for the car rental market, then aimed to push ahead with local production of fuel cell cars.

Shanghai received a fleet of 80 SAIC Maxus MIFA fuel cell minivans (again fitted with SHPT P390 modules) for use as a ride share service in October 2022, with an expectation of 200 units in total.

HYDROGEN REFUELLING STATIONS

By the end of 2022, China had 310 installed HRS (about 40% of the global total). Of these 90 are from Sinopec, with an optimistic plan for 1,000 HRS in the next two years. Guangdong province plans to build 300 new HRS by 2025 and provide subsidies of up to CNY5m (almost US$700,000) per refuelling station. Beijing is providing a similar subsidy for its hydrogen refuelling stations. The Daxing district of Beijing has the world's largest HRS, with a daily capacity of 4.8 tonnes of H_2. This HRS is part of the Daxing International Hydrogen Energy Demonstration Zone opened in Beijing, which aims to span the complete industrial chain covering the manufacture, storage, transportation, processing, and use of hydrogen energy, with 139 companies officially registered in the zone.

SHIPS & PLANES

Activity is yet to start in these areas in China. In May, the China Classification Society indicated it would begin construction of the first H_2 fuel cell boat, a 50 m ferry called the "Three Gorges Hydrogen Boat 1", for deployment in 2023.

BIG CHANGES IN EUROPE AND THE UNITED STATES

Two major supportive events took place in 2022. Firstly, the EU gave the go-ahead to several major transnational projects in the fuel cells area. Secondly, the Inflation Reduction Act was enacted in the US, with significant implications mainly for hydrogen and, to a lesser extent, to the development of fuel cells. These initiatives have taken place at a time of heightened concern over energy security and climate change.

FUEL CELL PROJECTS WITH IPCEI FUNDING

In 2020, 22 EU countries and Norway signed a manifesto paving the way for a clean H_2 value chain, with a commitment to launch 'important projects of common European interest' (IPCEIs) in the hydrogen sector.

The IPCEI framework is designed to bring together actors to undertake large-scale transformative projects that will deliver a global edge to innovation and manufacturing to the European Union. Shortlisted proposals are fielded by national governments to the European Commission to obtain State Aid approvals.

The signatories to the 2020 manifesto committed to jointly design and coordinate IPCEIs. They also agreed that projects should cover the full clean hydrogen value chain, from renewable and low-carbon hydrogen production to hydrogen storage, transmission and distribution, and hydrogen application, notably in industrial sectors.

Following an assessment by the Commission, the first set of clean hydrogen projects received approval in July 2022. France is the most represented country with 10 validated projects, including fuel cell plants adapted to road, rail and naval mobility uses (Symbio, Hyvia, Helion by Alstom, Arkema), electrolysers (Elogen, Genvia, John Cockerill, McPhy), and tanks (Faurecia, Plastic Omnium). Italy is the next beneficiary by number of projects, with 6 projects selected, followed by Germany.

There are 41 projects located in 15 EU countries that will receive up to €5.4bn in public funding. This is expected to unlock an additional €8.8bn in private investments. Of the approved projects, 17 were part of the fuel cells technology focus area (TF2). The projects are set to transform capacities and competencies in the fuel cell industry, with the engagement of significant actors. The individual projects typically involve budgets of the high tens to hundreds of millions of Euros generally. Most of the projects focus on mobility.

Under TF2, Plastic Omnium will develop a series-ready hydrogen fuel cell system for heavy duty vehicle applications (trucks, buses, etc.) as well as the necessary production process. Iveco CZ Bus will focus on hydrogen intercity and tourist buses. Daimler Truck aims to redirect most of its R&D spending to ZEV technologies by 2025. Under IPCEI, 100 long-haul heavy-duty fuel cell trucks will be fielded for at least 4 years, the practicality of LH2 refuelling technology will be evaluated, with a comprehensive monitoring and analysis exercise.

Also, in TF2, EKPO will develop and industrialise a new generation of high-performance PEM modules for heavy-duty applications, for trucks, buses, rail and maritime, and for stationary systems. Symbio has started the project HyMotive with IPCEI co-funding. This large-scale project targets mass production of fuel cells for mobility at the Saint-Fons plant, close to Lyon. Hyvia, the JV of Renault Group and Plug Power, has secured IPCEI funds to help build a fuel cell production facility. Hyvia's five-year project will lead to a gigafactory scale manufacturing capacity, and several generations of H_2-powered vehicles for the European market.

Fincantieri, one of the world's largest shipbuilding companies, has secured IPCEI funding to identify synergies for fuel cells across different mobility sectors. The project scope includes low and high temperature fuel cells, focused on a hybrid architecture for ships. The construction of the prototype ships will take place in two Italian yards of Fincantieri.

Alstom aims to develop hydrogen-fuelled traction units to replace diesel-based regional passenger trains and locomotives. The first phase will define and standardize traction architectures for regional needs (for both new build and retrofits) at lowest delivered cost. The second phase seeks to create a vertical supply chain. This may end up with Helion displacing its current supplier, Accelera (Cummins).

In the project M2H2I, led by Arkema, the aim is to develop and industrialize high-performance sustainable polymers and composites to produce, store, and transport H_2 for mobility end uses.

Within the Fuel Cell Giga Factory (FCGF) project, Nedstack will develop a 1 GW/annum scale fuel cell production plant by 2026. Applications span shipping, off-grid power and clean industry, focused on hydrogen-to-power systems.

In Bosch's IPCEI project, the focus is on the first industrial deployment of its modular 100 kW SOFC systems, with production sites to be ramped up and a supply chain to be established. Bosch expects to begin series production of its stationary units at annual capacity of 200 MW by around 2025.

THE US WAKES UP TO HYDROGEN

DOE issued its draft National Clean Hydrogen Strategy and Roadmap in September, providing a snapshot of H_2 production, transport, storage, and use in the United States today. Opportunities for domestic H_2 are estimated as 10 mtpa production by 2030, 20 mtpa by 2040, and 50 mtpa by 2050. The Strategy and Roadmap will be finalized in early 2023 and updated per Bipartisan Infrastructure Law at least every 3 years.

In August 2022, the Senate passed the Inflation Reduction Act (IRA), which includes US$370bn in tax incentives for low carbon energy technologies. Only a small fraction of the energy-related provisions will go to fuel cells, however. The IRA makes several changes to the federal tax credits previously available to clean energy projects. Broadly, the credits divide between energy generation, vehicles, manufacturing, and fuels.

A Clean Energy Investment Tax Credit (ITC) for Energy Property (Section 48 of the tax code), covering renewable energy investments, including fuel cell generators above 1 MW in capacity, is available at up to 30% of project costs, but with project construction needed to begin by 2025, fuel cell actors will need to be quick to take advantage of this credit. Historically, nearly all of this credit has been taken by solar. After this, a technology neutral Clean Energy ITC will be available to projects (Section 48E), at up to 30% of investment costs, once a facility is placed in service. In its previous incarnations, Congress has repeatedly repealed and suspended this credit, changing the amount of the credit and rules for eligibility, so the extended timescale to 2032 will be welcomed.

A new Residential Clean Energy Credit (Section 25D of the tax code) applies to new clean energy devices for homes, with a ceiling of 30% of the installed device cost, tapering to 22% through 2035. Fuel cells at the property are limited to US$1,667 for each half kilowatt of capacity for homes with several residents. There is no requirement for hydrogen fuelling. This credit may have a significant impact for companies like Upstart Power and Watt Fuel Cell.

A Clean Vehicle Credit of $7,500 is available to purchasers of qualified new clean vehicles, including electric vehicles, plug-in hybrids, and hydrogen fuel cell vehicles (Section 30D). The credit only applies if the price of the car is less than US$55,000, or for a van less than US$80,000. This limit rules out many vehicles. A new Previously Owned Clean Vehicle Credit is available for second-hand purchases, for vehicles selling below US$25,000 (Section 45E). A Commercial Clean Vehicle Credit is available for Class 1-4 trucks, at up to US$45,000 (Section 45W). The credit is relatively small and while available to fuel cell trucks, it is hard to see this making much of a change to the fuel cell market.

A Domestic Manufacturing Conversion Grant (referencing Section 712 of the Energy Policy Act of 2005) is available through 2031, with US$2bn for retooling existing auto manufacturing facilities to promote domestic production of clean vehicles, including hybrids, plug-in hybrids, BEVs, and FCEVs. However, this will quickly be swallowed up by battery electric vehicle producers, with a ceiling of US$500m per applicant, and 15 awards expected. An Advanced Energy Project Credit (48C) creates funding for new manufacturing plants, including fuel cells, electrolysers and hydrogen infrastructures. Tax credits totalling US$10bn are available for eligible projects, ranging from 6% of expenditure to 30% for plants that invest in employees and apprenticeships. Applications for this credit are vetted first by the DOE.

The most attractive incentive relates to clean hydrogen production. The IRA creates a new Production Tax Credit (PTC) for hydrogen (45V) at a maximum rate of $3/kg multiplied by a percentage based on the lifecycle greenhouse gas emissions intensity of the gas produced. Companies can receive their PTCs for clean H_2, CCUS, and advanced manufacturing during the five years of a facility's service life.

Overall, the IRA creates opportunities for fuel cells but does not give as great an emphasis on creating supply-chain clusters reaching from manufacturing to end uses, as targeted by the EU's IPCEI initiative. On the other hand, the headline budget of the IRA may act as an attractor to some, in moving activity to the US.

As at the end of 2022, the EU was still formulating its response to the IRA. The EU is also responding to the changes to the energy landscape resulting from the invasion of Ukraine. This has resulted in the RePowerEU plan, which seeks a more diverse energy supply. The 2030 targets for H_2 production associated with this initiative are 10 mtpa from domestic sources and 10 mtpa from imports. The Hydrogen Valleys initiative is also growing, with a total of €39bn investment by the end of 2022, covering 38 projects worldwide in 20 countries.

MORE HYDROGEN ROADMAPS

2021 closed with 31 national plans published, at varying states of commitment. This increased to 40 by the end of 2022, still with most still focused on hydrogen as a vector for long-distance energy movements, and for application to energy-intensive industries and mobility.

The national plans consider the existing energy supply modes as well the potential for exports and imports of H_2 where relevant. Chile focuses on green H_2 from electrolysis, for example, while South Korea and Japan focus on blue hydrogen. Some, like the UK and Germany, cover both blue and green hydrogen. While some, like Australia, focus on hydrogen from coal.

The lack of CCS facilities and the widespread use of grey hydrogen is leading to many 'greenwashing' claims. The Netherlands has become the first European country to launch a Guarantee of Origin scheme, issuing certificates in October 2022.

The Netherlands' scheme aims to create transparency in the carbon intensity of the H_2 production and transportation. This aspect is becoming increasingly more pressing as fossil-rich countries like Canada promote blue hydrogen. Claims of 90% carbon reduction for blue H_2 may appear attractive at first sight, but in the absence of CCS, this reduces to less than 50%.

ELECTROLYSER PROJECTS WITH IPCEI FUNDING

Given the concern over realising genuine carbon savings and given the slant on the H_2 policies, it is unsurprising that some of the projects in the TF2 area of Hy2Tech are more focused on electrolysers. All three main classes of electrolyser are covered.

In Elcogen's Advent Green HiPo project, design, development and manufacture of both fuel cells and electrolysers is covered. The final goal of the research work is to build a gigafactory in Estonia. Core products as parts of systems will be validated in different European countries in cooperation with IPCEI partners during 2025-2027.

Schlumberger SA (now called SLB) and CEA have formed a JV called Genvia to facilitate the development and industrial deployment of solid oxide fuel cells and electrolysers. The project aims to establish a pilot line by 2024 leading to a large-scale production plant by 2027.

In project IANUS, led by Ansaldo Green Tech (AGT), the first objective is to develop high temperature electrolysers based on solid oxide technology, which can "potentially" operate also as fuel cells. The second and third steps will set-up a manufacturing plant with a 300 MW capacity per year and commission an installed fleet equal to 350 MW. The first electrolyser is expected to be ready for operation by mid-2025 and be complete by 2029.

Industrie De Nora and SNAM have come together in a special purpose vehicle called De Nora Italy Hydrogen Technologies, which aims to design, construct and validate a 2 GW gigafactory for water electrolysis components and for fuel cells, though the real focus is on modular containerized alkaline electrolysers. Construction work on the factory (in Italy) is scheduled to start in the second half of 2023, with continuous operation by early 2026.

A total funding of euro €782m (US$829m) for Advent's Green HiPo project will be made available over a period of six years. The project involves the development, design, and manufacture of HT-PEM fuel cells and electrolysers for the production of power and green hydrogen, respectively. The project is expected to take place in Western Macedonia, and aid significantly in the region's transition from a coal-based economy to a greener economic model. The project involves direct and indirect cooperation with 20 European actors. The plan is for 1.5 GW of electrolysers to be produced over 6 years, alongside 120 MW of fuel cells.

Overall, the electrolyser projects commit to several more GW of production capacity by the end of the decade. To the extent this capacity translates into shipments is yet to be seen. Some of the projects will directly or indirectly help in developing supply chains that can also feed into the fuel cell industry.

DATA TABLES

Shipments by application					
1,000 Units	**2018**	**2019**	**2020**	**2021**	**2022f**
Portable	5.7	3.9	4.1	6.1	7.8
Stationary	51.9	52.2	56.8	47.9	50.7
Transport	10.9	16.4	20.9	32.0	30.7
Total	**68.5**	**72.5**	**81.8**	**86.0**	**89.2**

Shipments by region of adoption					
1,000 Units	**2018**	**2019**	**2020**	**2021**	**2022f**
Europe	7.7	10.7	13.2	14.0	13.2
North America	9.3	8.1	10.8	15.4	14.6
Asia	50.9	53.5	57.6	56.2	60.9
RoW	0.6	0.2	0.2	0.4	0.5
Total	**68.5**	**72.5**	**81.8**	**86.0**	**89.2**

Shipments by fuel cell type					
1,000 Units	**2018**	**2019**	**2020**	**2021**	**2022f**
PEMFC	39.7	45.7	53.1	55.2	54.2
DMFC	3.7	3.7	3.8	5.3	7.8
PAFC	0.2	0.3	0.3	0.2	0.1
SOFC	24.9	22.8	24.6	25.2	27.0
MCFC	0.0	0.0	0.0	0.0	0.0
AFC	0.0	0.0	0.0	0.1	0.1
Total	**68.5**	**72.5**	**81.8**	**86.0**	**89.2**

DATA TABLES

Megawatts by application					
Megawatts	**2018**	**2019**	**2020**	**2021**	**2022f**
Portable	0.7	0.4	0.5	0.7	0.9
Stationary	220.6	274.8	325.1	348.8	378.5
Transport	584.5	921.1	1,012.0	1,966.2	2,113.0
Total	**805.8**	**1,196.3**	**1,337.6**	**2,315.6**	**2,492.4**

Megawatts by region of adoption					
Megawatts	**2018**	**2019**	**2020**	**2021**	**2022f**
Europe	41.2	113.0	150.2	204.3	228.1
North America	425.3	339.2	252.3	614.2	485.0
Asia	337.9	743.9	929.0	1,493.2	1,769.9
RoW	1.2	0.2	5.1	3.9	9.4
Total	**805.8**	**1,196.3**	**1,337.6**	**2,315.6**	**2,492.4**

Megawatts by fuel cell type					
Megawatts	**2018**	**2019**	**2020**	**2021**	**2022f**
PEMFC	609.0	948.0	1048.2	2000.8	2150.4
DMFC	0.4	0.4	0.5	0.5	0.9
PAFC	86.4	130.9	132.2	95.8	53.7
SOFC	84.1	106.8	147.8	206.9	249.3
MCFC	25.8	10.2	8.8	11.1	37.4
AFC	0.1	0.0	0.1	0.5	0.7
Total	**805.8**	**1,196.3**	**1,337.6**	**2,315.6**	**2,492.4**

NOTES

- Data for 2014 to 2022 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 2022 dataset contains firm numbers for the period January to end of the year. These comprise direct numbers from shippers and from syntheses, including collation of press releases, where direct numbers were not available.
- We will revise data for 2022 in our 2023 edition if the shipment estimates need to change. Our final figures for 2021 are little changed from our past forecast, with only minor variances in units shipped for grid support, off-grid power and light duty vehicles. 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) that can be physically, as well as larger units that are specifically used in semi-permanent modes and can be lifted and dropped in place, up to 20 kW in output. (Larger power output units that require lifting equipment to be moved are included in the stationary category). Toys and educational kits are not reported in shipment numbers.
- 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 in this category.
- 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.

SUSTAINABILITY IS OUR BUSINESS

E4tech is now part of ERM, and we continue to help our clients to understand and profit from opportunities in sustainable energy, as we have been doing since 1997. As the largest global pure play sustainability consultancy, ERM partners with the world's leading organisations, creating innovative solutions to sustainability challenges and unlocking commercial opportunities that meet the needs of today while preserving opportunity for future generations.

ERM's diverse team of 8,000+ world-class experts in over 150 offices in 40 countries and territories combine strategic transformation and technical delivery to help clients operationalise sustainability at pace and scale. ERM calls this capability its "boots to boardroom" approach - a comprehensive service model helping organisations accelerate the integration of sustainability into their strategy and operations. Find public examples of our work at: **erm.com/insights**

ERM regularly conducts influential analyses including in renewables, low carbon fuels and chemicals; batteries and other energy storage; low carbon transport, innovation policy and support and sustainability more broadly. Fuel cells, electrolysers and hydrogen are one of several core strengths, in which we carried out hundreds of projects for early-stage companies, SMEs, large companies, financiers and governments worldwide.

The Review effort is led by those below, and supported by many ERM staff, gathering data, drafting and interpreting in different languages, such as Chinese, French, Italian and German.

Follow **ERM** and the co-authors on LinkedIn to keep up to date with industry news and activity.

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Jonathan Lewis has over twenty years' experience in business development, from strategy and policy through business plans to technology commercialisation. With over two decades working in the fuel cell and hydrogen area, he was with Rolls-Royce Fuel Cell Systems Ltd, and is now an independent adviser, working with public and private sector clients, multi-nationals and SMEs. He has held a variety of roles working with the CH JU.

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.

Business and strategy support: Could your business plan or strategic approach be strengthened? 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.

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 reach out to us through our **contact form** and we'll find the right person for you to talk with.

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49	Design rendering of MV Hydrogen One methanol-fuelled hybrid tow boat	e1 Marine
52	Images of 9-19 and 40-80 seat aircraft ZeroAvia plans to develop	ZeroAvia
63	9-unit Multi-Picea storage system in residential property	Home Power Solutions
63	Bosch SOFC system at its plant energy supply centre in Salzgitter, Germany	Robert Bosch
65	FC-Rack hydrogen powered generator	Helion
67	EFOY fuel cells powered LiveView Technologies surveillance unit	SFC Energy
67	Scitem portable energy generator	Nikkei (Scitem)
68	H_2Genset on test at a construction site in Vienna	TEST-FUCHS
69	GEH2 power supply for telecoms	EODev
73	Sunwin Bus fuel cell bus deliveries in Jinshan, Shanghai.	Hydrogen Jet Technology

NOTE ON CURRENCIES

The exchange rates below can be used as guidance to convert currencies stated in this report.

These are the average mid-point rates from 31st December 2021 to 31st December 2022.

US$1 = € 0.9457	€1 = US$ 1.0600	1£ = US$ 1.2445	1¥ = US$ 0.0078
US$1 = £ 0.8067	€1 = £ 0.8525	1£ = € 1.1734	1¥ = € 0.0073
US$1 = ¥ 129.99	€1 = ¥ 137.27	1£ = ¥ 160.98	1¥ = £ 0.0062