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2019 Fuel Cell Technologies Market Report

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The 2019 Fuel Cell Technologies Market Report covers major activities and advancements through December 31, 2019. The information in this report was gathered from public websites, reports, articles, and conference presentations, as well as through personal contact and communication with fuel cell and hydrogen companies and international organizations and associations.

The authors relied upon the hard work and valuable contributions of many men and women in the global fuel cell and hydrogen industry, representing both public organizations and governments and the private sector.

International currencies converted to U.S. dollars are based on either the stated amount from company materials at the time of release or converted by the authors using the "Yearly Average Exchange Rates for Converting Foreign Currencies into U.S. Dollars" for 2019 by the Internal Revenue Service. (https://www.irs.gov/individuals/international-taxpayers/yearly-average-currency-exchange-rates).

Notice

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Overview

This report provides an update on the status of the hydrogen and fuel cell industry, including deployments and demonstrations of various applications, as well as a snapshot of the business and governmental landscape for the year 2019. Supported by the U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office, it follows the format of prior market reports and provides a factual, unbiased view of the technology and market status.

For the global fuel cell and hydrogen industry, 2019 was a year of growth through a number of joint ventures, manufacturing expansions, product advancements, collaborations, and cooperation agreements. There was also consolidation resulting from major acquisitions. Interest and investment in fuel cells and hydrogen from the public and private sector increased in a number of areas around the world and fueled expansion into new markets.

Fuel cells electrochemically combine fuel (such as hydrogen) and oxygen to produce electricity, water, and heat, and they continuously generate electricity as long as a source of fuel is supplied. Fuel cells do not burn fuel and have no moving parts, making the process quiet, pollution-free, and efficient—and if hydrogen is used as the fuel, the only emissions are water vapor and some heat. Fuel cells are scalable and can be built to accommodate various specifications or energy needs, ranging from a few watts to many megawatts in power.

There are three overarching markets for fuel cell technology: stationary power, transportation, and portable power. Stationary power includes any application in which the fuel cells are operated at a fixed location for primary power, backup power, or combined heat and power (CHP). Transportation applications include motive power for vehicles (heavy-, medium-, and light-duty) such as buses, heavy-duty trucks, delivery vans, passenger cars, specialty vehicles, trains, and material handling equipment (MHE). Other applications in the transportation sector include fuel cells as range extenders for battery vehicles and as auxiliary power units (APUs). In recent years, the transportation paradigm has grown to include motive power in the air and on the sea, including hydrogen-powered drones and unmanned aerial vehicles as well as fuel cell ships, ferries, submarines, planes, and more. Portable/off-grid applications include fuel cells that are not permanently installed and fuel cells in a portable device, such as systems that provide power for equipment used in remote areas, recreation, and electronics.

There are several types of fuel cells to power this diverse array of applications, typically denoted by the electrolyte used in the electrochemical cell: molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), phosphoric acid fuel cells (PAFC), alkaline fuel cells, low- and high-temperature proton exchange membrane (PEM) fuel cells, and direct methanol fuel cells.

Hydrogen, the predominant fuel used in a fuel cell, is primarily produced by the reforming of conventional hydrocarbons, typically natural gas. Electrolysis, a process in which an electric current is run through water to produce streams of hydrogen and oxygen gases, is starting to gain a greater share of the hydrogen production market due to its ability to generate hydrogen carbon-free with renewable energy. A fuel cell system can be a truly low- or zero-emission source of electricity when the hydrogen is produced from decarbonized sources.

Around the world, the fuel cell and hydrogen footprint has increased steadily over the years, with different countries or regions initially focusing on specific sectors:

- United States—fuel cell powered light-duty vehicles, material handling equipment (MHE), large-scale stationary fuel cell installations, and small-scale fuel cell systems for backup power
- Japan—small-scale fuel cell residential installations (Ene-Farm), fuel cell powered light-duty vehicles
- South Korea—multi-megawatt fuel cell power parks
- China—fuel cell powered buses
- Europe—fuel cell powered buses, large-scale electrolyzer/power-to-gas projects, small-scale fuel cell residential installations (Ene-Field)

Other countries are involved in research, development, and deployment of fuel cells and hydrogen, and there is universal interest and investment in large-scale hydrogen production to meet broad global decarbonization goals, for energy storage, and as a fuel for fuel cell powered heavy- and medium-duty transportation. This report features summaries of activity in 2019 related to different applications with overviews of each sector and its major activities, as well as special "Spotlight" sections on Heavy-Duty Trucking and Large-Scale Hydrogen Generation and Supply.

The Year in Numbers

2019 Shipments

Between 2016 and 2019, sales of fuel cells rose modestly, from 62,000 units to 70,000 units per year. However, the total power of the units shipped more than doubled, from 500 MW in 2016 to more than 1.1 GW shipped in 2019, a major achievement for the industry. The large increase in total fuel cell power shipped also reveals the increase in average power for individual fuel cells.

The numbers in Table 1 (below) are drawn from data obtained from UK consulting firm E4Tech and an independent assessment of fuel cell manufacturers and other key stakeholders around the world. The authors also compiled publicly available information on annual sales and shipments in different market sectors.

The authors' findings show that the transportation sector alone—fuel cell systems in light-duty passenger cars, MHE, and medium- and heavy-duty vehicles such as buses, trucks, and trains—accounted for more than 1 GW of the shipments for 2019. The stationary sector, including both large-scale and small-scale systems, totaled around 160 MW.

The yearly worldwide shipments and total power of those shipments shown below provide context for the years between the 2016 and 2019 *Fuel Cell Technologies Market Reports.*

Table 1: Annual Worldwide Fuel Cell Shipments 2016-2019. ***Source: Fuel Cell Technologies Market Report (2016), Fuel Cell Industry Review (E4Tech – 2017-2019), FCHEA Survey 2019***

Annual Worldwide Fuel Cell Shipments 2016-2019		
Year	Number of Units Shipped	Total Power
2016	62,000	500 MW
2017	70,000+	670 MW
2018	68,000	800 MW
2019	**70,000**	**1.1+ GW**

More details on 2019 sales, shipments, and deployments can be found in the respective sections of this report.

Current Status/Milestones

Global data on hydrogen and fuel cell deployments is reported below, based on information provided through the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). IPHE was formed in 2003 to foster international cooperation and accelerate progress globally. It now has over 20 member countries and the European Commission. As of November 2019, 13 member countries collectively reported a total of more than 15,800 fuel cell cars, 2,980 fuel cell buses, 1,200 fuel cell trucks, 26,800 fuel cell powered forklifts, and 370 hydrogen fueling stations currently or soon to be deployed. This is an approximate and conservative number that could be significantly higher, as some of the IPHE countries had not provided recent updates, and other reports did not extend through the end of 2019. One specific example is China, where the China Association of Automobile Manufacturers reports approximately 6,178 vehicles (cars, buses, trucks) by the end of 2019, a difference of more than 2,000.

Table 2: Snapshot of Fuel Cell Vehicles and Hydrogen Fueling Station Progress in IPHE Partner Countries

Snapshot of Fuel Cell Vehicles and Hydrogen Fueling Station Progress in IPHE Partner Countries*					
Country	Cars	Buses	Trucks	Forklifts	Hydrogen Stations
Brazil[1]	N/A	4, 1 hybrid	N/A	N/A	1, with 1 in development
Canada[2]	17	1	2	>400	9
China	50	2,800	1,200	2	35
France[3]	324	0	1	180	25
Germany	530	21	2	100	76
Italy[4]	15	10	0	5	4
Japan	3,433	22	N/A	160	133, with 10 in development
South Korea	3,216	7	N/A	N/A	24
Netherlands	162	8, with 12 scheduled	16	0	7
Norway[5]	159	5	N/A	10	6
South Africa	0	0	0	1	N/A

Snapshot of Fuel Cell Vehicles and Hydrogen Fueling Station Progress in IPHE Partner Countries*					
Country	Cars	Buses	Trucks	Forklifts	Hydrogen Stations
United Kingdom[6]	100	20	0	N/A	N/A
United States	7,800	35, with 39 in development	Demonstrations underway	>26,000	>40
Total Deployed	15,806	2,934	1,219	27,658	360

*Unless noted below, numbers in chart were reported to IPHE as of November 2019. Some IPHE member countries do not have any deployments and are not listed.

1. Brazil numbers as of July 2019
2. Canada numbers as of December 2018
3. France numbers as of November 2018
4. Italy numbers are of January 2020
5. Norway numbers as of April 2019
6. UK numbers as of April 2019

Source: IPHE (www.iphe.net)

Throughout the year, several significant milestones were met and impressive numbers reported:

- In just seven months, between Earth Day in April to National Hydrogen and Fuel Cell Day in October, Hyundai's fleet of NEXO and Tucson fuel cell vehicles in the U.S. accumulated almost a million miles. In April, Hyundai reported the fleet had collectively accumulated more than 7.5 million miles,[1] and in October, that number was reported to be more than 8.4 million miles.[2]
- In August, FuelCell Energy's portfolio of fuel cell installations reached 9 million MWh (9 TWh) of operation.[3]
- In November, Plug Power's fleet of 30,000 fuel cell powered material handling vehicles amassed more than 270 million hours and 1 billion miles of operation. The 80 hydrogen stations Plug Power constructed to support these vehicles provided more than 23 million fuelings, using 22 tons of liquid hydrogen per day.[4]

Business Development

This section provides an overview of fuel cell and hydrogen company business activities in 2019, including mergers and acquisitions, joint ventures, manufacturing facility expansions, and industry investments.

Acquisitions, Partnerships, Collaborations, and Joint Ventures

Several fuel cell and hydrogen companies grew their business activities through mergers, acquisitions, and joint ventures. The acquisition of smaller, market-focused companies by larger or more stable ones is an indication that these larger companies view fuel cells and hydrogen technologies as growth areas.

Acquisitions

Cummins, a U.S. Fortune 500 corporation that designs, manufactures, and distributes engines, components, and power generation products, expanded its existing fuel cell portfolio via investments in and acquisitions of fuel cell and hydrogen companies.

In June 2019, Cummins acquired GE's SOFC business assets to expand its capabilities in the stationary power market. The transaction included a leased facility in Malta, New York, which contains test cells, manufacturing space and an outside test pad for larger scale systems.

In September, Cummins finalized the $290 million acquisition of Hydrogenics Corporation, a fuel cell manufacturer and hydrogen generation company based in Mississauga, Ontario.[5] Before the purchase, The Hydrogen Company, an Air Liquide subsidiary, which had acquired an 18.6% stake in Hydrogenics for $20.5 million, contributed all of its shares to Cummins.[6]

That month, Cummins also invested in Loop Energy of Burnaby, British Colombia, which will supply Cummins with fuel cell range extender systems to incorporate into medium- and heavy-duty demonstration trucks.[7] Cummins also entered into a memorandum of understanding (MoU) with Hyundai Motor Company to develop and commercialize electric and fuel cell powertrains for the North American commercial vehicle market.[8]

Other significant acquisitions in 2019 included the following:

- In February, OneH2, a hydrogen fuel and infrastructure provider based in Long View, North Carolina, signed a definitive agreement to acquire all PowerTap® hydrogen generation and production assets of Nuvera Fuel Cells, LLC, based in Billerica, Massachusetts, a wholly owned subsidiary of Hyster-Yale Materials Handling, Inc.[9]
- In June, hydrogen and fuel cell systems manufacturer Plug Power acquired the technology, assets, and personnel of EnergyOr, based in Montreal, Quebec.[10] This purchase expands Plug Power's portfolio into small-scale robotics, unmanned aerial vehicles (UAVs or drones), and other autonomous applications.
- Plug Power launched several other partnerships and business ventures in 2019 as well:
  - **April**: Partnered with Chung-Hsin Electric and Machinery Manufacturing Corporation (CHEM) of Taiwan to integrate Plug Power's ProGen systems into CHEM's stationary power products for grid support and backup power applications in Asia, Africa, and India.[11]
  - S**eptember**: Signed agreement with ENGIE of France to accelerate the adoption of hydrogen and fuel cell systems, packaging Plug Power's fuel cell technology with ENGIE's hydrogen infrastructure, renewable energy, and service programs.[12]
  - **September**: Signed a three-year reserved product supply agreement with Pennsylvania-based United Hydrogen for liquid hydrogen.[13]
  - **November**: Entered into an agreement with Madrid-based Compañía Logística de Hidrocarburos to develop hydrogen production assets and downstream markets in Spain for distribution to Plug Power customers throughout Europe.[14]

Joint Ventures

The year saw many joint ventures formed between synergistic companies, bringing together complementary product and market goals, technological expertise, and stakeholder resources. These official collaborations were key to reinforcing global investment and support in hydrogen and fuel cell technologies.

Table 3: Examples of 2019 Joint Ventures

Examples of 2019 Joint Ventures				
Joint Venture	Companies Involved	Focus Sector	Focus Region	Details
Air Liquide Houpu Hydrogen Equipment Co., Ltd.	Air Liquide and Chengdu Huaqi Houpu Holding Co., Ltd.	Hydrogen infrastructure	China	Announced in April and focused on the development, production, and distribution of hydrogen refilling stations.
Green H2 Norway	H2 Energy AS, Nel, Greenstat AS, and Akershus Energi Infrastruktur AS	Hydrogen infrastructure	Norway	Formed in December to establish large-scale electrolysis plants to generate renewable hydrogen for a fleet of Hyundai fuel cell trucks ordered for Norway.[15]
Hydrogen Energy Network (HyNet)	Air Liquide, Nel ASA, Hyundai and eleven other South Korean industrial firms	Hydrogen infrastructure	South Korea	Goal is to install 100 hydrogen fueling stations in South Korea by 2022.[16]
HysetCo	Air Liquide, Toyota, Idex, and Société du Taxi Électrique Parisien (STEP)	Transportation	Paris, France	Toyota will deliver 500 additional Mirai fuel cell vehicles (FCVs) to the existing fleet of 100 to reach the objective of 600 taxis by the end of 2020.[17]
NEXUS-e GmbH	Proton Motor Fuel Cell GmbH and Schäfer Elektronik GmbH	Stationary/ Transportation	N/A	Developing fuel cell powered quick charging stations for EVs that can provide more than 1 MW of power, either as a standalone unit or connected to electric grid.[18]
SYMBIO, a Faurecia Michelin Hydrogen Company	Michelin and Faurecia	Transportation	Europe, China, and the United States	The companies initially invested €140 million (US$157 million) to develop new-generation fuel cells, launch mass production, and establish three industrial sites supplying automotive markets in Europe, Asia, and the United States.[19]

Examples of 2019 Joint Ventures				
Joint Venture	Companies Involved	Focus Sector	Focus Region	Details
Weichai Ballard Hy-Energy Technologies Co.	Ballard Power Systems and Weichai Power Co., Ltd.	Transportation	China	In December, Ballard received a $19.2 million order[20] from Weichai Ballard Hy-Energy Technologies Co., Ltd., for MEAs. This order, added to one for $44 million[21] from Weichai in May for a range of fuel cell products and components, will help Weichai meet its goal of supplying a minimum of 2,000 fuel cell modules for commercial FCVs in China.
N/A	ITM Power and Linde	Hydrogen infrastructure	N/A	Will market and develop hydrogen projects for large-scale industrial users, particularly in the metals and glass, electronics, refinery, chemical, and steel industries.
N/A	Nikola Corporation,Industrial Vehicles Corporation (IVECO), and FPT Industrial	Transportation	North America and Europe	To develop and distribute cab-over hydrogen fuel cell and battery-electric trucks for the European market.

Memoranda of Understanding and Other Partnerships

Another means of growth in the hydrogen and fuel cell sector in 2019 was through partnerships and MoUs signed between companies working together to advance mutual goals and collaborate on various projects.

- In March, UK fuel cell manufacturer Intelligent Energy and Korean-based hydrogen technology company MetaVista entered into an MoU to collaborate on fuel cell drone development.[22]
- In June, Hyundai signed an MoU with petroleum company Saudi Aramco to cooperate on expanding hydrogen supplies in both countries, hydrogen infrastructure in South Korea, fuel cell vehicles in Saudi Arabia, and research on non-metallic materials and future automotive technologies.[23]
- In November, Linde signed an MoU with Baowu Steel Group's new subsidiary, Baowu Clean Energy Ltd., to cooperate on research and development to further develop China's hydrogen market for industrial and mobility applications.[24] Under the agreement, Linde and Baowu Clean Energy will also explore investing in liquid hydrogen plants and infrastructure.
- Also in November, ITM entered into a collaboration agreement with Iwatani Corporation of America, a wholly owned subsidiary of Iwatani Corporation,[25] to deploy multi-MW electrolyzer systems in North America, hydrogen fueling stations in California, and large-scale liquid and gaseous renewable hydrogen production for domestic and export markets.

- Air Liquide signed an MoU in November with Chinese petroleum company Sinopec to study hydrogen development, including regulatory frameworks.[26]
- German multinational engineering and technology company Bosch formed an alliance with Powercell Sweden AB to jointly develop PEM fuel cells for the global automotive market.[27]
- German fuel cell manufacturer Proton Power Systems plc joined the "Pure Power Pool" consortium with UMSTRO GmbH and Klaus Ostermeier GmbH to develop fuel cell and electrolysis projects.[28]
- Rolls-Royce Power Systems is collaborating with Lab1886, an innovation laboratory affiliated with Mercedes-Benz, to develop its MTU-branded fuel cells for vehicles for stationary power generation. The collaboration involves a pilot project to develop a fuel cell system based on Mercedes-Benz Fuel Cell GmbH modules for Rolls-Royce's data center in Friedrichshafen.[29]

Manufacturing Expansions

Several companies expanded by constructing new facilities or taking over existing properties in 2019.

Table 4: 2019 Fuel Cell and Hydrogen Manufacturing Expansion Announcements

2019 Fuel Cell and Hydrogen Manufacturing Expansion Announcements			
Company	Location	Size/Capacity	Details
Arcola Energy	Knowsley, UK	15,000 sq. ft.	New manufacturing, installation, and maintenance facility. Will be used to install fuel cell systems in a fleet of double-decker buses for Liverpool.
Bosch	Wuxi, China	N/A	New development center to supply hydrogen injection valves, electronic air compressors, and fuel cell systems. Bosch's first fuel cell development facility outside Germany.
Linde and ExxonMobil	Jurong Island, Singapore	N/A	In June, Linde signed an agreement with ExxonMobil to expand its existing hydrogen production facilities on Jurong Island in Singapore, investing $1.4 billion.[30] The hydrogen will primarily be used by ExxonMobil for production of petrochemicals, but other customers will also use the hydrogen supply.
PDC Machines	Warminster, Pennsylvania	Will be able to produce equipment for up to 400 compression systems.	PDC's third manufacturing plant.
Plug Power	Rochester, New York	Includes engineering and administrative offices, R&D laboratory, and warehouse.	Plug Power expanded the manufacturing facility that it opened in 2018.

2019 Fuel Cell and Hydrogen Manufacturing Expansion Announcements			
Company	Location	Size/Capacity	Details
Proton Motor Fuel Cell GmbH	Nuremburg, Germany	Production capacity of 5,000-10,000 fuel cell units per year could be expanded to 30,000-50,000 per year.	New fuel cell production facility incorporating an innovative manufacturing robot as part of the FCH-JU project "Fit-4-AMandA" (Fit for Automatic Manufacturing and Assembly).
Umicore	Seoul, South Korea	New production plant near technology development center.	Announced late December 2018, with commissioning expected at end of 2019. Expanding its production capacity for fuel cell catalysts to support Hyundai Motors Group and other customers.

Investments

The financial community recognizes the value of the fuel cell and hydrogen industry, which saw significant investments in 2019.

AP Ventures, an investment fund with a focus on technologies and companies that use platinum group metals to address global challenges, launched Fund I in 2018 with a pre-existing portfolio from main investors Anglo American Platinum and the Public Investment Corporation. That portfolio included investments in businesses involved in the hydrogen value chain and fuel cell electric mobility.

Fund II received capital commitments totaling $90 million in a first close in 2018, and in 2019, AP Ventures announced several major advancements:

- **July**: The Mirai Creation Fund II, backed by Toyota Motor Corporation, became a limited partner in AP's Fund II.[31]
- **September**: Plastic Omnium committed $30 million to Fund II and became a limited partner and advisory board member.[32] Separately, Plastic Omnium opened two new R&D centers in July 2019: Δ-Deltatech, in Brussels, to conduct advanced research on clean energy systems, and ω-Omegatech, in Wuhan, China, to develop Asian projects and hydrogen.

Also in July, AP Ventures joined with Dutch tank and storage company Royal Vopak, Mitsubishi Corporation, and chemical company Covestro to invest €17 million (US$19 million) in Hydrogenious LOHC (liquid organic hydrogen carrier) Technologies.[33] In December, Hydrogenious received an additional €3.5 million (US$3.9 million) from the Winkelman Group.[34]

Nikola Motors entered into a strategic and exclusive partnership with CNH Industrial N.V., an American–Italian multinational company that acquired a $250 million strategic stake in Nikola as the lead Series D investor.[35]

In October, ITM Power, based in the UK, received a £38 million (US$48 million) investment by Linde UK Holdings No. 2 Limited (a member of Linde AG group) to enhance electrolyzer manufacturing capabilities.[36]

Also in October, Hyundai Motor Company announced that it had invested in three companies to expand its work in fuel cell vehicles and hydrogen infrastructure:[37]

- Impact Coatings of Sweden, a supplier of ceramic coatings, to research and develop next-generation materials, processes and equipment for fuel cells and hydrogen production
- H2Pro of Israel, to work on the company's E-TAC water splitting technology for hydrogen production
- GRZ Technologies, a hydrogen energy storage company in Switzerland

Government Initiatives, Funding, and Activities

U.S. Federal Activity

From funding the first commercial use of fuel cell systems in the Gemini space missions to today's continued investments in research and development, the U.S. federal government has long been a leader in promoting fuel cell and hydrogen technologies in the United States.

The support of federal agencies and initiatives has led to significant R&D improvements for fuel cell and hydrogen technologies, as well as demonstrations of fuel cells in new applications that have proved market viability and allowed the industry to prosper in the United States. These programs have helped grow interest and markets for fuel cell and hydrogen technologies around the world.

U.S. Department of Energy

U.S. DOE, the federal agency leading the portfolio of national energy activities, has been instrumental in supporting and advancing research, development, and deployment of fuel cell and hydrogen technologies, particularly in early-stage R&D, feasibility testing, and inter- and intra-agency collaboration. The DOE's Hydrogen Program includes activities across multiple DOE offices, including Energy Efficiency and Renewable Energy (EERE), Fossil Energy, Nuclear Energy, Electricity, and Science, and it coordinates with the Advanced Research Program Agency–Energy.

DOE's Hydrogen and Fuel Cell Technologies Office (HFTO) within EERE has been the focal point of the federal government's efforts in fuel cell and hydrogen technologies, emphasizing R&D that has led to significant cost reductions and increased durability in fuel cell and hydrogen systems.[38]

Other offices in DOE work with HFTO on a wide range of R&D and demonstration projects, including the Advanced Manufacturing Office, Bioenergy Technologies Office, Vehicle Technologies Office, ARPA-E, Office of Science, the Office of Fossil Energy, and Nuclear Energy, and several National Laboratories. The 2019 DOE Annual Merit Review, which was held April 29–May 1, 2019, provided presentations and status updates on these intra-agency projects.[39] Interagency collaborations between HFTO and other federal agencies, such as the Federal Transit Administration, Federal Railroad Administration, U.S. Environmental Protection Agency (EPA), and others were highlighted as well.

In 2019, HFTO supported the launch of the Center for Hydrogen Safety (CHS), led by Pacific Northwest National Laboratory (PNNL) and the American Institute of Chemical Engineers (AIChE). The CHS promotes hydrogen safety and best practices worldwide by providing access to AiChE's

60,000 stakeholders in hydrogen safety, codes and standards across 110 countries. In direct response to the DOE's federal advisory committee on hydrogen and fuel cells, PNNL's partnership with AiChE to form the CHS, addresses a barrier identified in terms of providing safety resources to a growing number of new stakeholders involved in hydrogen.[40]

HFTO's H2@Scale concept explores the potential for wide-scale hydrogen production and use in the United States. This initiative has emerged as DOE's leading force in driving innovation and deployment of new applications of fuel cells and hydrogen, including medium- and heavy-duty transportation, metals refining, data centers, marine applications, and synthetic natural gas production. In 2019, HFTO continued building on the successes of H2@Scale by awarding more than $40 million to 29 projects to advance the H2@Scale vision of large-scale hydrogen production, storage, transport, and use across sectors.[41] Among the projects selected, three H2@Scale projects will demonstrate integrated hydrogen production, storage, and fueling systems in Texas, Illinois, and Florida, including collaborations with utilities and expanded electrolyzer operations with nuclear facilities.

HFTO joined the Vehicles and Bioenergy Technology offices in funding $50 million for 24 projects that will address R&D challenges in gaseous fuels, including several projects on hydrogen.[42] Projects relating to hydrogen included one project for Northwestern University to explore new materials for hydrogen storage, as well as three projects on high-throughput hydrogen fueling for medium- and heavy-duty transportation with Air Products and Chemicals, Nel Hydrogen, and Electricore. In addition, General Motors, Nikola Motors Corporation, and Carnegie Mellon University all received funding for high-durability, low platinum group metal membrane electrode assemblies (MEAs) for medium- and heavy-duty truck applications.

Additional DOE projects funded in fiscal year 2019 included novel hydrogen carrier development, hydrogen materials compatibility research and development, advanced water-splitting materials research, research on affordable biological hydrogen production from biomass, co-production of hydrogen and value-added byproducts, and reversible fuel cell development and validations. Examples of companies that received funding for these awards included FuelCell Energy, Proton Energy Systems, Giner ELX, Nexceris, Redox Power Systems, The Chemours Company, and a wide range of universities and research institutions.

In 2019, DOE also engaged with its counterparts on the international stage at a variety of high-level workshops, meetings, and announcements. Increased global collaboration in hydrogen emerged as a predominant theme during multiple international engagements with minister-level participation including the Hydrogen Energy Ministerial by Japan and the Clean Energy Ministerial, launched by Canada with the U.S. as one of the co-leads, as well as the G20 Summit, where a key report was released by the IEA on hydrogen. These meetings set key priority areas and provided guidance for working level participation in partnerships between governments, including the IPHE. A key outcome in 2019 was the Global Action Agenda, through Japan's Hydrogen Energy Ministerial which includes global, aspirational targets to provide a signal to the investment community by countries worldwide intending to deploy "10, 10, 10" - 10 million fuel cell systems and 10 thousand hydrogen fueling stations (for multiple applications) in 10 years. HFTO continued to play a key role in all these international collaborations and coordinate activities to avoid duplication and leverage resources.

U.S. Department of Defense

In addition to DOE, many other federal departments and agencies have been active in supporting the development of the fuel cell and hydrogen industry in the United States, including the Department of Defense (DOD).

For years, DOD has been demonstrating novel uses of fuel cell technologies to better equip our nation's military and protect national security. From early deployments of fuel cell vehicles to portable fuel cell power for individual soldiers to unmanned vehicles and power for logistics equipment, the DOD has been driving fuel cell and hydrogen innovation.

In October 2019, DOE's EERE announced a collaboration with the U.S. Army's Ground Vehicle Systems Center and the U.S. Army Corps of Engineers to develop and demonstrate "H2Rescue"—a hydrogen fuel cell powered emergency relief truck.[43] The H2Rescue project will include a feasibility study and the development of a joint plan for demonstration to ensure that the truck meets the needs of users in the emergency management field.

Through a DOD Commercial Technologies for Maintenance Activities cooperative agreement,[44] the National Center for Manufacturing Sciences awarded a team from Nikola Powersports and Pratt & Miller Engineering a project to integrate a hydrogen fuel cell into the Nikola Reckless electric vehicle.

In addition to these highlights, DOE's various Offices, as well as branches of the military through DOD, invested in a range of projects via different programs and funding mechanisms throughout 2019. A comprehensive list of all federal funding awards for the fuel cell and hydrogen sector are detailed in Appendix I.

International Initiatives, Funding, and Roadmaps

In 2019, many countries reaffirmed support for fuel cells and hydrogen through investment programs, policy frameworks, roadmaps, collaborations, partnerships, and other major initiatives to move the industry forward. Specific activities to advance and support fuel cell vehicles, as well as hydrogen infrastructure and generation, are outlined in the respective sections.

South Korean government agencies unveiled the country's *Hydrogen Economy Roadmap*[45] at the beginning of the year, laying out a list of goals for fuel cell and hydrogen deployment:

- Production of 100,000 FCVs for both domestic use and export by 2025, increasing to 6.2 million (2.9 million domestic and 3.3 million for export) by 2040
- 1.8 million FCVs deployed by 2030
- 1,200 hydrogen fueling stations by 2040
- 2,000 fuel cell buses by 2022, and the replacement of all police buses (820) with fuel cell buses by 2021, increasing to 40,000 fuel cell buses by 2040
- 80,000 fuel cell taxis and 30,000 heavy-duty trucks by 2040
- 1,500 MW of stationary fuel cells by 2022, increased manufacturing of fuel cell systems to reach 15 GW by 2040, with 8 GW for domestic use

In February, the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), a European public-private organization, released *Hydrogen Roadmap Europe: A Sustainable Pathway for the European Energy Transition*,[46] a report that reinforces the important role hydrogen must play to meet decarbonization goals.

To help with that transition, FCH JU is funding important R&D projects in a host of areas involving fuel cells and hydrogen technologies. Projects announced in 2019 under FCH JU's Horizon 2020 (2014-2020) program (funding not yet allocated) are outlined in Appendix II, and several that began during 2019 are included in this report.

- At the end of the year, the European Commission presented the European Green Deal, making hydrogen a key component of reaching its goal of net-zero carbon emissions by 2050.[47]
- A net-zero plan that mandates net-zero GHG emissions by 2050 was passed in the United Kingdom in June.[48]
- Also in June, Canada's Minister of Environment and Climate Change and the Chair of the California Air Resources Board (CARB) signed an MoU committing both governments to work together on zero-emission vehicle (ZEV) regulations to cut greenhouse gas emissions from light-duty vehicles.[49]
- Australia released its National Hydrogen Roadmap in November, providing a plan for the country to develop a hydrogen industry and encourage investments to make hydrogen competitive in various market sectors.[50]

Additional initiatives, funding, and activities for specific markets are outlined in the respective sections of this report.

Stationary Fuel Cell Sales and Installations

The stationary sector includes fuel cell systems that operate at a fixed location for primary power, backup power, or CHP. Fuel cells are being developed for both large-scale (100 kW and up) and small-scale (up to 100 kW) applications and deployed to a wide range of customers, including retail operations, data centers, residential, telecommunications, utilities, and many more. This sector is organized by large scale, small scale, and backup and remote power.

The U.S. is home to several of the world's largest fuel cell companies, which primarily manufacture large-scale fuel cell systems. The country also boasts the most installations of these systems, and in 2019 reached more than 550 MW of installed fuel cell capacity.*

While other countries have some installations of multi-MW fuel cell systems, none come anywhere close to the U.S. in terms of the number of large-scale installations. South Korea claims some of the world's largest installations, with several multi-MW fuel cell power parks installed at major utilities and approximately 300 MW of total systems deployed. Japan and Europe have a handful of larger systems but are mainly focused on small-scale fuel cell systems for homes and businesses. In the U.S., small-scale fuel cell systems are primarily used for backup power for communications

* Based on Fuel Cell and Hydrogen Energy Association (FCHEA) internal calculations

sites, with customers that include telecommunications, railroad, utilities, government, and traffic/emergency systems. To reinforce the role fuel cells can play in reducing carbon emissions from residential and commercial buildings in Europe, a Joint Declaration on Stationary Fuel Cells for Green Buildings was signed in November by industry and key stakeholders, emphasizing the potential of stationary fuel cells to decarbonize the buildings sector in Europe.[51]

New Products

There were several new product launches in 2019 in the large-scale market:

- Bloom Energy, based in Sunnyvale, California, with a manufacturing facility in Newark, Delaware, manufactures large-scale solid oxide fuel cell systems. In 2019, Bloom announced new products in its portfolio, including the AlwaysON Microgrid Solution[52] and energy servers that will run on hydrogen.[53] The company also now offers short-term financing options for the AlwaysON system.
- FuelCell Energy, based in Danbury, Connecticut, manufactures both MCFC and SOFC systems. The company relaunched its sub-MW SureSource 250 and SureSource 400 MCFC fuel cell distributed generation solutions in Europe.[54] These fuel cell systems are manufactured at its facility in Torrington, Connecticut, and assembled in Taufkirchen, Germany.
- In small-scale systems, UK SOFC manufacturer Ceres Power introduced its new CHP fuel cell system, designed exclusively for use with hydrogen fuel,[55] and Italy-based SOLIDpower also introduced its next generation SOFC-based BlueGEN BG15.

In addition to the building sector, fuel cells made headway in a new market—powering charging systems for battery electric vehicles. In addition to the joint venture between German companies Proton Motor Fuel Cell GmbH and Schäfer Elektronik GmbH for this application, in December, UK alkaline fuel cell manufacturer AFC Energy launched its H-Power™ modular, self-contained fuel cell powered charging system.[56] This product launch was the result of a successful demonstration project earlier in the year, where AFC's CH2ARGE™ electric vehicle charger was deployed at Dunsfold Aerodrome in Surrey, UK. The CH2ARGE fueled up a BMW i8 FCV at the BBC Top Gear test track.[57]

Large-Scale Stationary Systems

In 2019, there were more than 130 MW of publicly announced sales and installations of large-scale fuel cell systems around the world. In addition to fuel cell manufacturers with commercially available stationary fuel cell products, automakers Hyundai and Toyota installed stationary systems adapted from the fuel cells used in FCVs.

Table 5: Examples of Publicly Disclosed Large-Scale Orders and Installations in 2019

Examples of Publicly Disclosed Large-Scale Orders and Installations in 2019			
Customer/Partner	Location	Power	Details
Ballard Power Systems			
Hydrogene de France (HDF Energy)	French Guiana	3 MW total	In December, Ballard signed a product development agreement with HDF Energy to develop and integrate two fuel cell systems totaling 3 MW into HDF Energy's Renewstable® power plant and install it in French Guiana, under the Centrale Electricité de l'Ouest Guyanais (CEOG) project. The project will involve 90 MWh of hydrogen energy storage.[58]
Bloom Energy			
Agilent Technologies	Santa Clara, California, and Little Falls, Delaware	3.5 MW total	Two units—one installed in April at Agilent's corporate headquarters in Santa Clara, California, and the other at its business unit in Little Falls, Delaware.[59]
Atelier Global	Bangalore, India	1 MW	As announced in August, Atelier Global, GAIL Limited and Indian Oil Corporation plan to install the fuel cell system in Whitefield Tower, a commercial real estate development in Bangalore, India.[60]
Duke Energy One	Customer sites in California, Connecticut, Maryland, and New York	37 MW	Duke Energy One, a non-regulated subsidiary of Duke Energy, will purchase approximately 37 MW of Bloom Energy servers for customers at more than 30 sites in California, Connecticut, Maryland and New York, including hospitals, technology companies, data centers, and universities.[61]
Extreme Networks	San Jose, California	N/A	As announced in March, Extreme Networks will install the fuel cell system at its corporate headquarters.[62]
Fordham University	Bronx, New York	250 kW	In September, Bloom announced that a fuel cell system will be powering the William D. Walsh Family Library at Fordham University.[63]
II-VI Incorporated	Warren, New Jersey	2.5 MW	In March, II-VI began operation of a Bloom Energy system in a microgrid configuration at its manufacturing facility.[64]
Korea Midland Power Co. (KOMIPO)	Seoul, South Korea	6 MW	In January, SK Engineering & Construction (SK E&C) of South Korea announced three contracts to install Bloom Energy systems for KOMIPO. The systems will be installed in a cultural park in Seoul to provide electricity directly to the national grid.[65]
KT Corporation	Seoul, South Korea	1.8 MW total	In another SK E&C project, two 900 kW systems installed for telecommunications company KT Corporation will provide electricity to the national grid.
The Ratkovitch Company	Alhambra, California	1 MW	As announced in April, the Ratkovitch Company design firm is installing the fuel cells at the Alhambra, a 40-acre mixed-use urban community.[66] Ratkovitch first installed Bloom fuel cells in 2010.
Doosan Fuel Cell America			
City of Bristol	Bristol, Connecticut	400 kW	In April, Doosan Fuel Cell America signed a contract to install its fuel cell system at the Bristol, Connecticut, wastewater pollution control facility.[67]

Examples of Publicly Disclosed Large-Scale Orders and Installations in 2019			
Customer/Partner	Location	Power	Details
Centrica Business Solutions	South Windsor, Connecticut	4.99 MW	In March, Centrica Business Solutions, part of Centrica plc, invested in the development of a 4.99 MW fuel cell facility that will deliver power to the local utility, Eversource Energy, under a 20-year power purchase agreement (PPA).[68]
EIP, LLC	New Britain, Connecticut	19.98 MW	In October, EIP LLC, a project developer, broke ground on the construction of an energy and innovation park that will house data storage for large technology companies. When completed, it will be the world's largest indoor fuel cell installation.
Daesan Green Energy	Chungnam, South Korea	50 MW	In August, Daesan Green Energy, a joint venture between Korea East-West Power, Hanwha Energy and Doosan, announced that the world's largest hydrogen power plant will be installed at the Seosan Hanwha site.[69]
FuelCell Energy			
City of San Bernardino	San Bernardino, California	1.4 MW	In April, FCE announced it will be installing a 1.4 MW fuel cell at the San Bernardino Municipal Water Department's water reclamation plant. The fuel cell will run on anaerobic digester gas generated at the facility.[70]
National Energy Technology Laboratory	Pittsburgh, Pennsylvania	200 kW	Solid oxide fuel cell.
City of Tulare	Tulare, California	2.8 MW	In December, Tulare's wastewater treatment facility began commercial operation of a 2.8 MW system, running on renewable biogas generated onsite.[71]
Hyundai			
Hyundai Mobis	Chungju, South Korea	450 kW	In February, Hyundai Mobis, the automotive parts supplier for the Hyundai Motor Group, announced the installation of a hydrogen fuel cell power system at its FCV components manufacturing facility.[72] The fuel cell system is composed of five Hyundai NEXO FCV power systems and will be used for emergency power during power grid failures at the factory and as auxiliary power during seasonal peak times.
Korea East-West Power (EWP) and Deokyang	Ulsan, South Korea	1 MW	In April, Hyundai signed an MoU with EWP and Deokyang for a pilot project to install two container-type 500 kW generator modules that will utilize byproduct hydrogen brought from a nearby petrochemical complex through a pipe network.[73]
Toyota			
Toyota	Toyota City, Japan	100 kW	In September, Toyota installed a stationary fuel cell based on its Mirai FCV and installed it at its Honsha Plant in Toyota City for testing.[74]

In addition to new customers announced in 2019, Bloom Energy will upgrade the fuel cells at an existing 30 MW fuel cell project at two sites in New Castle and Newark, Delaware.[75] This upgrade is enabled by an investment by Southern Power, a subsidiary of Southern Company.

Expanding further into South Korea, in February Bloom also entered a new distributorship agreement with SK D&D, a development company, to supply fuel cells for SK D&D projects.[76]

In addition to the sales and installations listed in Table 5, FuelCell Energy had several other significant ventures during the year:

- Closed on the acquisition of the 14.9 MW fuel cell park in Bridgeport, Connecticut, with Dominion Energy.[77]
- Completed an initial $80 million draw, of a $200 million loan, to go towards construction and engineering costs associated with inflight projects, including the CMEEC Fuel Cell Micro-Grid Project in Groton, Connecticut, and the Tulare BioMAT project, which went into operation in December.[78]
- Worked with E.ON Business Solutions GmbH of Germany to focus on the European market.[79]

In addition, FuelCell Energy expanded its footprint in the carbon capture sector.

- In June, the company entered into a $10 million license agreement with EMRE, a wholly owned subsidiary of ExxonMobil Corporation, to facilitate the further development of its SureSource Capture™ product.[80]
- In October, FuelCell Energy signed a new, $60 million, two-year expanded joint development agreement with EMRE to further enhance its carbonate fuel cell technology to capture carbon dioxide (CO_2) from industrial facilities.[81]
- FuelCell Energy also entered a new contract with Drax Power Station in the UK to provide a front-end engineering and design study evaluating the use of its fuel cell systems to capture CO_2 from biomass boilers.[82]

Small-Scale Stationary Systems

Smaller stationary fuel cells (100 kW or less) are commercially available from different manufacturers around the world, geared for a variety of applications and end users. As with large-scale stationary systems, there is a range of fuel cell options, including PEM, SOFC, and alkaline. The fuel source for these fuel cells varies from country to country. In Japan and Europe, fuel cells installed at homes or businesses tend to run on natural gas, town gas, or other comparable fuels. In the U.S., small-scale fuel cells primarily use hydrogen and are installed for backup power to support communications networks or railroad and traffic signals. Some fuel cell systems are also configured to use methanol or ammonia.

Small-scale fuel cells were deployed in 2019 for primary and backup power for a range of customers and applications.

The residential market has taken hold primarily in Japan and Europe. In Japan, Ene-Farm brand micro-CHP fuel cell systems are manufactured by several companies (Panasonic, Toshiba, and others) and offer capacities ranging from 0.3 kW to 1 kW.

- According to Japan's New Energy and Industrial Technology Development Organization's Agency for Natural Resources and Energy, 30,000 Ene-Farm

residential fuel cell systems were sold in 2019,** bringing the cumulative number since the units were first introduced to 306,000. The 2019 number is down from 2018, when 41,300 Ene-Farms were sold. There are several companies manufacturing both PEM and SOFC fuel cells under the Ene-Farm brand name.

- The Japanese company Miura, not part of the Ene-Farm brand of products/companies, is working with UK-based fuel cell manufacturer Ceres Power to develop a new 4.2 kW CHP fuel cell system, the FC-58, for the commercial building sector.[83]
- Ceres also entered into a two-year, £8 million (US$10 million) agreement with Doosan Fuel Cell of South Korea to develop a low-carbon 5–20 kW SOFC power system for South Korea's commercial building market.[84]
- Ballard Power Systems' European subsidiary, Ballard Power Systems Europe A/S, signed framework agreements to supply its FCgen®-H2PM direct hydrogen backup power systems to the communications companies Eniig and Fibia A/S in Denmark.[85] Ballard also received initial orders for a total of 30 FCgen-H2PM 5 kW systems—20 for Eniig and 10 for Fibia—including installation, hydrogen storage, and power management equipment.
- GenCell Energy, an Israel-based alkaline fuel cell manufacturer, began the year by installing one of its 5 kW hydrogen-fueled G5 Long-Duration UPS fuel cell systems at the Hillel Yaffe Medical Center in Hadera, Israel.[86]
- In February, GenCell entered into a strategic partnership with the multinational technological manufacturer Flex, enabling the company to scale capacity and launch a new jointly designed production line.[87] Flex will initially manufacture GenCell fuel cells at its facility in Ofakim, Israel. GenCell announced new capabilities to its G5 fuel cell in March.[88]
- GenCell also expanded into the Philippines in May,[89] and soon afterward it appointed information technology provider AMOREL Technology Inc. to represent the company there, marketing its fuel cell systems to business, military, and first responder customers.[90]
- Proton Motor Fuel Cell GmbH was involved in pilot projects in Switzerland and Italy, using its S8 fuel cell module to power zero-emissions houses with partner GKN Powder Metallurgy and its Hy2green storage system.[91]
- In May, AFC Energy announced it had achieved the first successful integration of alkaline fuel cells with an ammonia cracker for hydrogen production.[92] The research and development was supported with funding from the FCH JU's Alkammonia Project and enabled AFC Energy to successfully demonstrate a scaled-up multi-MW solution.

Portable/Off-Grid Systems

Fuel cells have been developed and deployed in diverse portable applications, including consumer electronics battery charging, reliable backup or primary power for traffic and rail signal stations, surveillance, energy exploration, weather sensing and other equipment, low-heat, long-lasting

** Data sent to FCHEA

portable power for military applications, and auxiliary power for aircraft, marine, and recreational vehicle applications.

Table 6: Publicly Announced 2019 Portable/Off-Grid Sales and Orders

Publicly Announced Portable/Off-Grid System Sales and Orders in 2019		
Product	Customer	Order Details
Intelligent Energy		
1 kW fuel cell module	AJC Trailers	February: will be integrated into zero-emissions EcoSmart construction site "welfare cabins."
SFC Energy		
JENNY 1200 (50 W)	International Defense Organization	February: €I million (US$1.1 million) order to be used in multi-day military missions.
JENNY 600S and EMILY 3000	Defense customer (Asia)	May: €I.4 million (US$1.6 million) order includes SFC Power Manager 3G. Will power off-grid border protection equipment, electrical equipment, and mission-critical communication and radio systems.
EFOY hybrid power solutions	Okanagan Aggregates Ltd. (Canada)	September: will provide power for LED lighting arrays, rest stop washroom lighting, and a small weather station at each of the roadside areas along the Trans-Canada Highway in Canada's Yoho National Park.
SFC hydrogen fuel cells	adKor GmbH	November: for radio tower sites in several federal states in Germany. Total order volume potential of ~€1.8 to 5.3 million (US$2–6 million).

SFC Energy, based in Germany, has several subsidiaries and resellers operating in different countries around the world. In 2019, in addition to the sales orders outlined in the table above, the company received a €1 million order from a German mobility and security technology group to conduct energy and environmental impact analyses on military vehicles.[93]

SFC Energy's subsidiary Simark Controls Ltd. signed several EFOY Pro hybrid fuel cell solution distribution agreements in 2019, expanding its network into North America:

- Vector Controls and Automation Group to service its oil and gas, water, and wastewater industry customers in Texas, Kansas, Oklahoma, and New Mexico.[94]
- LaTech Equipment for its oil and gas, mining, security, telecom and radio, environmental monitoring, and rail signal and control customers in Utah, Idaho, Wyoming, Montana, Colorado, and North Dakota.[95]
- Axsera Inc. to power critical off-grid telecommunications equipment in Canada and the U.S.[96]

While portable fuel cells also include smaller units for battery charging or replacement, that market sector had minimal activity in 2019.

After an announcement in February that it had signed a non-exclusive distribution agreement and order for 2,000 of its JAQ Hybrid with Trenditrade 21 fuel cell based power bank in Africa, Swedish

fuel cell manufacturer myFC shut down its consumer products division in May.[97] The company did not fulfill any existing orders after that announcement.

Transportation

Fuel cell technology is being developed, incorporated, and commercialized into different vehicle platforms, ranging from light-duty passenger cars and sport utility vehicles to medium- and heavy-duty buses, vans, and trucks, and even to trains, planes, and ships. Fuel cell powered material handling and logistics equipment is also being deployed in warehouses and distribution centers and expanding to ports and airports to help increase energy efficiency as well as increase the equipment's productivity.

Spotlight On: Heavy-Duty Trucks

The transportation sector is one of the leading contributors to global pollution. In the U.S., the EPA reports that in 2017, the transportation sector was responsible for 29% of all U.S. greenhouse gas (GHG) emissions. Of that 29%, 23% is attributed to medium- and heavy-duty trucks.[98] In Europe, 25% of all transportation GHG emissions are from heavy-duty trucks.[99] Canada's freight industry, which includes ships and rail as well as trucks, contributes 10.5% of the country's total GHG emissions.[100]

Traditional heavy-duty vehicles, while making up a small portion of the overall vehicle market, consume a significant amount of fuel because of their low fuel economies. In China, the heavy-duty sector accounts for 50% of fuel consumption while making up just 10% of total vehicles on the road.[101]

Most heavy-duty vehicles use diesel engines, which are notably noisy and emit high levels of pollutants. To help reduce the amount of GHG and other emissions from diesel fuel, a wide range of government entities are enacting or proposing regulations on carbon emissions and fuel economy standards for heavy-duty trucks.

In 2005, Japan adopted the world's first fuel economy regulations for heavy-duty vehicles.[102] In March 2019, the country enacted the second phase of these standards, requiring a further 13.4% efficiency improvement over the first phase.[103] These standards will begin for model year 2025.

In the United States, the U.S. EPA and the National Highway Traffic Safety Administration (NHTSA) work together on medium- and heavy-duty truck standards for GHG emissions and fuel economy. To differentiate between the different classes of commercial motor vehicles, the EPA uses the gross vehicle weight rating (GVWR). Medium-duty trucks are used for a variety of purposes; the most common are delivery vans and municipal applications. These medium-duty vehicles are categorized as commercial truck Classes 4, 5, and 6 and operate with a GVWR range of 14,001–26,000 lbs.

Heavy-duty trucks are primarily used to transport goods from one location to another in long-haul and short-haul operations. These heavy-duty vehicles make up Class 7, which includes vehicles with a GVWR of 26,001–33,000 lbs, and Class 8, vehicles with a GVWR of more than 33,001 lbs.

The most recent EPA/NHTSA standards in effect, known as Phase 2, were finalized in 2016 and cover model years 2018-2027 for certain trailers and model years 2021-2027 for semi-trucks,

large pickup trucks, vans, and all types and sizes of buses and work trucks. Phase 2 also focuses on increasing fuel efficiency and encourages the development of new and advanced technologies. According to the EPA, these standards are expected to lower CO_2 emissions by approximately 1.1 billion metric tons, reduce oil consumption by up to two billion barrels, and save consumers more than $170 billion on fuel costs.[104]

In June 2019, the Council of the European Union adopted the country's first standard for CO_2 emissions for heavy-duty trucks, mandating that new trucks will have to reduce emissions by 15% by 2025 and 30% by 2030, compared to 2019 levels.[105]

In China, the government is aiming to decrease the fuel consumption of heavy-duty vehicles by ~15% to reduce its total vehicle emissions. The standard will apply to new commercial trucks, buses, and tractors beginning in July 2021.[106]

Many jurisdictions—ports, airports, urban and residential areas, and others—are also proposing or passing regulations and legislation restricting the use of loud diesel engines in order to reduce harmful noise pollution.

Fuel Cells for Heavy-Duty Trucking

There are already tens of thousands of fuel cell powered cars and material handling vehicles deployed around the world, as well as hundreds of fuel cell buses, demonstrating that the technology can be scaled and is well-suited for larger vehicles. Fuel cell use in the medium- and heavy-duty sector is steadily growing, with investments, demonstrations, initial orders, and deployments of fuel cell powered trains, ferries, and, most predominantly, trucks.

Fuel cells are more efficient than gasoline or diesel engines and provide a variety of benefits compared with those technologies. In the medium- and heavy-duty sector, those benefits are amplified. With no tailpipe emissions and quiet operation, fuel cell powered trucks are able to serve customers in low-emission zones, as well as in urban, residential, or noise-restricted areas, at any hour.

Unlike batteries, fuel cell systems can be scaled up to meet any power need without sacrificing performance. They also operate at a steady rate in cold temperatures, with no voltage sag. In addition to refueling times faster than battery charging, hydrogen, including the weight of the hydrogen storage tank, has much higher gravimetric energy density than batteries. In trucks, the weight and volume of the batteries needed to meet the required range can limit the amount of cargo that can be carried, and the added weight means the vehicle needs more energy to operate. Finally, fuel cells also do not suffer from a significant loss of range due to cold or hot temperatures.

Smaller fuel cell systems can be integrated as range extenders into battery electric vehicles (BEVs), and larger ones can provide primary power, adding much less weight than batteries when scaled up for larger Class 8 vehicles.

Early Tests Provide Pathway

While garnering significant attention only from trade media and various industry stakeholders, fuel cells have long been trialed in a range of medium- and heavy-duty vehicles. Some of the first demonstrations of fuel cells in transportation were in farming and utility vehicles: The earliest, an

Allis-Chalmers tractor with a 15 kW fuel cell motor, was in 1959. Other examples of initial fuel cell vehicle demonstrations, decades later, include the following:

- In 1999, a utility truck developed by Coval H2 Partners for the UK government. Used for parks maintenance.
- In 2006, a step van developed by Hydrogenics and used by the maintenance team at Hickam Air Force Base in Hawai'i. Vehicle had a 65 kW fuel cell.
- In 2007, a mine loader developed by Fuelcell Propulsion Institute, Nuvera, Caterpillar, and other partners and supported by DOE. The vehicle had a 160 kW fuel cell.

The U.S. DOE, through HFTO, has invested in the nascent medium- and heavy-duty fuel cell vehicle market sector through numerous demonstration projects over the past decade. These projects brought together public and private sector teams to develop and test fuel cell powered vehicles in the real world—at ports and on delivery and transit routes. These demonstrations included initial work on fuel cells for auxiliary power units (APUs), transport refrigeration units (TRUs), range extenders, and primary power.

In the early to mid-2000s, there was increased interest in using fuel cells as APUs—to power on-board electronics and air conditioning while trucks idled—on heavy-duty trucks using diesel fuel. DOE funded several projects testing the use of solid oxide fuel cells for these APUs.[107] DOE found that using fuel cell APUs would save approximately 700 million gallons of diesel fuel, resulting in substantial cost savings, and reduce carbon dioxide (CO_2) by 8.9 million metric tons per year.[108]

In 2013, DOE funded two separate demonstration projects to determine the feasibility of fuel cell powered TRUs, awarding $650,000 to fuel cell manufacturers Plug Power and Nuvera and their teams of trucking, logistics, and other partner companies. Plug Power worked with Carrier Transicold, Sysco Corporation (Long Island, New York), and Air Products, while Nuvera's team included Thermo King, Sysco Corporation (Riverside, California), and grocery chain H-E-B. Pacific Northwest National Laboratory oversaw both demonstrations.

That work evolved into demonstrations of fuel cell powered trucks, utility vehicles, and baggage tow tractors at ports and airports, all of which helped validate the feasibility of the technologies in medium- and heavy-duty vehicles.

The focus on ports for several of its market transformation projects was due to the large impact ports have on the surrounding environment, with pollutants coming from not only the cargo ships but from the vehicles moving and transporting the goods once they arrive. This includes material handling vehicles of all sizes, delivery vans, yard trucks, and larger Class 8 drayage trucks that move cargo, particularly containerized cargo, to and from the ships and marine terminals.

California Snapshot

California's policies are also focusing on reducing emissions, and in July 2016, the state published the *California Sustainable Freight Action Plan*[109] that set targets of improving freight efficiency by 25% and deploying more than 100,000 low- and zero-emission freight vehicles, powered by renewable energy, by 2030. Fuel cell vehicles fueled by renewably generated hydrogen would help California meet that goal.

Two of the biggest ports in the country, the ports of Los Angeles (POLA) and Long Beach (POLB), have been part of DOE and other demonstration projects testing the feasibility of fuel cell powered heavy-duty trucks and other logistics vehicles throughout the past decade, even before the *Freight Action Plan* was released. These projects have had numerous industry partners working together and were supported by funding from DOE and/or several state agencies, including the California Energy Commission, CARB, the South Coast Air Quality Management District (AQMD), and the Los Angeles Department of Water and Power.

For fiscal years 2016-2017, CARB solicited both on-road and off-road advanced technology demonstration projects and funded two significant demonstrations of fuel cell trucks. Both projects began in spring 2018 and run through spring 2020.

Table 7: CARB Advanced Technology Demonstration Fuel Cell Projects for FY 2016/2017

CARB Advanced Technology Demonstration Fuel Cell Projects for FY 2016/2017			
Project	Awardee/Partners	Amount/Partner Match	Details
Fast Track Fuel Cell Project[110]	Gas Technology Institute (GTI)/ TransPower, TTSI, Daylight, Frontier Energy, Center for Sustainable Energy, Hydrogenics, Loop Energy, Peterbilt Motors, OneH2	$5 million/$1.7 million	GTI and TransPower will deploy a total of five fuel cell electric hybrid trucks in Southern California. The three trucks deployed in the first phase will be operated for 15 months at the Port of Los Angeles. Two additional trucks, using a different fuel cell, will be deployed in a second phase and will be operated for 12 months throughout the San Diego and Los Angeles regions.
C-PORT: The Commercialization of POLB Off-Road Technology Demonstration Project[111]	POLB/Academy of Global Logistics, Air Products, BYD, CARB, CNHTC/ Sinotruk, Grant Farm, Green Education, Inc., ILWU, Long Beach Container Terminal, Loop Energy, South Coast AQMD, SSA Marine, Taylor Machine Works, Tetra Tech, UQM Technologies	$5.3 million/$3 million	Includes a head-to-head comparison of battery electric and fuel cell electric yard trucks at POLB. Loop Energy is providing the fuel cell for the yard truck.

In April 2017, automaker Toyota made big news when it unveiled its fuel cell powered Class 8 truck as part of "Project Portal," which tested the technology in drayage trucks servicing POLA and POLB. The first model, Alpha, used an 85 kW fuel cell system from Ballard Power Systems. The second, Beta, was powered by two Toyota Mirai FCV fuel cell systems. Both trucks are Kenworth T680 Class 8 models. The vehicles have logged more than 14,000 miles in service at the ports.[112]

The Zero and Near-Zero Emission Freight Facilities Project (ZANZEFF) program, which CARB announced in September 2018, awarded $205 million to 11 projects involving port and rail freight and goods movement vehicles.[113] Including private and public cost-sharing, the full investment in the ZANZEFF program is $400 million.

Four of the 11 projects include medium- and heavy-duty fuel cell powered vehicles and the supporting hydrogen infrastructure. Between them, the deployments include 10 Class 8 trucks, 19 delivery vans (two locations), and two yard trucks used to move semi-trailers within a cargo yard. The project timeline is winter 2019 through spring 2021. CARB is providing $58.8 million towards the four projects, and another $58.7 million from participating partners brings the total investment in these fuel cell and hydrogen projects to $117.5 million.

Table 8: CARB Zero and Near-Zero Emission Freight Facility (ZENZEFF) Program Fuel Cell Projects

CARB Zero and Near-Zero Emission Freight Facility (ZENZEFF) Program Fuel Cell Projects			
Project	Awardee	Amount/Partner Match	Details
Zero-Emission Freight "Shore to Store" Project	Port of Los Angeles	$41.1 million/$41.4 million	Ten Class 8 fuel cell powered trucks and two new large-capacity hydrogen fueling stations
Zero Emissions for California Ports	Gas Technology Institute (GTI)	$8 million/$6.3 million	Two hybrid fuel cell electric yard trucks and stationary mobile tube-trailer hydrogen fueling system
Next Generation Fuel Cell Delivery Van Deployment	Center for Transportation and the Environment (CTE)	$5.4 million/$5.8 million	Four fuel cell hybrid electric delivery vans for UPS for a minimum 12-month demonstration project in Chino
Fuel Cell Hybrid Electric Delivery Van Deployment	CTE	$4.3 million/$5.2 million	Expansion of UPS project in Ontario: 15 new fuel cell hybrid electric delivery vans

The "Shore to Store" project, awarded $41 million by CARB, focused on ten new fuel cell powered Class 8 trucks, developed by Toyota and Kenworth, to move cargo from the Port of Los Angeles, initially to the Los Angeles basin and then expanding to various locations. Several different companies will operate the trucks: Toyota Logistics Services will receive four, UPS will receive three, Total Transportation Services, Inc. will receive two, and Southern Counties Express will receive one.[114]

California also offers up to $300,000 in vouchers for fuel cell powered Class 7 and 8 trucks through its Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP).[115]

Industry Advancements

In 2019, Hyundai became another automotive original equipment manufacturer (OEM) to join Toyota in moving from fuel cell powered light-duty vehicles to the heavy-duty sector. In April, Hyundai joined with H2 Energy AG of Switzerland and established Hyundai Hydrogen Mobility.[116] As part of this venture, Hyundai will deliver 1,600 hydrogen fuel cell heavy-duty trucks from 2019 through 2025 to Hyundai Hydrogen Mobility, which will then lease them to the Mobility Switzerland Association and other industry stakeholders in Switzerland. Hyundai unveiled its new Class 8 fuel cell truck in October 2019.[117]

In addition to OEMs, several established fuel cell manufacturers have begun offering products to support and power medium- and heavy-duty platforms, and new startup companies have formed

solely to focus on this market. In 2019, the medium- and heavy-duty fuel cell market continued its growth with several key partnerships and investments across the sector.

- In January 2019, Proton Power Systems plc, based in Puchheim, Germany, joined with private holding company Höpen GmbH and transport provider Hary AG to establish Clean Logistics GmbH, a joint venture to develop fuel cell powered heavy-duty trucks.[118] The trucks will use Proton's fuel cells in the 75–100 kW range.
- In April, PowerCell, a fuel cell stack and system manufacturer based in Sweden, joined with global supplier Bosch to work on large-scale production of PowerCell's MS-30 fuel cell systems for both cars and trucks.[119] In November, PowerCell unveiled a new product, the MS-100 fuel cell, for the heavy-duty sector.[120]
- Nuvera Fuel Cells completed testing of its new 45 kW fuel cell engine and is working with partners in Europe and China to integrate the systems into medium- and heavy-duty vehicles.[121]
- In September, Cummins, an American Fortune 500 corporation that designs, manufactures, and distributes engines, components, and power generation products, made two major investments in fuel cell companies, with a focus on heavy-duty applications. These investments included:
  - Cash investment in Loop Energy, a provider of fuel cell electric range extenders for medium- and heavy-duty transport applications[122]
  - A $290 million acquisition of Hydrogenics Corporation, a fuel cell manufacturer and hydrogen generation company[123]

Table 9: Examples of Commercially Available Fuel Cell Systems for Medium- and Heavy-Duty Vehicles

Examples of Commercially Available Fuel Cell Systems for Medium- and Heavy-Duty (MD/HD) Vehicles			
Company	Product	Size	Details
Ballard	FCveloCity®	30 kW, 85 kW, 100 kW	MD/HD Class 4-8 Range extender, primary power
	FCmove™	70 kW	Primary power
Cummins/ Hydrogenics	HyPM-HD	30 kW – 180 kW	MD/HD Class 4-8 range extender, primary power
	Celerity™	60 kW	Integration-ready
	CelerityPlus™	60 kW	Drop-in installation
Loop Energy	Range extender	30 kW, 50 kW	Port drayage, container trucks, vocational trucks
Nuvera	Nuvera® 45 kW Fuel Cell Engine	45 kW	Range extender, primary power
Plug Power	ProGen	20 kW – 100 kW	Range extender, primary power
PowerCell	MS-30	10-30 kW	Range extender
	MS-100	100 kW	Primary power
U.S. Hybrid	FCe™ 10, 40, 50, 80, 100, 150	10, 40, 50, 80, 100, 150 kW	Range extender, primary power
	LEGACY UTCPOWER	120 kW	Primary power

Start-up company Nikola Motors introduced the Nikola One Class 8 concept truck, which can integrate fuel cells or batteries, in 2016. Since then, the company has announced that it has received reservations for the truck valued at $10 billion.[124] In April 2019, Nikola unveiled the Nikola Two, with fuel cell powertrain partner Bosch.[125] The third iteration, the Nikola Tre, is geared toward the European market. The fuel cell version is slated to be available to customers in 2023.[126]

Nikola has also gained a number of investors: In 2019, the company announced major partners including Bosch, Hanwha, and CNH. The total investment from these three companies is close to US$500 million.[127, 128] The company entered into a joint venture with IVECO, part of CNH, in December 2019.

One customer, Anheuser-Busch InBev, headquartered in Leuven, Belgium, placed an order for 800 of Nikola's fuel cell trucks in 2018, and in November 2019 completed a "zero-emission beer delivery" from the company's St. Louis, Missouri, headquarters, using one of the hydrogen-fueled trucks for the first part of the trip.[129]

Table 10: Examples of Fuel Cell Powered Trucks in Development

Examples of Fuel Cell Powered Trucks in Development					
Company	Vehicle	Type	Fuel Cell	OEM Make and Model	Status
Chereau	ROAD	Refrigerated semi-trailer	H2SYS	Carrier Transicold	Began testing in July 2019.
Cummins		Class 8 Truck	90 kW, scalable in 30 kW or 45 kW increments up to 180 kW	Cummins	Demonstration vehicle unveiled October 2019.
Daimler Truck & Buses	Vision F-Cell	Class 8 Truck	135 kW	Mitsubishi Fuso Truck and Bus Corporation	Unveiled in October 2019 at the Tokyo Motor Show. Daimler committed to goal of series production by end of 2020s.
Horizon Fuel Cell Technologies/JMC		Class 8 Truck	150 kW	Ford Motor Company	Working with Ford joint venture with Jiangling Motors (JMC). Demonstration vehicle unveiled in September 2019.
Hyundai	HDC-6 NEPTUNE/ Xcient	Class 8 Truck	190 kW	Hyundai	In development.
Nikola Motor Company	Nikola One	Class 8 Truck	PowerCell	Nikola	Sleeper model for North America set for 2022 release.
	Nikola Two	Class 8 Truck	Bosch	Nikola	Day cab model for North America set for 2022 release.
	Nikola Tre	Class 8 Truck	Bosch	Nikola	Scheduled for release to European market in 2023.

Examples of Fuel Cell Powered Trucks in Development					
Company	Vehicle	Type	Fuel Cell	OEM Make and Model	Status
Scania	N/A	Fuel cell garbage truck	PowerCell	JOAB	Developed in partnership with the Swedish Energy Agency and Stockholm's Royal Institute of Technology, the truck is expected to be delivered by 2020.
Toyota Motor Company	Project Portal	Alpha	Ballard	Kenworth T680	Testing at POLA/POLB.
		Beta	Toyota	Kenworth T680	
U.S. Hybrid	H2Cargo™	Plug-in Step Van	30 kW (Hydrogenics)	Workhorse or FCCC MT-45	In production.
	H2Ride™	Plug-In Shuttle Bus	30 kW (Hydrogenics)	Eldorado Aero Elite 29 Model	In production.
	H2Truck™	Class 8 Truck	80 kW	International, ProStar Day Cab	In development.
	H2Tug™	Fuel Cell Plug-In Hybrid Electric C-17 Tow Tractor	30 kW (Hydrogenics)	TUG Technologies Model U30	In development.
WaterstofNet		Fuel cell garbage truck	Size N/A (Hydrogenics)	E-trucks Europe	Unveiled in April 2019. Part of a pilot project to test in ten European cities.

2019 U.S. Government Initiatives

As the sector has garnered interest and proven its viability, U.S. DOE is focusing on R&D projects that help drive the technology forward. In March 2019, DOE's EERE released a $51.5 million FY19 commercial truck and off-road application funding opportunity announcement (FOA) that included three topic areas specific to fuel cell and hydrogen R&D for heavy-duty applications.[130] The FOA allocated up to $28.5 million in funding:

- Up to $16.5 million for gaseous fuels research and technology integration for medium- and heavy-duty vehicles
- Up to $6 million for high-throughput hydrogen fueling technologies for medium- and heavy-duty transportation
- Up to $6 million for high-durability, low platinum group metal MEAs for medium- and heavy-duty truck applications

Nikola Motors was one of the recipients of this funding, securing a $1.7 million grant to advance its research into fuel cell MEAs. It is working with Carnegie Mellon University, Northeastern University, and the Georgia Institute of Technology on the project.[131]

In December 2019, EERE released a notice of intent to issue an FOA in support of its H2@Scale initiative that includes fuel cell R&D for heavy-duty applications.[132]

There are heavy-duty truck demonstration projects underway in Canada and Europe. The Alberta Zero-Emissions Truck Electrification Collaboration (AZETEC) and H2Haul, both announced in 2019, bring together a range of industry partners.

Table 11: Recent Heavy-Duty Truck Demonstration Projects

Recent Heavy-Duty Truck Demonstration Projects					
Project	Location	Companies Involved	Year Announced	Funding	Number of Vehicles
Alberta Zero-Emissions Truck Electrification Collaboration (AZETEC) project	Alberta, Canada	Ballard Power Systems, Trimac Transportation, Bison Transport	2019: four-year project	US$11.2 million (CAN$15 million)	Two fuel cell electric hybrid trucks.
H2Haul	Belgium, France, Germany, and Sweden	Air Liquide, Colruyt Group, Element Energy Limited, ElringKlinger, FPT Industrial, H2 Energy, Hydrogen Europe, IRU, IVECO, Enabling Transport Solutions (VDL ETS), PowerCell, Thinkstep, BMW Group, WaterstofNet	2019: five-year project	US$13 million (€12 million)	Sixteen fuel cell trucks at four sites. The trucks will be operated by a German logistics company (for BMW Group logistics), Coop, Colruyt Group, Carrefour (Chabas and Perrenot), and Air Liquide.

Several countries have announced goals for fuel cell truck deployments. According to data compiled by the IPHE, these targets include:

- France: 200 fuel cell trucks by 2023 and 800–2,000 by 2028
- South Korea: 30,000 fuel cell trucks by 2040
- The Netherlands: 500 fuel cell trucks by 2020 and 3,500 by 2025

China Snapshot

Worldwide, the greatest concentration of fuel cell trucks currently on order or already deployed is in China. The country's big investment in a domestic "New Energy Vehicle" market aims to have 1,000 hydrogen stations in operation by 2030 to fuel 1 million fuel cell vehicles, including commercial buses and trucks, and has encouraged fuel cell development partnerships and business ventures.

Ballard Power Systems is already working with Chinese partners on fuel cell buses and is supplying its systems for 1,200 fuel cell trucks to several entities in the country (see Table 12). The initial deployments had already accumulated more than 5 million kilometers as of April 2019.[133] Ballard has entered into several joint ventures with Chinese partners, such as Guangdong Synergy Ballard

Hydrogen Power Co., Ltd., in Yunfu, China,[134] to not only integrate its fuel cell systems into delivery and other trucks, but to manufacture them in China.

Table 12: Ballard Power Systems — Recent Heavy-Duty Sales/Orders from Chinese Customers

Ballard Power Systems — Recent Heavy-Duty Sales/Orders from Chinese Customers				
Partner/Integrator	Number of Systems	Deployment Location	Fuel Cell Size/ Model	Notes
Broad-Ocean (Zhongshan Broad-Ocean Motor Co., Ltd.)	600	Pearl River Delta (Shenzhen)	FCveloCity®	For buses and trucks. Broad-Ocean plans to set up three module assembly operations in China.
Re-Fire (Shanghai Reinventing Fire Technology Company Ltd.)	500	Shanghai	30 kW FCvelocity 9SSL Ballard 9SSL stacks manufactured locally by JV	The trucks are operated by Shanghai Sinotran New Energy Automobile Operation Co., Ltd. for intra-city deliveries of goods.
SinoHytec	100	Pearl River Delta (Zongshan)	MD30 modules	Logistics service.

In December, Ballard received a $19.2 million order[135] for MEAs from Weichai Ballard Hy-Energy Technologies Co., Ltd., a joint venture between Ballard and Weichai Power Co., Ltd. This purchase, added to a $44 million[136] order from Weichai in May for a range of fuel cell products and components, will help Weichai meet its goal of supplying a minimum of 2,000 fuel cell modules for commercial FCVs in China.

- Nuvera Fuel Cells is working with Zhejiang Runfeng Hydrogen Engine Co., Ltd. to manufacture and assemble 45 kW fuel cell engines for buses and delivery vans in Ningbo, Hangzhou, Kunming, and Xi'an[137] and with the Hangzhou district government of Fuyang to establish a manufacturing facility to produce fuel cell stacks.[138]
- In October of 2019, Loop Energy established a joint venture and non-exclusive license agreement with Chinese company IN-Power to collaborate on fuel cell systems for heavy-duty buses and trucks in China.[139]
- Horizon Fuel Cell Technologies is working with Jiening New Energy and delivered 20 fuel cell trucks in September.[140] Horizon is developing the trucks with JMC, a subsidiary of Ford Motor Company.

Hydrogen Fueling for Heavy-Duty Trucks

In February 2019, Air Liquide, Hyundai, Nel, Nikola Motors, Royal Dutch Shell PLC, and Toyota signed an MoU to standardize hardware and components for hydrogen fueling of heavy-duty vehicles.[141] The effort includes the creation of specifications for 70 MPa high-flow fueling nozzles and hoses, test planning, and developing a solicitation to find suppliers.

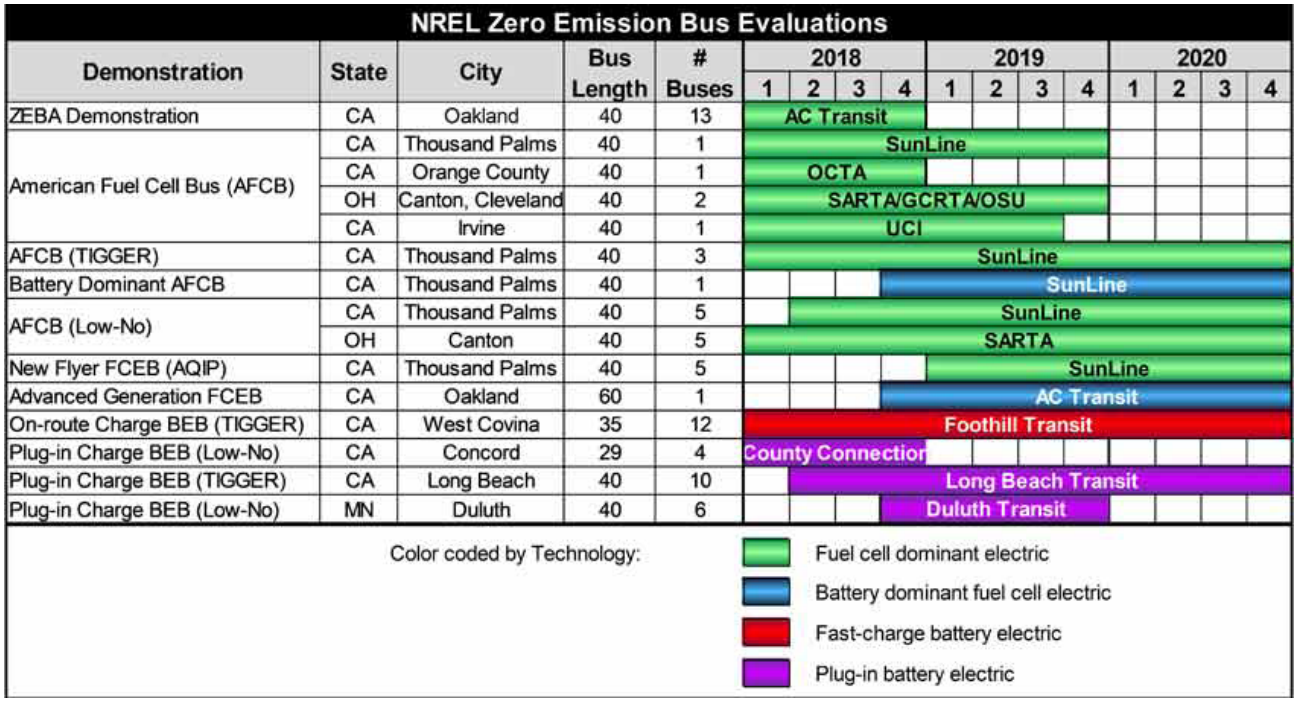
As more fuel cell trucks enter the market, the need grows for more high-capacity hydrogen stations to support them. Two refueling stations funded under the ZANZEFF program and three other previously announced hydrogen stations will create a small network in the Los Angeles area to support vehicles currently in operation and any future deployments. More details about progress

made in the areas of hydrogen generation, supply, and infrastructure development that happened in 2019 can be found in the Spotlight: Hydrogen Generation section as well as other sections of this report.

Buses

In the U.S., DOE's National Renewable Energy Laboratory (NREL), is currently evaluating 38 fuel cell buses that are currently or soon to be in operation in California and Ohio.[142]

Figure 1: NREL Zero-Emission Bus Evaluations



In addition to those in NREL's evaluation, there are other fuel cell buses in operation in California run by several different transit agencies, including AC Transit, Orange County Transportation Authority, and SunLine Transit. According to the California Fuel Cell Partnership, there are 48 fuel cell buses in operation in the state.[143] In addition to government-operated transit agencies, several universities also have fuel cell buses or shuttles that operate on their campuses, including the University of California–Irvine and the University of Delaware.

Outside the U.S., there have been hundreds of fuel cell buses in operation for years. In 2019, several countries reinforced their commitments to expanding fuel cell bus deployments.

- In January, the New Zealand Ministry of Energy and Resources announced a NZD 250,000 (~$169,000) project to demonstrate a fuel cell bus and light-duty vehicles at the Port of Auckland.[144] The vehicles will use hydrogen generated from a plant that was separately funded by project partners Auckland Transport, Auckland Council, and KiwiRail.
- In February, as part of its Hydrogen for Transport Programme Stage 2 Competition, the UK's Department for Transport awarded approximately £9 million (US$11.5 million) for two projects that will lead to the deployment of 33 buses.[145] The projects, Northern Ireland Hydrogen Transport and Deployment of FCEV Buses and Hydrogen Refueling, fund three fuel cell

buses in Belfast, Northern Ireland, five fuel cell buses in Aberdeen, Scotland, and 25 in Liverpool, England.

- In Europe, the Joint Initiative for Hydrogen Vehicles Across Europe (JIVE) and JIVE2 projects, launched in 2017 and 2018, respectively, aim to deploy ~300 fuel cell buses in 22 cities in the UK, Germany, Denmark, Norway, Sweden, France, and the Netherlands.[146] In April 2019, Proton Motor Fuel Cell GmbH received an order from ebe EUROPA GmbH for fifteen 60 kW fuel cells for buses for four German city councils as part of the JIVE project.[147] As outlined in the table below, in 2019, Ballard Power Systems received orders for 55 fuel cell systems under the JIVE and JIVE2 programs.
- There was an even bigger commitment by the H2Bus Consortium, formed in June 2019 and consisting of Nel Hydrogen, Hexagon Composites, Ballard Power Systems, Wrightbus, Ryse Hydrogen, and Everfuel Europe.[148] The members committed to deploying 1,000 fuel cell buses and supporting hydrogen infrastructure to European cities, including 600 buses—200 each to Denmark, Latvia, and the UK—in the first phase. The EU's Connecting Europe Facility is supporting H2Bus with €40 million (US$45.1 million) in funding.
- One of the H2Bus partners, Ballard Power Systems, unveiled the eighth generation of its high-performance fuel cell module, FCmove™-HD, the first in a family of FCmove products specifically designed for transit buses, to coincide with the H2Bus launch.[149]
- Earlier in the year, New Flyer Industries Canada ULC and New Flyer of America Inc. completed testing of their 40-foot and 60-foot Xcelsior fuel cell-electric buses, which use Ballard's FCveloCity-HD 85 kW modules, at the Altoona Bus Research and Testing Center in Pennsylvania.[150] The buses are now commercially available.

In 2019, Ballard publicly announced orders for 75 fuel cell buses.

Table 13: Ballard Power System's Publicly Announced 2019 Fuel Cell Bus Sales/Orders

Ballard Power System's Publicly Announced 2019 Fuel Cell Bus Sales/Orders			
Location	Customer	Number	Details
Aberdeen, Scotland	Wrightbus	15	FCveloCity-HD 85 kW fuel cell modules for double-decker buses in Aberdeen, Scotland under the JIVE funding program.
Bolzano, Italy	Solaris Bus & Coach S.A.	12	Twelve FCmove-HD fuel cell modules for 12 buses to be deployed with SASA Bolzano, the public transport operator in Bolzano, Italy, under the JIVE program.
Groningen, the Netherlands	Van Hool	20	Under the JIVE2 program, FCveloCity-HD 85 kW modules will power 20 Van Hool A330 model buses.
London, England	Wrightbus	20	Twenty FCveloCity-HD 85 kW fuel cell modules to power double-decker London buses under the JIVE program.
Pau, France	Syndicat Mixte de Transports urbains – Pau Portes des Pyrénées (SMTU-PPP) and the Société de Transport de l'Agglomération Paloise (STAP).	8	Eight ExquiCity tram-buses built by Van Hool NV and powered by eight Ballard FCveloCity-HD 100 kW fuel cell modules for Pau's bus rapid transit system.

Another FCH JU bus project, Environmentally Friendly Efficient Electric Motion (3Emotion), began in 2015 and is set to be completed in 2022. In 2019, as part of the project, the North Denmark Region and the Municipality of Aalborg signed two contracts for the delivery of three VanHool fuel cell buses and a hydrogen production and filling station from Danish company GreenHydrogen.[151]

In addition to expanding into the stationary and heavy-duty trucking space, automakers also extended their reach into the bus market in 2019. In June, Hyundai unveiled its new mass-produced 45-seat hydrogen fuel cell bus in Changwon City, South Korea.[152] The South Korean government plans to operate 35 of the buses across seven cities. In August, Toyota launched its updated Sora1 fuel cell electrified vehicle bus,[153] and, in October, delivered a fuel cell system to CaetanoBus SA in Portugal to integrate into a city bus.[154]

- As of November 1, 2019, Japan's Ministry of Economy, Trade, and Industry reported that 22 fuel cell buses were in operation in the country.
- According to the China Association of Automobile Manufacturers, in 2019 the country produced 2,833 fuel cell vehicles and sold 2,733, an increase from 2018 of 85.5% and 79.2%, respectively, as well as reaching an all-time high.[155] The association reports that the majority of these vehicles are buses.
- Intelligent Energy announced a grant from the UK's Advanced Propulsion Centre to integrate fuel cell systems ranging from 30 kW to 120 kW into SUVs and buses in cooperation with Changan UK Ltd., a Chinese car manufacturer, and Alexander Dennis Ltd., a UK bus manufacturer.[156]

Light-Duty Vehicles

In California, the only state in the U.S. where fuel cell light-duty vehicles (passenger cars) are commercially available, 2,089 vehicles were bought or leased by the general public in 2019. According to the California Fuel Cell Partnership, using data from Baum and Associates, this is a 12% decline from 2018, when 2,368 FCVs were sold.[157] The majority of the vehicles, 1,502, were Toyota Mirai FCVs.

Table 14: Monthly Fuel Cell Vehicle Sales in California in 2019

Monthly Fuel Cell Vehicle Sales in California in 2019											
Jan.	Feb.	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.
113	99	198	232	283	243	198	179	120	133	180	111

Worldwide, it was reported that there were 7,500 FCVs sold in 2019.

- Hyundai Motor Group launched its 2020 next generation NEXO fuel cell vehicle in September, 2019.[158]
- In October 2019, Toyota debuted the final-stage development model of its second-generation Mirai, the Mirai Concept.[159] Throughout 2019, Toyota deployed its Mirai fuel cell vehicle to several fleets and other organizations around the world.
  - Las Catalinas, Costa Rica, is using the Mirai in a car-sharing service for

residents and guests. Ad Astra Rocket Company Costa Rica will supply renewable hydrogen.[160]

- Thirty-five Mirai FCVs will be used as taxis by Noot Personenvervoer in The Hague, Netherlands, as part of a care transport system for elderly and disabled people.
- An initial fleet of 50 FCVs was delivered to the Government of Quebec (announced in 2018).[161]
- Toyota offered the Mirai for purchase to employees of Ballard Power Systems.[162]

- In China, a new company, Grove Automotive, launched in April, announced plans to introduce a fuel cell powered four-door sport utility vehicle.[163]
- In January, the government of Denmark announced a plan to transition all taxi cabs to zero-emissions vehicles starting in 2025, with 300 of the 500 licenses issued in 2019 and 2020 to be designated as such.[164] In addition, zero-emission taxis will be first in line at stations and other public transport hubs to promote their use by passengers.
- In February, the UK's Department for Transport awarded approximately £14 million (US$18.1 million), through its Hydrogen for Transport Programme Stage 2 Competition, for five fuel cell vehicle and hydrogen refueling infrastructure projects across the country.[165] Combined, the projects will deploy 106 fuel cell vehicles—73 cars and 33 buses—and five hydrogen fueling stations.

Table 15: UK Department for Transport Hydrogen for Transport Programme Stage 2 Competition Awardees

UK Department for Transport Hydrogen for Transport Programme Stage 2 Competition Awardees				
Project	Partners	Funding	Vehicles	Hydrogen Stations
Hydrogen Mobility Expansion Project II	Element Energy, ITM Power Ltd., Toyota (GB) Plc, Hyundai Motor UK Ltd.	£3.07 million (US$3.98 million)	51 FCVs	One in Crawley, England
Northern Ireland Hydrogen Transport	Viridian Energy Supply Limited, Translink (Ulsterbus), HyEnergy Consultancy Ltd.	£1,953,937 (US$2.5 million)	3 fuel cell buses	One in Belfast, Northern Ireland
Riversimple Clean Mobility Fleet	Riversimple Movement Ltd., Monmouth County Council	£1,249,670 (US$1.6 million)	17 FCVs	N/A
Tees Valley Hydrogen Transport Initiative	Tees Valley Combined Authority (UK), Materials Processing Institute, Northern Gas Networks	£1,303,500 (US$1.67 million)	5 FCVs	Two in Middlesbrough and Stockton-on-Tees
Towards Commercial Deployment of FCEV Buses and Hydrogen Refueling	BOC Ltd., Merseytravel (Liverpool City Region, Aberdeen City Council and Arcola Energy)	£6.419,038 (US$8.1 million)	30 fuel cell buses: five in Aberdeen and 25 in Liverpool	One in St. Helens, England

Medium-Duty and Other Vehicles

Generally, medium-duty vehicles include smaller trucks and vans used for a variety of purposes, most commonly municipal applications such as waste collection and delivery services. In the U.S., these vehicles are classified as Classes 4, 5, and 6, and weigh between 14,001 and 26,000 lbs.

In 2019, fuel cells received a lot of attention from some of the world's largest delivery service companies:

- In March, Plug Power launched its 30 kW ProGen hydrogen fuel cell engine for medium- and light-duty transportation applications, such as delivery vans, and light- and medium-duty cargo box trucks.[166]
- In May, Plug Power entered a new agreement with electric vehicle manufacturer StreetScooter to integrate its ProGen hydrogen fuel cell engines into StreetScooter's electric delivery vehicles for customer Deutsche Post DHL.[167]
- Already involved in demonstrations of fuel cell powered baggage tow tractors at airports and forklifts in warehouses, FedEx is also testing the feasibility of fuel cell powered delivery vans in its operations. In Albany, New York, FedEx Express is working with Plug Power, while UPS is testing Class 6 delivery trucks using Ballard Power Systems fuel cells.
- As shown above in Table 8, UPS is working with CTE on two CARB ZANZEFF projects—next generation fuel cell delivery van deployment and fuel cell hybrid electric delivery van deployment. The $20.7 million ($9.7 million from CARB and $11 million cost-share from partners) funds a total of 19 fuel cell hybrid electric delivery vans, with four in Chino and 15 in Ontario, California. UPS had previously tested Ballard's 30 kW FCveloCity-MD fuel cell as a range extender, and the next generation fuel cell delivery van deployment project will test Ballard's larger systems for a larger role in vehicle propulsion.[168]
- Anglo American purchased nine of Ballard's FCveloCity-HD 100 kW fuel cell modules to power a retrofitted ultra-heavy-duty mining truck at Anglo American's South Africa mining operation.[169]
- Intelligent Energy completed a year-long trial of fuel cell powered scooters by London's Metropolitan Police in February[170] as part of a collaborative project led by Intelligent Energy. The seven Burgman scooters were loaned to the Metropolitan Police by Suzuki Motor Corporation. The program was partially funded by the Advanced Propulsion Centre, and Suzuki GB and Cenex were also partners.

Material Handling/Logistics

The logistics sector has seen tremendous growth in the past few years, with the U.S. leading the world in fuel cell powered material handling equipment (MHE) deployments.

Plug Power reported 30,000 fuel cell powered MHE vehicles deployed as of November 2019.[171] That fleet amassed more than 270 million hours and 1 billion miles of operation.

- February: Began standard production of its next generation Class 1 GenDrive fuel cell system for industrial lift trucks.[172]
- April: Received order from Lipari Foods of Warren, Michigan, to power and fuel its electric material handling fleet with GenDrive fuel cells and a GenFuel hydrogen fueling station.[173]
- April: Delivered ProGen fuel cell powered electric cargo tuggers to FedEx at the Albany International Airport, in Albany, New York.[174] The vehicles were built by Charlatte America.

During the third quarter of 2019, the company deployed over 1,700 GenDrive fuel cell systems to new and recurring customers, including Walmart, Kroger, and Sysco. Additionally, Plug Power secured Fiat Chrysler Automobiles, in Detroit, Michigan, as a new GenKey (turnkey services) customer.[175]

Internationally, Plug Power expanded its contract with FM Logistic to GenKey in July, increasing FM Logistic's fleet of GenDrive fuel cells and adding a GenFuel hydrogen fueling station and maintenance for five years.[176] The new hydrogen refueling station will be located at FM Logistic's operation in Neuville aux Bois, France.

In October, Plug Power entered into a partnership with German specialty vehicle manufacturer MULAG to provide 60 ProGen fuel cell powered electric cargo tow tractors and hydrogen fueling capabilities to Hamburg Airport.[177] The two companies had previously partnered to build, test, and evaluate a vehicle at the airport.

Other companies also made news in 2019.

- Early in the year, Linde Material Handling unveiled a fuel cell powered concept version of its Linde Roadster industrial forklift.[178]
- Intelligent Energy launched its new fuel cell power product for the Class 3 European electric hand truck (fleet order picker) market with German partner FES Fahrzeug Entwicklung Sachsen GmbH.[179]

A new FCH JU project, H2PORTS—Implementing Fuel Cells and Hydrogen Technologies in Ports, launched in February.[180] The €4 million (US$4.4 million) endeavor involves the demonstration of fuel cell vehicles at the Port of Valencia in Spain, including a reach stacker for loading, unloading, and transporting containers, a terminal tractor for roll on/roll off operations, and a mobile hydrogen refueling station.

Marine

For many years, the fuel cell sector's focus has centered on land-based transportation, but recently interest in fuel cells for transforming maritime applications has grown. The marine sector is increasingly exploring fuel cells and hydrogen to decarbonize propulsion on ships, equipment that operates in and around ports, and associated logistics systems. Many gains were made in this space with a range of new developments, collaborations, and deployments in 2019:

- In January, the Japanese Fisheries Research and Education Agency announced a collaboration with Toyota Motor Corporation to develop a fuel cell powered fishing boat that will be demonstrated at a tuna farm in the Goto Islands in 2022.[181] The boat will use hydrogen generated by an offshore wind farm.
- Hydrogen Europe and the Waterborne Technology Platform signed an MoU in May to explore scaling up the development of hydrogen technologies in marine applications, ports, and industrial zones.[182]
- In May, Hyundai Motor signed an MoU with Gangwon Province (South Korea) to integrate its fuel cell systems into small 5-ton fishing boats.[183]
- In June, investment group SW/TCH Maritime announced that it would become the primary investor and eventual owner of the "Water-Go-Round," a fuel cell powered ferry in San Francisco, California.[184] The ferry will use BAE Systems electric motors, with fuel cell and hydrogen storage provided by Hydrogenics and Hexagon Composites.
- Ballard Power Systems Europe A/S, a subsidiary of Ballard Power Systems, Inc., signed an equipment supply agreement with Norled A/S, one of Norway's largest ferry and express boat operators, to provide two Ballard 200 kW fuel cell modules for a hybrid ferry.[185] The fuel cells will be designed and manufactured at Ballard's Marine Center of Excellence at its facility in Hobro, Denmark. The Marine Center of Excellence, announced in April 2019, is dedicated to the design and manufacture of heavy-duty fuel cell modules for the marine industry, with an expected annual production capacity of more than 15 MW.[186]
- GE and Nedstack entered into a partnership to develop hydrogen fuel cell power systems for cruise ships.[187] The companies have designed the concept for a 2 MW fuel cell power plant on an expedition vessel. Table 16 details two projects focused on the development and deployment of fuel cell marine vessels in Europe.

Table 16: EU Fuel Cell Marine Projects

EU Fuel Cell Marine Projects				
Program	Partners/Participants	Funding	Locations	Details
FLAGSHIPS	Compagnie Fluvial de Transport, VTT Technical Research Centre of Finland Ltd., NCE Maritime Cleantech, Norled, ABB, Westcon Power & Automation, LMG Marin, Ballard Power Systems, PersEE	€7 Million (US$7.8 million) from FCH JU Horizon 2020	Lyon, France and Stavenger, Norway	Two vessels: pushboat in Lyon and passenger and car ferry in Stavenger.
H2SHIPS	Thirteen partners from five countries: Europaeisches Institut für Energieforschung, Hynamics, University of Birmingham, Havenbedrijf Amsterdam, Technische Universiteit Delft, Navalu, SYCTOM, Port Autonome de Paris, Haven Oostende, Steinbeis 2i GmbH, Hydrogen Europe, Transport & Environment, Tata Steel Europe	€6.3 million (US$7 million)	Netherlands and Belgium	Launched in July, two pilot programs: port and island waterway vessel in the Netherlands, and hydrogen fueling in Belgium.

In addition to participating in the FLAGSHIPS program, Ballard Power Systems received a purchase order for three of its FCveloCity 100 kW fuel cell modules from BEHALA, a port and logistics specialist based in Berlin, to power a push boat named Elektra that will transport goods between Berlin and Hamburg and service other routes in Berlin.[188]

SFC Energy announced that two Finnish customers are now integrating its EFOY fuel cell systems into boat offerings to provide power to on-board electronics: AuroraHut Oy is offering the fuel cell systems in its AuroraHut igloo houseboats,[189] and Sarin Boats is integrating fuel cells into its Sargo all-season boat line.[190]

Rail

Fuel cell powered trains have been in development for a long time. The first publicly reported fuel cell train was a mine locomotive that was tested in 2002 in Canada. Since then, there have been "hydrail" projects, testing, and demonstrations in various forms.

Most of the progress in hydrail has been in Europe. In May, S*tudy on the Use of Fuel Cells and Hydrogen in the Railway Environment*,[191] a report commissioned by the FCH JU and Shift2Rail Joint Undertaking (S2R JU), analyzed 10 different case studies in Europe to identify potential and barriers. Some cases showed a positive total cost of ownership for fuel cells and significant market potential.[192]

Train manufacturer Alstom, based in France, using fuel cells from Hydrogenics, is now offering the Coradia iLint fuel cell passenger train as part of its product line. Two of these trains have been in regular passenger service in the Lower Saxony area of Germany since September 2018. The two transit authorities involved, Landesnahverkehrsgesellschaft Niedersachsen and Eisenbahnen und Verkehrsbetriebe Elbe-Weser, will receive 14 Coradia iLint trains in 2021.[193]

In the first two months of 2019, Alstom showcased its fuel cell powered Coradia iLint to six federal states in Germany, starting in Rhineland-Palatinate and continuing in Baden-Württemberg, Saxony, Thuringia, Berlin, and Brandenburg.

In May, Rhein-Main-Verkehrsverbund, the public transport network of the Frankfurt Rhine-Main area in Germany, ordered 27 Coradia iLints, via its subsidiary fahma, to replace diesel-powered trains.[194] The contract is valued at €500 million (US$559 million) and received funding support from Germany's Federal Ministry of Transport and Infrastructure. The trains are expected to be delivered by December 2022. In addition to the trains, the order also includes the supply of hydrogen and maintenance for 25 years. Alstom offers the supply of hydrogen in cooperation with Infraserv GmbH & Co. Höchst KG, with the filling station being located on the premises of the Höchst industrial park. Alstom has sold a total of 41 Coradia iLints.[195]

In October, Alstom and the Province of Groningen, local operator Arriva, Dutch railway infrastructure manager ProRail, and Engie signed plans for a pilot project to test the Coradia iLint in the Netherlands.[196]

Alstom is also working on other fuel cell train models and in January unveiled a design for a new "Breeze" train that converts the existing British Rail Class 321 electric multiple-unit trains to use fuel cells.[197] In May, Alstom and Eversholt Rail of the UK showcased a 1.2 meter scale model of the train.

There have been other rail companies announcing plans to either develop or test fuel cell trains, including SNCF in France, East Japan Railway Co., Hyundai Rotem, the locomotive subsidiary of Hyundai, in South Korea, and others:

- Vivarail, a railroad company in the UK, partnered with Arcola Energy and introduced a modified fuel cell powered class 230 train.[198]
- In June, the Birmingham Centre for Railway Research and Education and Porterbrook, a UK train company, received a grant of $9.9 million from the UK's Department for Transport to develop a fuel cell train prototype, the HydroFLEX.[199]

UAVs/Aviation

The U.S. and other countries have been researching, testing, and deploying UAVs (drones) for various military missions and uses. UAV use is growing for a range of applications in the commercial/industrial and consumer/recreational sectors as well, such as surveillance, photography, mapping, search and rescue, delivery, and more. Fuel cells provide a lightweight and longer-running power option for extended flight times, among other benefits, so as these markets grow, opportunities for fuel cells do as well.

In 2019, there were several record-setting demonstrations of fuel cell powered UAVs, product launches, and other significant progress in this sector.

- Intelligent Energy (IE) has partnered with MetaVista of South Korea, and in January the companies flew a multicopter UAV with a 650 W fuel cell for 10 hours and 50 minutes.[200] In March, IE launched its power path module, which doubles the power output from its UAV fuel cell power modules. In April, the companies broke the January record with a flight time of 12 hours, 7 minutes and 5 seconds. The UAV was equipped with IE's 800 W fuel cell and MetaVista's 6-liter liquid hydrogen cylinder.[201] IE has also been working with ISS Aerospace of the UK to develop the Sensus UAV.[202] In November 2019, the first commercial operation was a success—the fuel cell UAV surveyed 200 kilometers of gas fields in Iraq.
- In April, Ballard Unmanned Systems Inc. (a subsidiary of Ballard Power Systems, formerly Protonex, based in Southborough, Massachusetts), launched its FCair™ fuel cell product line for the UAV market, which includes the fuel cell system, hydrogen storage, pressure regulators, and refueling.[203]
- Ballard and Israel-based Elbit Systems Ltd. were selected for a Binational Industrial Research and Development Energy program award to develop a hydrogen fuel cell powered vertical take-off and landing drone.[204]
- In June, Plug Power acquired Montreal-based EnergyOr's technology, assets, and personnel.[205] This purchase expands Plug Power's portfolio into small-scale robotics, UAVs, and other autonomous applications.
- Horizon Energy Systems (HES), based in Singapore, launched its AEROSTAK 1500W standard hydrogen fuel cell power system for larger electric drones.

HES also unveiled its HYCOPTER hexacopter drone that has a flight duration of 3.5 to 4 hours. In October, HES delivered a six-rotor HYCOPTER to the Naval Postgraduate School in Monterey, California, for a feasibility test of compressed hydrogen on board naval platforms.[206]

- HES is also working with several different companies to deploy its HYCOPTER for inspection and surveillance work, including in Singapore for tall buildings and in Brazil for large-scale dam inspection.[207] The company also signed an MoU with Hy-Hybrid Energy of Scotland and GOLDI Mobility Kft of Hungary focusing on the HYCOPTER for the Hungarian market.[208]
- Doosan Mobility Innovation of South Korea is another company in this sector. In November 2019, Doosan's DS30 fuel cell drone completed a successful 43-mile test flight over open water between the U.S. Virgin Islands of St. Croix and St. Thomas as part of a U.S. Department of Health and Human Services test project.[209] The DS30 flew for one hour and 43 minutes, with 30 minutes' worth of hydrogen fuel remaining after the flight was completed. The UAV carried simulation vials as a proof of concept that fuel cell powered UAVs could provide medical and emergency relief to remote areas that boats and planes could not reach during a disaster or other situation.
- Also in November, Doosan won two awards at the 2020 Consumer Electronics Show, including the Best of Innovation award in the category of Drones and Unmanned Systems and an honoree award in the category of Sustainability, Eco-Design, and Smart Energy for its DS30 drone.[210]

In 2019, there was also significant movement into larger aircraft applications, with demonstrations of fuel cells integrated into electric vertical takeoff and landing (eVTOL) aircraft and small planes.

- Massachusetts-based Alaka'i Technologies unveiled its liquid hydrogen fuel cell air-taxi concept, Skai, in May.[211] The Skai is currently undergoing testing and certification. Alaka'i co-designed the Skai with DesignWorks, the design innovation studio for BMW Group, and is using a fuel cell from Hydrogenics.
- In January 2019, ZeroAvia, based in Hollister, California, tested its fuel cell plane, which achieved its first flight in February.[212] In September, the company received a £2.7 million (~US$3.3 million) grant from the UK's Department for Business Energy & Industrial, the Aerospace Technology Institute (ATI), and Innovate UK for its HyFlyer project.[213] ZeroAvia will set up a facility in the UK and work with Intelligent Energy on the development of the HyFlyer.
- In March, Toyota and the Japan Aerospace Exploration Agency entered an agreement to collaborate and accelerate work on a fuel cell powered manned, pressurized moon rover.[214]

Hydrogen

Spotlight On: Large-Scale Hydrogen Generation

Hydrogen is gaining traction throughout the world as a clean fuel capable of reducing emissions across a diverse group of industries, especially heavy-duty transportation, ship propulsion, and steelmaking. Many areas that substitute hydrogen for fossil fuels are extremely energy intensive, prompting the need for increased hydrogen production capacity. Thus the worldwide demand for hydrogen has created a push for larger, centralized hydrogen production facilities that can serve many industries.

Pure hydrogen is not found on earth in significant quantities and therefore cannot be mined or collected. Instead, hydrogen is produced: A chemical compound containing hydrogen atoms undergoes a chemical or electrochemical process that separates the molecules into hydrogen and other materials.

In the United States, around 95% of hydrogen is produced via steam methane reformation,[215] a thermal process that yields hydrogen gas with byproducts of CO and CO_2. Many of these plants are set up on site specifically for industrial processes such as metallurgy, petroleum refining, and industrial chemical manufacturing. Other, cleaner methods of producing hydrogen, such as electrolysis, biomass conversion, and methods involving fossil fuels with carbon capture and storage are becoming popular as a way to produce clean energy for use in stationary and transportation-focused fuel cells.

Investment in new infrastructure shows industry's commitment to hydrogen. In 2019, several global industrial gas companies expanded their U.S. hydrogen assets in preparation for a growth in demand. Air Liquide, a hydrogen and industrial gas production company, announced a $150 million investment to produce 30 tons of renewable liquid hydrogen per day in North Las Vegas, Nevada, for the California service mobility market.[216] Similarly, industrial gas company Air Products announced plans to build a second liquid hydrogen production facility in California to service fuel cell vehicles across the state.[217]

Electrolysis, a promising process for hydrogen production, generates hydrogen by splitting water with an electrical current. Electrolyzer units can be paired with solar plants, wind farms, and even nuclear power plants, a characteristic that is particularly useful for the long-term and large-scale seasonal energy storage that will be critical with the greater adoption of intermittent renewable electricity supply in the electric grid. Electrolyzers are versatile in size and deployment options.

Governments across the world are increasing funding to boost electrolyzer potential to the megawatt and gigawatt scale to accelerate the decarbonization of the energy and transportation sectors, industrial processes, and others.

Table 17: Examples of Commercially Available Large-Scale Electrolyzer Systems

Examples of Commercially Available Large-Scale Electrolyzer Systems				
Company	Product Name	Type	Capacity	Power Info
Nel Hydrogen	A Series	Alkaline	150-3,880 Nm^3/h	3.8-4.4 kWh/Nm^3, 2.2 MW per stack
	M Series	PEM	103-4,000 Nm^3/h	4.53 kWh/Nm^3
ITM Power	HGasXMW	PEM	4,050 kg/24h	10 MW (2 MW per module)

Examples of Commercially Available Large-Scale Electrolyzer Systems				
Company	Product Name	Type	Capacity	Power Info
McPhy	McLyzer	Alkaline	10-800 Nm3/h	0.057-4 MW per module, scalable to GW size
Hydrogenics/ Cummins	HySTAT	Alkaline	4-60 Nm3/h	4.9 or 5.2 kWh/Nm3H2, scalable to 500 Nm3/h
Giner ELX	Kennebec	PEM	60-2,200 kg/day	5 MW nominal output
	Allagash	PEM	30-400 Nm3/h, up to 900 kg/day	2 MWe nominal input
Siemens	Silyzer 200	PEM	225 Nm3/h	1.25 MW per stack
	Silyzer 300	PEM	100-2,000 kg/h	

In July 2019, Nel Hydrogen unveiled its medium-scale alkaline electrolyzer, the A1000.[218] The new electrolyzer can be sized from 600 to 970 Nm^3 per hour and is capable of generating 2 tons of hydrogen per day.

U.S. Hydrogen Development

As mentioned above, the bulk of U.S. hydrogen production relies on steam methane reformation. Much of this hydrogen is used for industrial processes and associated industries. However, the growth of hydrogen as a clean fuel has prompted the U.S. federal government and states to begin focusing on and investing in clean methods of hydrogen production.

The U.S. DOE, through HFTO, has been supporting the study and development of large-scale hydrogen production and use for grid stabilization, resiliency, and mobility through the H2@Scale initiative.[219]

- In March 2019, an H2@Scale FOA for up to $31 million was announced. Topic areas included advanced hydrogen storage and infrastructure R&D, innovative concepts for hydrogen production and use, and integrated production, storage, and fueling.
- In June 2019, Connecticut-based Proton OnSite, which was acquired in 2017 by Norwegian company Nel ASA, was awarded $2 million from that FOA and is also participating in DOE's Electrolyzer Manufacturing R&D Program.[220]
- California, the leader in fuel cell vehicle and hydrogen station deployments, is increasing the demand for renewable hydrogen with a mandate that requires all hydrogen stations to have a supply of at least 33% renewable hydrogen. The state reports that, as of June 2019, it had surpassed that goal, with 39% of the hydrogen used for transportation generated from renewable sources.[221]
- In Washington state, the governor signed a bill in 2019 that allows public utility districts to produce, distribute, and sell renewable hydrogen.[222]
- In September 2019, a $9 million grant was awarded for the purpose of researching the production of clean hydrogen using an electrolyzer at the Davis-Besse Nuclear Power Station in Oak Harbor, Ohio.[223] The project, called the LWR (light water reactor) Integrated Energy Systems Interface Technology Development & Demonstration, will use a light water reactor hybrid energy system designed by FirstEnergy Solutions Corporation in conjunction with electrolysis technology.

Worldwide Large-Scale Hydrogen Development

Countries around the world, particularly in Europe and Asia, are recognizing the benefits of hydrogen and are rapidly incorporating it into a comprehensive plan to combat climate change. A 2019 report, *The Potential Role of H2 Production in a Sustainable Future Power System*,[224] by the Joint Research Centre of the European Commission, estimated the current global capacity of electrolyzers at 8 GW.

To further accelerate the growth of large-scale systems, energy consulting group Wood Mackenzie estimates that between 2019 and 2025, 3,205 MW of renewable electricity-powered electrolyzers will be deployed globally.[225]

Germany is taking a proactive approach to developing its hydrogen economy and has become a leader in power-to-gas projects, i.e., the conversion of electrical energy into a storable gas such as hydrogen. Ludwig-Bölkow-Systemtechnik (LBST) reports that at the beginning of 2019, 50 power-to-gas plants with a total electrical capacity of approximately 50 MW were in operation or planned.[226] At the end of the year, that capacity had increased to 600 MW. One example of this rapid hydrogen growth: In February 2019, Amprion and Open Grid Europe announced plans to construct a 100 MW wind farm-electrolysis plant to produce renewable hydrogen.[227] The project is estimated to begin operations in 2023. In October 2019, Germany pledged €300 million (US$337 million) for renewable hydrogen research by 2023.[228]

In September 2019, the Netherlands Port of Rotterdam announced that it would evaluate the prospect of deploying a renewable hydrogen plant that will produce 45,000 tonnes (~49,604 tons) of renewable hydrogen annually using offshore wind turbines.[229] The evaluation is a result of the February 2019 release of *Investment Agenda Hydrogen Northern Netherlands*, a plan created by nineteen companies and governments that details the investment of €2.8 billion (US$3.15 billion) in hydrogen production over 12 years.[230] Included in the plan are more than thirty project proposals, some of which are massive MW to GW scale systems to generate hydrogen in the 2026–2030 timeframe. The Dutch plan also accounts for the current high price of hydrogen production and includes plans for biomass hydrogen generation.

In December 2019, Denmark awarded a grant to a consortium of partners, including Everfuel Europe A/S, Nel Hydrogen A/S, GreenHydrogen A/S, DSV Panalpina A/S, Hydrogen Denmark, Energinet Elsystemansvar A/S, and Ørsted, which will construct a 2 MW electrolysis plant at energy company Ørsted's Avedøre Power Station on Avedøre Holme, Denmark. The plant is planned to produce around 600 kg of hydrogen per day for fuel cell buses, trucks, and taxis.[231]

Australia, known for its strong potential for renewable energy, has increased investment in renewable hydrogen. In September 2019, the Australian Renewable Energy Agency (ARENA) provided funding to two ammonia plants for the development of renewable hydrogen, an important component of the ammonia production process. ARENA is providing AUD 1.9 million (US$1.31 million) to Queensland Nitrates Pty. Ltd. to assess the production of 20,000 tonnes (~22,046 tons) of ammonia per year from 3,600 tonnes (3,968 tons) of renewable hydrogen.[232] ARENA is also providing AUD 980,000 (US$673,000) to Dyno Nobel Moranbah Pty. Ltd. to assess the feasibility of building a renewable ammonia facility with a 160 MW electrolyzer and a 210 MW solar farm.[233]

Table 18: Examples of 2019 International Large-Scale Electrolyzer Orders and Deployments

Examples of 2019 International Large-Scale Electrolyzer Orders and Deployments				
Company	Location	Customer	Size	Details
Everfuel Europe A/S	Fredericia, Denmark	Shell	20 MW	Danish Energy Agency providing €6 million (US$6.74 million) for the HySynergy project. Everfuel will also install hydrogen storage and trailer filling stations and will operate hydrogen trailers to supply hydrogen fuel in Denmark.
Hydrogenics	Bécancour, Quebec	Air Liquide Canada	20 MW	PEM electrolyzer to be installed at hydrogen production facility.
Hydrogenics	New Zealand	Halcyon Power	1.5 MW	PEM electrolyzer will generate hydrogen using electricity from stable, cost-effective geothermal energy in Mokai, Taupo, located adjacent to an existing Tuaropaki power plant.
ITM Power	Australia	Three customers, one of which is Toyota Australia	1 MW total (four 0.25 MW systems)	As announced in January, Toyota Australia will install a 0.25 MW PEM electrolyzer at its facilities in Altona, a suburb of Melbourne.
ITM Power	Australia	BOC Australia	0.22 MW	Electrolyzer paired with 100 kW solar array to produce up to 2,400 kg of renewable hydrogen per month. The project is estimated at AUD 3.1 million (US$2.2 million).
ITM Power	Rhineland, Germany	Shell	10 MW	REFHYNE consortium of Shell, ITM Power, SINTEF, thinkstep and Element Energy secured €10 million from FCH JU to deploy an electrolyzer at a Shell refinery.
ITM Power	Veendam, Netherlands	Gasunie	1 MW	PEM electrolyzer is located at EnergyStock's Zuidwending salt cavern storage facility in northern Netherlands.
Nel Hydrogen	N/A	N/A	3.5 MW	Alkaline electrolyzer for large international company. The value of the contract is approximately $4 million.
Nel Hydrogen	Luleå, Sweden	Hydrogen Breakthrough Ironmaking Technology (HYBRIT) Development AB, a Swedish joint venture owned by SSAB, LKAB and Vattenfall	4.5 MW	The alkaline electrolyzer will be used to produce hydrogen for a steel production pilot plant that will operate from 2021 to 2024. After the demonstration phase, full-scale implementation is targeted for 2035.
Nel Hydrogen	Switzerland	Hydrospider AG	2 MW	The PEM electrolyzer will be used to produce green hydrogen for heavy-duty hydrogen trucks from Hyundai Motor Company. The purchase order has a value exceeding $3 million and is part of a 30 MW framework agreement.
Nel Hydrogen	South Africa	ENGIE	3.5 MW	Renewable hydrogen will fuel a fuel cell powered mining truck being developed in partnership with Anglo American PLC.
Siemens	Salzgitter, Germany	Salzgitter Flachstahl GmbH	2.2 MW	€50 million (US$56 million) project will supply renewable hydrogen for steel production. The electrolyzer will be powered by wind turbines and have a capacity of 400 Nm3 of hydrogen.

Currently, China produces the most hydrogen in the world, with more than 20 million tons produced in 2019 and capacity exceeding 25 million tons per year. The vast majority of China's production is done through coal gasification. Only 3% of China's hydrogen production is derived from electrolysis. Policy advisors are aiming to achieve 15% renewable generation by 2030 and 40% by 2040. However, hydrogen demand is expected to reach 35 million tons per year by 2030, requiring about 262.5 TWh of renewable generation.[234]

Hydrogen Fueling Stations

To support FCVs, fuel cell buses, and the burgeoning fuel cell truck sector, hydrogen fueling stations are being constructed around the world. According to LBST, 83 hydrogen stations opened around the world in 2019:[235] 36 in Europe, 38 in Asia, eight in North America, and one in Saudi Arabia. Breaking it down further, Germany expanded its network by 22 hydrogen stations, while South Korea added 18, and Japan 11. China opened 30 new hydrogen stations in 2019, bringing the country's total number to 61.[236]

At the end of 2019, LBST reported that 330 (out of 432 total) publicly accessible hydrogen stations were in operation worldwide, with an additional 220 in planning and development.

California, the only state in the U.S. where hydrogen stations are open and accessible to the public, opened six new stations in 2019. In May, Iwatani Corporation of America acquired four existing California hydrogen refueling stations from Messer (formerly Linde, LLC), located in West Sacramento, Mountain View, San Ramon, and San Juan Capistrano,.[237]

California is also exceeding the state's mandate of 33% renewable hydrogen at its stations. According to CARB's 2019 *Annual Evaluation of Fuel Cell Electric Vehicle Deployment & Hydrogen Fuel Station Network Development*, as of June 2019, 39% of the hydrogen used for transportation in the state was renewable.[238]

In addition to hydrogen infrastructure deployment for cars, buses, and trucks, Plug Power reports that as of November 2019, it had constructed more than 80 hydrogen stations at customer warehouses, distribution centers, and other facilities in support of the 30,000*** fuel cell powered material handling vehicles it has deployed.[239] Those stations have achieved more than 23 million fuelings using 22 tons of liquid hydrogen per day.

Table 19: Examples of 2019 Hydrogen Fueling Station Orders and Openings

Examples of 2019 Hydrogen Fueling Station Orders and Openings				
Location	Company	Partner/Customer	Number	Details
U.S.	Nel Hydrogen	N/A	N/A	Announced in January. H2Station™ fueling stations to support heavy-duty vehicles. Order has a total value of more than $6 million.
Los Angeles	Nel Hydrogen	Shell Oil Products U.S.	2	The purchase order has a total value exceeding $7 million. H2Station fueling stations will expand the fueling coverage for hydrogen-powered heavy-duty fuel cell electric trucks.

***This number is as of November 2019.

Examples of 2019 Hydrogen Fueling Station Orders and Openings				
Location	Company	Partner/Customer	Number	Details
Oakland, CA	FirstElement Fuel	N/A	1	Opened in September. True Zero station will be supplied with liquid hydrogen and have a capacity of more than 800 kilograms. It will also have two fueling positions with three nozzles, two at H70 and one at H35.
Sacramento, CA	Shell	N/A	1	Opened in May. Two nozzles at H70.
San Francisco, CA	Shell	N/A	1	Opened in December. Located on Harrison Street. 100% renewable hydrogen. The station's capacity is 513 kilograms and has two fueling nozzles at H70 pressure.
		N/A	1	Opened in November. Located on 3rd Street. 100% renewable hydrogen. The station's capacity is 513 kilograms and has two fueling nozzles at H70 pressure.
Burnaby, British Columbia	Shell	Hydrogen Technology & Energy Corporation (HTEC)	1	Opened in December. Shell and HTEC opened Canada's first retail hydrogen refueling station in 2018 in Vancouver.
Quebec City, Quebec	Harnois Energies	Government of Quebec City, Hydrogenics, Natural Resources Canada, Toyota Canada	1	Multi-fuel station opened in February and includes a pump and an on-site electrolyzer to service fifty Toyota Mirai fuel cell vehicles purchased by the city. Plans are underway for another station in Montreal, with support from Honda Canada as well.
Vancouver, British, Columbia	Nel Hydrogen	HTEC	1	The H2Station fueling stations will be installed at a conventional retail fueling station in the Vancouver area.
London	Nel Hydrogen	London Bus Services Ltd.	1	The contract has a total value of approximately €2.5 million and includes a 10-year service and maintenance contract. The H2Station fueling stations will service a fleet of 20 hydrogen fuel cell buses at Metroline's Perivale bus depot.
	ITM Power	Shell	1	Located at Gatwick Airport, part of the Hydrogen Mobility Europe (H2ME2) project, funded by the FCH JU and the UK Office of Low Emission Vehicles.
Copenhagen	Nel Hydrogen	Everfuel Europe A/S	1	The H2Station, which will fuel a fleet of fuel cell taxis, is supported by the European FCH JU.
Aachen, Germany	H2 Mobility	Linde	1	
Hamburg	H2 Mobility	Shell, Air Liquide	1	Opened in December, this Großmoorbogen station is funded by the European Commission in the trans-European Transport Network as part of the Connecting Hydrogen Refueling Stations project.

Examples of 2019 Hydrogen Fueling Station Orders and Openings				
Location	Company	Partner/Customer	Number	Details
Passau, Germany	H2 Mobility	Shell, Air Liquide	1	Station funded by FCH 2 JU as part of the H2ME project.
The Netherlands	Nel Hydrogen	OrangeGas	Multiple units	The contract has a total value of approximately €3 million (US$3.4 million) and also includes service and maintenance contracts.
Europe	Nel Hydrogen	N/A	2	The contract value is approximately €2 million (US$2.2 million).
Gamagori, Japan	Air Liquide	Japan Hydrogen Mobility (JHyM)	1	Opened in April.
Kusatsu City, Japan	Panasonic	Appliances company	1	H2 Kusatsu Farm was opened in November to support two fuel cell powered forklifts.
Oguchi, Japan	Air Liquide	JHyM	1	Opened in May.
Toyota City, Japan	PDC Machines	Ivys Energy Solutions	1	SimpleFuel system installed at Toyota's Motomachi Plant to supply hydrogen for fuel cell powered forklifts.
South Africa	Plug Power	ENGIE	1	Plug Power was selected by ENGIE to provide a custom renewable hydrogen refueling system with output of 1,000 kg per day for a fuel cell powered mine haul truck, which ENGIE is developing with Anglo American to be tested at one of its South African platinum mines.[240]
Saudi Arabia	Air Products	Saudi Aramco	1	Station will be located at Air Products' Technology Center in the Dhahran Techno Valley Science Park to fuel a pilot fleet of Toyota Mirai FCVs.
South Korea	Hyundai	National Assembly Proceeding Hall	1	In addition to the National Assembly hydrogen refueling station, the South Korean government also authorized Hyundai to install two other hydrogen stations in southern Seoul.
	Nel Hydrogen	Gangwon Technopark	2	One station in Gangneung will feature on-site production of hydrogen from a natural gas reformer. Hydrogen will be produced and distributed via trailers to the other H2Station in Samcheok. The value of the proposed station solution is ~€2.8 million (US$3.1 million).
		Korea Gas Technology Corporation	6	Four stations will be installed in Chungbuk province and two in Pyeongtaek city. The value of the purchase orders is ~€8 million (US8.9 million).
		HyNet	2	The value of the purchase order is ~€2.7 million (US$3 million).
		N/A	2	August purchase order has value of ~€2.7 million (US$3 million).

In January, the H2 Refuel Accelerator, a funding program geared towards early-stage companies developing hydrogen infrastructure and supply chain technologies, was launched. The program is led by the Urban Future Lab, Greentown Labs, and the Fraunhofer TechBridge Program and sponsored by Shell, Toyota, and the New York State Energy Research and Development Authority (NYSERDA).[241] In June, the winners were announced; they include a range of companies in the U.S. and one in Latvia.[242]

Table 20: 2019 H2Refuel Accelerator Winners

2019 H2 Refuel Accelerator Winners		
Company	Location	Focus Area
Celadyne	Austin, Texas	Nanocomposite membranes for high-performance electrolyzers and fuel cells
Ecolectro	Ithaca, New York	Materials for alkaline electrolyzers and fuel cells
Electro-Active Technologies	Knoxville, Tennessee	Developing a modular system to convert food waste and renewable electricity into hydrogen
HYGEN	Latvia	Supercharger
pH Matter	Columbus, Ohio	Catalyst materials and cell design for low-cost hydrogen generation for energy storage
Protium Innovation	Pullman, Washington	Lightweight liquid hydrogen tanks and fueling solutions.
Skyre	East Hartford, Connecticut	Waste hydrogen and CO2 conversion

In May, Air Liquide announced a new portable, compact hydrogen refueling unit that can provide 200 kg hydrogen per day and up to five fills per hour.[243] Air Liquide has also developed add-on components that improve capacity and back-to-back performance, as well as an optional public point of sale for commercial applications.

Both the UK and German governments announced significant funding awards for projects involving hydrogen station development. As outlined in the Transportation section, the UK Department for Transport selected five projects that will result in five new hydrogen fueling stations in the country.[244]

In Germany, NOW GmbH's National Innovation Program Hydrogen and Fuel Cell Technology announced the winners of the HyLand competition in November:[245]

- **HyExperts**: Thirteen regions were awarded €300,000 (US$336,000) each to create and analyze specific project ideas for hydrogen concepts.
- **HyStarter**: Nine regions were selected to provide organizational and content-related support to develop a local actor landscape (politics, municipal companies, industry, trade, society). They will also jointly develop initial concept ideas on the topics of hydrogen and fuel cells to develop renewable energies in transport and in the areas of heat, electricity, and storage.
- **HyPerformer**: Three winners were awarded €20 million in investment grants to implement existing regional concepts.

Table 21: HyPerformer Winners

HyPerformer Winners		
Project Name	Region	Details
HyBayern	Landshut, Munich and Ebersberg	To accelerate commercialization of fuel cell and hydrogen technologies, H2 Mobility will construct medium-sized hydrogen filling stations in each district to support fuel cell cars, buses, and commercial vehicles.
H2Rivers	Rhine-Neckar metropolitan region around Mannheim, Ludwigshafen and Heidelberg	H2 Mobility is building four hydrogen stations.

HyPerformer Winners		
Project Name	Region	Details
Hyways	Northwest Metropolitan Region (Oldenburg and the surrounding area)	Focusing on fuel cell cars, buses and waste-collection vehicles in the two big cities of Bremen and Oldenburg. H2 Mobility will build three medium-sized hydrogen filling stations, incorporating renewable hydrogen productions.

In addition, the German federal government is currently funding 20 laboratories nationwide to work with industry on industrial-scale hydrogen projects.

Conclusion

Interest and investment in fuel cell and hydrogen technologies continues to take hold and grow around the world, opening new markets and expanding existing ones. As more countries provide roadmaps and policies for public and private sector collaborations on further R&D and real-world deployments, the industry is finding not only more customers purchasing systems but support from other industries interested in reducing GHG emissions while increasing the reliability and efficiency of their operations.

As this report shows, the fuel cell industry continued to grow in 2019, with annual shipments topping 1 GW of power. A large portion of this growth is in the transportation sector, where there are already tens of thousands of fuel cell powered cars and material handling vehicles deployed around the world. There has been increased activity in the medium- and heavy-duty sector, in which decarbonization is more difficult, including investments, demonstrations, initial orders, and deployments of fuel cell powered trucks, trains, and ferries. The marine sector is increasingly exploring fuel cells and hydrogen to decarbonize propulsion on ships, the equipment that operates in and around ports, and associated logistics systems. Hydrogen for rail has also seen increased interest, mainly in Europe, while hydrogen for aviation uses is a rapidly growing field, as it provides long flight times for drones, UAVs and urban air mobility systems.

The hydrogen generation sector also received significant investments in 2019, laying the groundwork for market expansion to continue in the near- and long-term future. Hydrogen is gaining traction as a clean fuel capable of reducing emissions across a diverse group of industries. Many of these industries require large quantities of hydrogen, prompting the need for increased hydrogen production capacity. At the same time, the growth in intermittent renewable power production, combined with GHG emission reduction goals, has led to increasing demand for electrolyzers to produce renewable hydrogen.

While the information in this report provides a market snapshot of activities in 2019, the industry is progressing rapidly, and information will continue to be updated. In addition to deployments that ramp up scale, continued research and development is required to reduce costs and improve durability as well as to enable available and affordable hydrogen for various applications.

Appendix I: Federal Funding Awards

The following table shows funding awards released in 2019 from U.S. DOE, other federal agencies, and branches of the military.

DOE provides fuel cell and hydrogen funding primarily through FOAs and other solicitations from EERE's HFTO, the Office of Fossil Energy, the Office of Nuclear Energy, the Office of Basic Energy Science, and the Advanced Research Projects Agency–Energy.

DOE's Office of Technology Transitions (OTT), through the Technology Commercialization Fund (TCF), matches funds from the private sector to advance the commercialization of promising energy technologies and strengthen partnerships between DOE's National Laboratories and private sector companies to deploy these technologies to the marketplace.

DOE also provides funding through the Small Business Innovation Research (SBIR)/Small Business Technology Transfer (STTR) program, which other agencies, such as the National Science Foundation, the National Aeronautics and Space Administration, and branches of the military, also use to fund fuel cell and hydrogen research projects.

Awardee	Location	Amount	Program	Project Name
Advent Innovations Limited	Irmo, SC	$200,000	FY2019 EERE STTR Phase I Release 2: Fuel Cells	Polyvinylidene Difluoride (PVDF) Film for Robust Online Assessment of Composite Tanks (PROACT)
Air Products and Chemicals, Inc.	Allentown, PA	$1,674,100	EERE FY19 Commercial Trucks and Off-road Applications FOA Topic 3: High-Throughput Hydrogen Fueling Technologies for Medium- and Heavy-Duty Transportation	Ultra-Cryopump for High-Demand Transportation Fueling
CanmetENERGY	Ottawa, Ont.	$150,000	FY2019 OTT TCF–NREL	Novel Chemical Looping Process for Conversion of Natural Gas to Pure Hydrogen
Carnegie Melon University	Pittsburgh, PA	$2 million	EERE FY19 Commercial Trucks and Off-road Applications FOA Topic 4: High-Durability, Low-Platinum Group Metal MEAs for Medium- and Heavy-Duty Truck Applications	Durable High-Power Density Fuel Cell Cathodes for Heavy-Duty Vehicles
Celadyne Technologies, Inc.	Austin, TX	$24,971	FY2019 Air Force STTR Phase I	Nanoionics Enabled Proton Exchange Membranes
Chemours	Wilmington, DE	$1 million	H2@Scale Topic 2A: Advanced Water Splitting Materials Research (integrated with HydroGEN Consortium)	Performance and Durability Investigation of Thin, Low-Crossover Proton Exchange Membranes for Water Electrolyzers

Awardee	Location	Amount	Program	Project Name
Clemson University	Clemson, SC	$1 million	H2@Scale Topic 1B: H-Mat Materials Compatibility Consortium R&D: Hydrogen Effects in Materials for Fueling Infrastructure	Self-Healable Copolymer Composites for Extended Service H2 Dispensing Hoses
Colorado School of Mines	Golden, CO	$381,022	H2@Scale Topic 1A: Novel Hydrogen Carrier Development	High-Capacity Step-Shaped Hydrogen Adsorption in Robust, Pore-Gating Zeolithic Imidazolate Frameworks
		$1,443,648	H2@Scale Topic 1B: H-Mat Materials Compatibility Consortium R&D: Hydrogen Effects in Materials for Fueling Infrastructure	Low-Cost Alloys for Magnetocaloric Refrigeration
Composite Technology Development Inc.	Lafayette, CO	$199,930	FY2019 EERE SBIR Phase I Release 2: Fuel Cells	Thin-Ply Conductive Interleaving for Health Monitoring of COPVs, Topic 10d
C-Zero, LLC	Santa Barbara, CA	$999,878	H2@Scale Topic 2C: Co-production of H2 and Value-Add Byproducts	Binary Chloride Salts as Catalysts for Methane to Hydrogen and Graphitic Powder
Electricore, Inc.	Valencia, CA	$2,999,037	EERE FY19 Commercial Trucks and Off-road Applications FOA Topic 3: High-Throughput Hydrogen Fueling Technologies for Medium- and Heavy-Duty Transportation	High-Pressure, High-Flow Rate Dispenser and Nozzle Assembly for Heavy-Duty Vehicles
Element One, Inc.	Boulder, CO	$200,000	FY2019 EERE SBIR Phase I Release 2: Fuel Cells	Thin Film Hydrogen Sensor Development, Testing and Integration into Low-Cost Wireless Sensing Systems
eSpin Technologies Inc.	Chattanooga, TN	$206,500	FY2019 EERE SBIR Phase I Release 2: Fuel Cells	Nanostructured Proton Exchange Membrane
Exelon Corporation	Chicago, IL	$3,619,061	H2@Scale Topic 3: H2@Scale Pilot—Integrated Production, Storage, and Fueling System	Demonstration of Electrolyzer Operation at a Nuclear Plant to Allow for Dynamic Participation in an Organized Electricity Market and In-House Hydrogen Supply
Frontier Energy, Inc.	Oakland, CA	$5,400,000	H2@Scale Topic 3: H2@Scale Pilot— Integrated Production, Storage, and Fueling System	Demonstration and Framework for H2@Scale in Texas and Beyond
FuelCell Energy, Inc.	Danbury, CT	$2 million	H2@Scale Topic 2: Reversible Fuel Cell Development and Validation	High-Efficiency Reversible Solid Oxide System

Awardee	Location	Amount	Program	Project Name
General Engineering & Research, LLC	San Diego, CA	$1.15 million	FY2019 EERE STTR Phase II Release 2: Fuel Cells	Low-Cost Alloys for Magnetocaloric Refrigeration
General Motors, LLC	Pontiac, MI	$1,998,518	EERE FY19 Commercial Trucks and Off-Road Applications FOA Topic 4: High-Durability, Low-Platinum Group Metal MEAs for Medium- and Heavy-Duty Truck Applications	Durable Fuel Cell MEA Through Immobilization of Catalyst Particle and Membrane Chemical Stabilizer
Georgia Institute of Technology	Atlanta, GA	$999,997	H2@Scale Topic 2A: Advanced Water Splitting Materials Research (integrated with HydroGEN Consortium)	Interface and Electrode Engineering for Durable, Low-Cost Alkaline Anion Exchange Membrane Electrolyzers
Giner ELX, Inc.	Newton, MA	$4 million	H2@Scale Topic 3: H2@Scale Pilot—Integrated Production, Storage, and Fueling System	Demonstration of Integrated Hydrogen Production and Consumption for Improved Utility Operations
		$149,694	FY2019 Basic Energy Sciences STTR Phase I Release 1: Membranes for Electrochemical Applications	Novel Membranes for Electrochemical Compressors
		$999,595	FY2019 Basic Energy Sciences SBIR Phase II Release 1: Membranes and Materials for Energy Efficiency	Novel Fluorinated Ionomer for PEM Fuel Cells
		$829,846	FY2019 Navy SBIR Phase II	High-Energy-Density Hydrogen Delivery System
Glowink, Inc.	Montgomery Center, VT	$150,000	FY2019 OTT TCF—National Energy Technology Laboratory	Novel Chemical Looping Process for Conversion of Natural Gas to Pure Hydrogen
Hy-Performance Materials Testing, LLC	Bend, OR	$616,270	H2@Scale Topic 1B: H-Mat Materials Compatibility Consortium R&D: Hydrogen Effects in Materials for Fueling Infrastructure	Reducing the Cost of Fatigue Crack Growth Testing for Storage Vessel Steels in Hydrogen Gas
Intellisense Systems Inc.	Torrance, CA	$200,000	FY2019 EERE SBIR Phase I Release 2: Fuel Cells	10d. Composite Overwrapped Pressure Vessel Monitoring by Electrical Resistance
Luna Innovations Incorporated	Roanoke, VA	$1.048 million	FY2019 EERE SBIR Phase II Release 2: Fuel Cells	Detection of Micron-Scale Flaws Through Nonlinear Wave Mixing

Awardee	Location	Amount	Program	Project Name
Massachusetts Institute of Technology	Cambridge, MA	$1 million	H2@Scale Topic 1B: H-Mat Materials Compatibility Consortium R&D: Hydrogen Effects in Materials for Fueling Infrastructure	Micro-Mechanically Guided High-Throughput Alloy Design Exploration Towards Metastability-Induced Hydrogen Embrittlement Resistance
NanoSonic, Inc.	Pembroke, VA	$200,000	FY2019 EERE SBIR Phase I Release 2: Fuel Cells	High-Pressure, Low-Temperature Composite Nozzles for Long-Term H2 Dispensing
		$200,000	FY2019 EERE STTR Phase I Release 2: Fuel Cells	10a. Segmented and Blocky Hydrocarbon Ion Pair Membranes for Fuel Cells
		$50,000	FY2019 Air Force SBIR Phase I Release 1	Innovative H35/Aircraft Hoses for Immediate Transition to the H2 Market and Air Force
Nel Hydrogen	San Leandro, CA	$2 million	EERE FY19 Commercial Trucks and Off-Road Applications FOA Topic 3: High-Throughput Hydrogen Fueling Technologies for Medium- and Heavy-Duty Transportation	High-Speed and Dynamic Diaphragm Compressor for High-Capacity Fueling
Nexceris, LLC	Lewis Center, OH	$1 million	H2@Scale Topic 2A: Advanced Water Splitting Materials Research (integrated with HydroGEN Consortium)	Advanced Coatings to Enhance the Durability of SOEC Stacks
Nexceris, LLC		$206,500	FY2019 EERE SBIR Phase I Release 2: Fuel Cells	Innovative Catalyst Design for Direct Hydrogenation of CO2 to Methanol
		$1.05 million	FY2019 Basic Energy Sciences SBIR Phase II Release 1: Advanced Fossil Energy Technology Research	Functionally Gradient Seals for Solid Oxide Fuel Cells
		$1.05 million	FY2019 Basic Energy Sciences SBIR Phase II Release 1: Advanced Fossil Energy Technology Research	Superior Catalysts for Steam Methane Reforming to Syngas
Nikola Motor Company	Phoenix, AZ	$1.7 million	EERE FY19 Commercial Trucks and Off-Road Applications FOA Topic4: High-Durability, Low Platinum Group Metal MEAs for Medium- and Heavy-Duty Truck Applications	Durable MEAs for Heavy-Duty Fuel Cell Electric Trucks
Northwestern University	Evanston, IL	$1 million	EERE FY19 Commercial Trucks and Off-Road Applications FOA Topic 1a: Advanced Storage for Gaseous Fuels	Theory-Guided Design and Discovery of Materials for Reversible Methane and Hydrogen Storage

Awardee	Location	Amount	Program	Project Name
NuMat Technologies	Skokie, IL	$199,946	FY2019 EERE SBIR Phase I Release 2: Joint Topic: Advanced Manufacturing and Fuel Cell Technologies Office	Advanced Materials for Detection and Removal of Impurities in Hydrogen Adsorbents
		$999,511	FY2019 Basic Energy Sciences SBIR Phase II Release 1: Membranes and Materials for Energy Efficiency	General Techniques for Increasing Packing Density of Metal-Organic Frameworks for Enhanced Volumetric Storage of Hydrogen
Oregon State University	Corvallis, OR	$999,906	H2@Scale Topic 2B: Affordable Biological Hydrogen Production from Biomass Resources	Scalable and Highly Efficient Microbial Electrochemical Reactor for Hydrogen Generation from Lignocellulosic Biomass and Waste
Physical Sciences, Inc.	Andover, MA	$999,997	FY2019 Basic Energy Sciences SBIR Phase II Release 1: Membranes and Materials for Energy Efficiency	Controlled Porosity and Surface Coatings for Advanced Gas Diffusion Layers
Precision Combustion, Inc.	North Haven, CT	$156,491	FY2019 Basic Energy Sciences SBIR Phase I Release 1: Membranes for Electrochemical Applications	Ultra-Stable Anion Exchange Membrane for Solar-to-Hydrogen Generation
Proton Energy Systems, Inc.	Wallingford, CT	$2 million	H2@Scale Topic 2: Reversible Fuel Cell Development and Validation	A Novel Stack Approach to Enable High Round-Trip Efficiencies in Unitized PEM Regenerative Fuel Cells
Redox Power Systems, LLC	College Park, MD	$999,976	H2@Scale Topic 2A: Advanced Water Splitting Materials Research (integrated with HydroGEN Consortium)	Scalable High-H2 Flux, Robust, Thin Film Solid Oxide Electrolyzer
Skyre, Inc.	East Hartford, CT	$150,000	FY2019 OTT TCF – Los Alamos National Laboratory	Hydrogen Contaminant Detector
Southwest Sciences, Inc.	Santa Fe, NM	$1 million	FY2019 Basic Energy Sciences SBIR Phase II Release 1: Membranes and Materials for Energy Efficiency	Diode Laser Sensor for Contaminants in Hydrogen Fuel
SPEC Sensors, LLC	Newark, CA	$206,499	FY2019 EERE SBIR Phase I Release 2: Fuel Cells	Robust and Reliable Hydrogen Leak Detection and Warning Systems
Starfire Energy LLC	Aurora, CO	$200,000	FY2019 EERE SBIR Phase I Release 2: Solar	Low-CapEx Clean NH3 Synthesis for Seasonal Energy Storage and Hydrogen Fuel
Supercool Metals	New Haven, CT	$199,919	FY2019 EERE SBIR Phase I Release 2: Fuel Cells	Thermoplastic Forming of Bulk Metallic Glass Nozzles for High-Pressure, Low-Temperature Hydrogen Fueling

Awardee	Location	Amount	Program	Project Name
TDA Research, Inc.	Wheat Ridge, CO	$200,000	FY2019 EERE SBIR Phase I Release 2: Fuel Cells	Onboard Monitoring Method for Detection of Damage to Carbon Fiber Composite Overwrap on Hydrogen Fuel Tanks
		$1 million	FY2019 EERE SBIR Phase II Release 2: Fuel Cells	Highly Efficient Smart Tanks for Hydrogen Storage
Tetramer Technologies, LLC	Pendleton, SC	$199,956	FY2019 EERE SBIR Phase I Release 2: Fuel Cells	Improved Ionomers and Membranes for Fuel Cells
University of Alabama	Tuscaloosa, AL	$999,870	H2@Scale Topic 1B: H-Mat Materials Compatibility Consortium R&D: Hydrogen Effects in Materials for Fueling Infrastructure	Tailoring Carbide-Dispersed Steels: A Path to Increased Strength and Hydrogen Tolerance
University of California, Irvine	Irvine, CA	$999,999	H2@Scale Topic 2A: Advanced Water Splitting Materials Research (integrated with HydroGEN Consortium)	Development of Composite Photocatalyst Materials that Are Highly Selective for Solar Hydrogen Production and Their Evaluation in Z-Scheme Reactor Designs
University of California, San Diego	La Jolla, CA	$1 million	H2@Scale Topic 2A: Advanced Water Splitting Materials Research (integrated with HydroGEN Consortium)	New High-Entropy Perovskite Oxides with Increased Reducibility and Stability for Thermochemical Hydrogen Generation
University of Colorado–Boulder	Boulder, CO	$1 million	H2@Scale Topic 2C: Co-Production of H2 and Value-Added Byproducts	Extremely Durable Concrete Using Methane Decarbonization Nanofiber Co-Products with Hydrogen
University of Florida	Gainesville, FL	$999,589	H2@Scale Topic 2A: Advanced Water Splitting Materials Research (integrated with HydroGEN Consortium)	A New Paradigm for Materials Discovery and Development for Lower Temperature and Isothermal Thermochemical H2 Production
University of Hawaii	Honolulu, HI	$994,326	H2@Scale Topic 1A: Novel Hydrogen Carrier Development	Development of Magnesium Borane Containing Solutions of Furans and Pyroles as Reversible Liquid Hydrogen Carriers
University of Illinois at Urbana-Champaign	Champaign, IL	$2 million	H2@Scale Topic 1B: H-Mat Materials Compatibility Consortium R&D: Hydrogen Effects in Materials for Fueling Infrastructure	Tailoring Composition and Deformation Modes at the Microstructural Level for Next Generation Low-Cost High-Strength Austenitic Stainless Steels

Awardee	Location	Amount	Program	Project Name
University of Oregon	Eugene, OR	$500,000	H2@Scale Topic 2A: Advanced Water Splitting Materials Research (integrated with HydroGEN Consortium)	Pure Hydrogen Production Through Precious-Metal-Free Membrane Electrolysis of Dirty Water
University of South Carolina	Columbia, SC	$1 million	H2@Scale Topic 2A: Advanced Water Splitting Materials Research (integrated with HydroGEN Consortium)	A Multifunctional Isostructural Bilayer Oxygen Evolution Electrode for Durable Intermediate-Temperature Electrochemical Water Splitting
University of Southern California	Los Angeles, CA	$1 million	H2@Scale Topic 1A: Novel Hydrogen Carrier Development	Hydrogen Release from Concentrated Media with Reusable Catalysts
University of South Florida	Tampa, FL	$800,000	EERE FY19 Commercial Trucks and Off-road Applications FOA Topic 1a: Advanced Storage for Gaseous Fuels	Metal-Organic Frameworks Containing Frustrated Lewis Pairs for H2 Storage at Ambient Temperature
University of Toledo	Toledo, OH	$750,000	H2@Scale Topic 2A: Advanced Water Splitting Materials Research (integrated with HydroGEN Consortium)	Perovskite/Perovskite Tandem Photoelectrodes for Low-Cost Unassisted Photoelectrochemical Water Splitting
Washington State University	Pullman, WA	$1 million	H2@Scale Topic 1A: Novel Hydrogen Carrier Development	A Reversible Liquid Hydrogen Carrier System Based on Ammonium Formate and Captured CO2
William Marsh Rice University	Houston, TX	$799,998	H2@Scale Topic 2A: Advanced Water Splitting Materials Research (integrated with HydroGEN Consortium)	Highly Efficient Solar Water Splitting Using 3D/2D Hydrophobic Perovskites with Corrosion Resistant Barriers
Xergy, Inc.	Harrington, DE	$1.05 million	FY2019 Basic Energy Sciences STTR Phase II Release 1: Membranes and Materials for Energy Efficiency	Novel Membranes for Electrochemical Hydrogen Compression Enabling Increased Pressure Capability and High Pumping Efficiency

Appendix II: FCH JU Horizon 2020 Projects Announced in 2019

In Europe, FCH JU, a public-private organization, funds important research and demonstration projects, and, in 2019, announced 17 new programs, including many aimed at cost reduction testing, as well as pilot demonstrations of hydrogen supply and production technologies.

Program Name	Details
ANIONE: Anion Exchange Membrane Electrolysis for Renewable Hydrogen Production on a Wide Scale	To develop a high-performance, cost-effective and durable anion exchange membrane water electrolysis technology.
EMPOWER: European Methanol-Powered Fuel Cell CHP	A methanol-fueled 5 kWe mini-CHP system based on HTPEMFC technology to be developed, manufactured, and validated in a relevant environment.
CAMELOT: Understanding Charge, Mass and Heat Transfer in Fuel Cells for Transport Applications	To bring together highly experienced research institutes, universities, fuel cell MEA suppliers, and transport OEMs to improve understanding of the limitations in fuel cell electrodes.
CHANNEL: Development of the Most Cost-Efficient Hydrogen Production Unit Based on Anion Exchange Membrane Electrolysis	To develop a low-cost and efficient electrolyzer stack and balance of plant (BoP) that will become a game-changer for the electrolyzer industry.
FURTHER FC: Further Understanding Related to Transport Limitations at High Current Density Towards Future Electrodes for Fuel Cells	Aims at understanding performance limitations due to the coupling between electrochemical and transport issues in the cathode catalyst layer (CCL).
HEAVENN: Hydrogen Energy Applications for Valley Environments in Northern Netherlands	To bring together core elements—production, distribution, storage, and local end use of H_2—into a fully integrated and functioning "H_2 valley" (H2V), that can serve as a blueprint for replication across Europe and beyond.
HIGGS: Hydrogen in Gas Grids—a systematic validation approach at various admixture levels into high-pressure grids	To pave the way to decarbonization of the gas grid and its usage by covering the gaps in knowledge of the impact that high levels of hydrogen could have on the gas infrastructure, its components, and its management.
HyResponder: European Hydrogen Train the Trainer Programme for Responders	To develop and implement a sustainable train-the-trainer program in hydrogen safety for responders throughout Europe, to support the commercialization of hydrogen and fuel cell.
MultiPLHY: Multi-Megawatt High-Temperature Electrolyzer to Generate Green Hydrogen for Production of High-Quality Chemical Products	To install, integrate and operate the world's first high-temperature electrolyzer system at multi-megawatt scale at a chemical refinery in Salzbergen, Germany, to produce hydrogen for the refinery's processes.
NEWELY: Next Generation Alkaline Membrane Water Electrolyzers with Improved Components and Materials	To redefine anion exchange membrane water electrolysis and surpass the current state of alkaline water electrolysis, bringing it closer to proton exchange membrane water electrolysis in efficiency but at lower cost.
NewSOC: Next Generation Solid Oxide Fuel Cell and Electrolysis Technology	To improve the performance, durability, and cost competitiveness of solid oxide cells and stacks.
PRHYDE: Protocol for Heavy-Duty Hydrogen Refueling	To build the foundations of non-proprietary heavy-duty refueling protocols for large tank systems (larger than 10kg), such as the ones found in heavy-duty hydrogen applications.

Program Name	Details
RUBY: Robust and Reliable General Management Tool for Performance and Durability Improvement of Fuel Cell Stationary Units	To develop and implement a tool able to perform integrated monitoring, diagnostic, prognostic and control functions for production μ-CHP and backup systems.
ShipFC: Piloting Multi-MW Ammonia Ship Fuel Cells	To prove and show the case for large-scale zero-emission shipping through developing, piloting and replicating modular 2 MW fuel cell technology using ammonia as fuel.
SWITCH: Smart Ways for In-Situ Totally Integrated and Continuous Multi-source Generation of Hydrogen	To demonstrate a 25 kW (SOFC)/75 kW (SOEC) system operating in a relevant industrial environment for at least 5,000 hours.
THyGA: Testing Hydrogen Admixture for Gas Applications	To enable the wide adoption of hydrogen and natural gas (H_2/NG) blends by closing knowledge gaps regarding technical impacts on residential and commercial gas appliances.
VIRTUAL FCS: Virtual and Physical Platform for Fuel Cell System Development	To develop a fully open source software-hardware (cyber-physical) tool that can be adopted as a global standard for FC system design.

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