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Developing hydrogen fueling infrastructure for fuel cell vehicles: A status update

This briefing provides a synthesis of information regarding the global development of hydrogen fueling infrastructure to power fuel cell vehicles. The compilation includes research on hydrogen infrastructure deployment, fuel pathways, and planning based on developments in the prominent fuel cell vehicle growth markets around the world.

INTRODUCTION

Governments around the world continue to seek the right mix of future vehicle technologies that will enable expanded personal mobility and freight transport with near-zero emissions. This move toward zero emissions is motivated by the simultaneous drivers of improving local air quality, protecting against increased climate change impacts, and shifting to local renewable fuel sources. Electricity-powered plug-in vehicles and hydrogen-powered fuel cell electric vehicles offer great potential to displace the inherently high emissions associated with the combustion of petroleum-based gasoline and diesel fuels.

Hydrogen fuel cell electric vehicles offer a unique combination of features as a zero-emission alternative to conventional vehicles. Fuel cell powertrains, converting hydrogen to electric power to propel the vehicle, tend to be about twice as efficient as those on conventional vehicles. Hydrogen fuel cell vehicles are typically capable of long trips (i.e., over 500 kilometers or 300 miles) and a short refueling time that is comparable to conventional vehicles. Furthermore, fuel cell vehicles are expected to be less expensive than conventional vehicles in the long run. The

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diversity of fuel pathways to produce hydrogen allows for the use of lower-carbon, renewable, and nonimported sources. A related benefit is that hydrogen can provide a complement to renewable power generation, storing energy from excess solar- and wind-generated electricity during periods of low demand. Although plug-in electric vehicles are being commercialized more rapidly, these attributes ensure that hydrogen fuel cell vehicles remain an appealing long-term strategy, especially for larger and longer-range vehicles.

However, fuel cell vehicles, like other zero-emission alternatives, have barriers to widespread adoption. The hydrogen fueling infrastructure is limited, the cost of producing and delivering hydrogen fuel to service stations is currently high at low volumes, and it is still far cheaper to produce hydrogen from fossil fuels than from renewable energy. Additionally, fuel cell vehicle production costs will have to drop considerably from their current levels, and consumer understanding of the technology and its benefits will have to improve, for fuel cell vehicles to reach the mainstream market.

This paper assesses the development of hydrogen fueling infrastructure networks around the world. We compile data on the current state of development of fuel cell vehicle technology. We summarize research on hydrogen fueling infrastructure, technology pathways, station planning, and funding from prominent fuel cell vehicle development markets. The paper focuses on infrastructure for hydrogen fueling for fuel cell vehicles, but does not address the systems or processes necessary to produce the hydrogen. Much of the data and analytical research are based on work in California, Europe, Japan, and Korea due to more extensive study and activity in these regions. Included in this assessment are investments by energy companies, automakers, station developers, and governments that could help pave the way for accelerated fuel cell vehicle market growth in the years ahead. We conclude with a discussion of implications for public policy and investment strategies based on this assessment to help guide hydrogen infrastructure deployment.

STATUS OF FUEL CELL VEHICLE DEVELOPMENT

In this section, we summarize the status of fuel cell vehicle development as of mid-2017. We summarize the early developments with light-duty vehicles and include vehicle manufacturer announcements for deployment, as well as efficiency comparisons for the most prominent fuel cell vehicles in the market today. In addition, we summarize several developments with heavy-duty fuel cell vehicles.

Figure 1 summarizes global fuel cell vehicle deployment since 2012, totaling about 4,500 cumulative vehicles as of July 2017. Fuel cell deployment in 2016 was about six times higher than in 2015, and it appears to be headed for another major increase in 2017. As shown, three automakers are selling or leasing most of these fuel cell vehicles. The Toyota Mirai accounts for about 75% of global fuel cell vehicles sold; this is followed by Hyundai, with its Tucson and ix35 models at 11%; Honda, with its Clarity and earlier FCX model at 10%; and Renault’s Kangoo at 4%. Approximately 48% of the fuel cell vehicle sales have been in California, followed by about 35% in Japan, 14% in Europe, and 3% in Korea. The deployment of fuel cell vehicles in these markets, of course, is linked to hydrogen availability, which is assessed below.

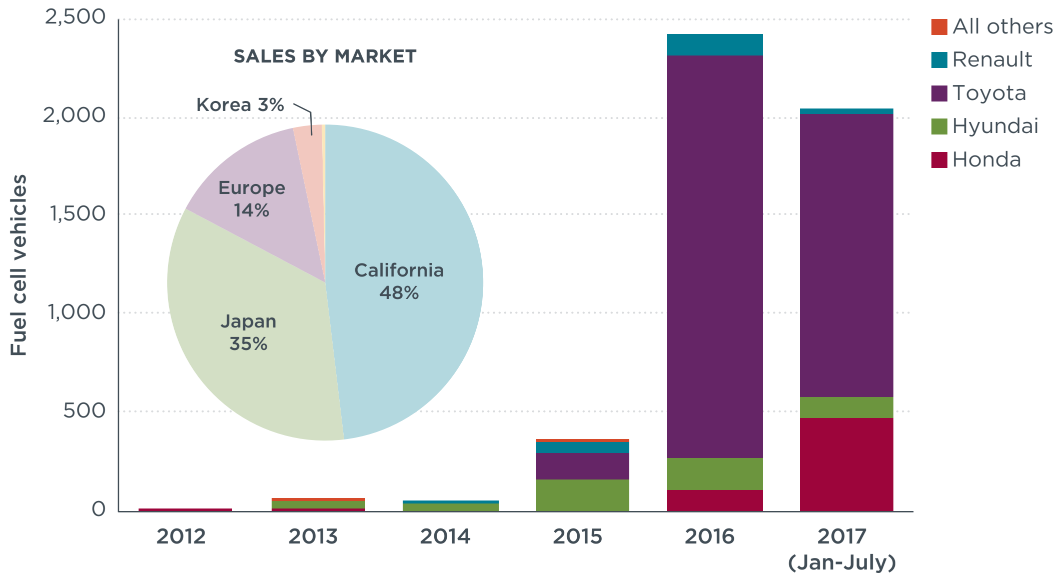

Figure 1. Fuel cell vehicle deployments for 2012 through mid-2017, by company and locale.

Beyond the deployments shown in Figure 1, many manufacturers have made major research and development investments and have plans for future fuel cell vehicle deployment. Several groups of manufacturers are working together to co-develop fuel cell systems to reduce costs and accelerate production. BMW, Daimler, General Motors, and Kia have all announced that they plan to sell fuel cell vehicles by 2020. Toyota has announced plans to sell 30,000 fuel cell vehicles per year by 2020.[1] Hyundai Motor Group expects sales to be in the thousands with a next-generation fuel cell system that is 30% less expensive, 30% denser, 20% lighter, and 10% more efficient compared to its current version.[2]

Fuel cell vehicle technology offers a substantial efficiency advantage over conventional vehicles. Figure 2 compares the fuel economy of three major fuel cell vehicles with comparable gasoline vehicles of the same automaker brand for model year 2017.[3] The figure shows data from the vehicles' fuel economy and environment labels, developed and published jointly by the U.S. regulatory agencies. The data are shown both in miles per gallon gasoline equivalent (left axis) and in the corresponding liters per 100 kilometer equivalent (right axis). As illustrated, the fuel cell vehicles are about twice as efficient as comparable gasoline models, and 40%–70% more efficient than comparable hybrids.

1 Hans Greimel, "Toyota outlines ambitious plan to slash CO_2," Automotive News, October 14, 2015, http://www.autonews.com/article/20151014/OEM05/151019954/toyota-outlines-ambitious-plan-to-slash-co2

2 Christian Seabaugh, "Hyundai FE Fuel Cell concept previews 497-mile hydrogen SUV," Motor Trend, March 7, 2017, http://www.motortrend.com/news/hyundai-fe-fuel-cell-concept-previews-497-mile-hydrogen-suv/

3 U.S. Department of Energy and U.S. Environmental Protection Agency, "Fuel Economy Data" (2017). http://www.fueleconomy.gov/feg/download.shtml. We note the Toyota Mirai is closer in size to the Toyota Corolla, but could also be compared to the Toyota Camry.

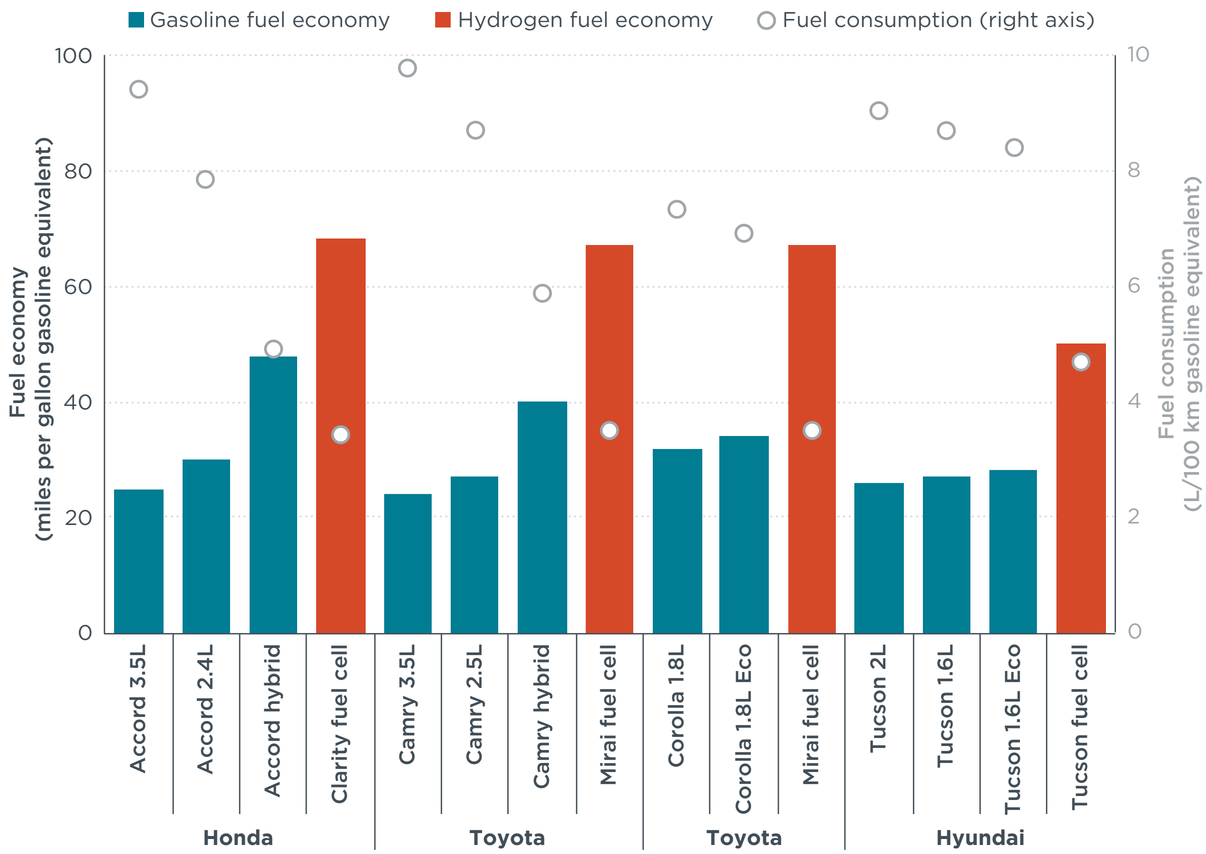

Figure 2. Fuel economy of fuel cell vehicles and similar gasoline vehicle models.

The model year 2017 fuel cell vehicles shown in Figure 2 are available for purchase or lease in select markets, primarily in California. They typically have list prices between $55,000 and $60,000 and leasing rates have been about $350–$500 per month. Although these rates are roughly 1.5 to 2 times those of conventional models offered by each automaker, some have included 3 years of free fuel. The U.S. Department of Energy expects that production volumes of 100,000 fuel cell vehicles would realize a 50% cost reduction for today's fuel cell system, solely through economies of scale.[4] Based on a literature review of several expert studies, fuel cell vehicle costs are expected to decrease by more than 70% from 2015 to 2030, reducing the incremental vehicle cost from more than $20,000 to roughly $5,000 by 2030.[5] This forecast assumes fuel cell stack innovations, production at 100,000 per year, and stack level costs of $60 per kilowatt power output. The National Research Council (NRC) estimates that fuel cell stacks could fall to $30 per kilowatt enabling fuel cell vehicles to cost less than conventional vehicles by 2045.[6]

For heavy-duty vehicles, hydrogen fuel cell technology has been deployed in several demonstration and evaluation fleets.[7] Table 1 shows a selection of hydrogen fuel cell

4 U.S. Department of Energy, "Fuel Cell Technologies Office Accomplishments and Progress" (2016). https://energy.gov/eere/fuelcells/fuel-cell-technologies-office-accomplishments-and-progress

5 Paul Wolfram, Nic Lutsey, Electric vehicles: Literature review of technology costs and carbon emissions. (ICCT: Washington DC, 2016). http://www.theicct.org/lit-review-ev-tech-costs-co2-emissions-2016

6 National Research Council, "Transitions to alternative vehicles and fuels" (2013). http://www.nap.edu/catalog.php?record_id=18264

7 Marissa Moultak, Nic Lutsey, Dale Hall. Transitioning to zero-emission heavy-duty freight vehicles. International Council on Clean Transportation. September 2017. http://www.zevalliance.org/zero-emission-freight-trucks-2017

heavy-duty truck and bus projects in operation in 2016 and 2017. As shown, the table includes projects with urban delivery trucks, heavy-duty drayage trucks around ports, and urban passenger buses. The technologies differ by vehicle manufacturer, supplier, fleet operator, and location. The various projects also differ in their hydrogen delivery systems, with a mix of liquid hydrogen delivery, on-site electrolysis of hydrogen from grid electricity and solar power, and on-site natural gas reforming. Although there are no long-haul tractor-trailer demonstrations in the table, a prominent announcement from the startup Nikola suggests work toward a hydrogen tractor-trailer with a range of more than 1,200 kilometers. In addition, Toyota has announced it will deploy 100 hydrogen buses in advance of the Tokyo Olympic Games in 2020. We estimate that there are currently several hundred fuel cell buses in operation globally.

Table 1. Selection of 2015–2017 fuel cell heavy-duty truck and bus projects

	Organizations	Location(s)	Year	Vehicles
Urban delivery	FedEx, Plug Power, Workhorse Group	Tennessee, California	2016	20
	CTE, UPS, University of Texas, Hydrogenics, Valance	California	2015	17
	Scania, Asko	Norway	2016	3
	Renault Trucks, French Post Office	France	2015	1
Drayage truck	Gas Technology Institute, U.S. Hybrid, Richardson Trucking, University of Texas	Houston, Texas	2015	3
	Hydrogenics, Siemens, Total Transportation Services	Los Angeles & Long Beach, California	2015	1
	Toyota	Los Angeles & Long Beach, California	2017	1
	SCAQMD, CTE, TransPower, U.S. Hybrid, Hydrogenics	Los Angeles & Long Beach, California	2015	6
Bus	AC Transit ZEBA Demo, UTC Power, Van Hool	Oakland, California	2017	13
	Proterra/Hydrogenics	Flint, Michigan	2017	1
	American Fuel Cell Bus, SunLine, BAE, El Dorado, Ballard	Thousand Palms, California	2017	3
	American Fuel Cell Bus, Flint Mass Transportation Authority, BAE, Ballard, El Dorado	Flint, Michigan	2017	1
	American Fuel Cell Bus, Nuvera, MBTA	Boston, Massachusetts	2017	1
	American Fuel Cell Bus, Orange County Transit Authority, BAE, Ballard, El Dorado	Orange County, California	2017	1
	American Fuel Cell Bus, SARTA, BAE, Ballard, El Dorado, CALSTART	Columbus & Canton, Ohio	2017	1
	American Fuel Cell Bus, UC Irvine, BAE, Ballard, El Dorado	Irvine, California	2017	1
	Aberdeen, High Vlo City, HyTransit, Hydrogenics	Aberdeen, United Kingdom	2017	10
	Mercedes-Benz, PostBus Switzerland	Aargau, Switzerland	2017	5
	Mercedes-Benz, Hamburger Hochbahn	Hamburg, Germany	2017	4
	Mercedes-Benz, Società Autobus Servizi d'Area	Bolzano, Italy	2017	5
	Mercedes-Benz, Milan	Milan, Italy	2017	3
	Mercedes-Benz, Stuttgarter Straßenbahnen	Stuttgart, Germany	2017	4
	Mercedes-Benz, Karlsruhe Institute of Technology	Karlsruhe, Germany	2017	2
	Tokyo Metropolitan Government, Toyota	Tokyo, Japan	2017	1

Sources: International Council on Clean Transportation; National Renewable Energy Laboratory; NuCellSys

HYDROGEN PRODUCTION TECHNOLOGIES

There are many pathways to produce, distribute, store, and dispense hydrogen for use in fuel cell vehicles, each with its own life-cycle emissions profile. Fuel cell vehicles' life-cycle emissions are greatly affected by the source of energy used for hydrogen production. As previously noted, fuel cell vehicles' drivetrains are substantially more efficient than those in conventional vehicles. Moreover, because no emissions are produced during vehicle operation, total life-cycle emissions are almost entirely driven by the upstream fuel production process.

One advantage of hydrogen is that it can be produced from many different energy sources and pathways. This analysis will focus on the two pathways most commonly used today: production from natural gas or methane via steam reforming, and from electricity via electrolysis. For reforming, the majority of emissions are associated with the conversion of natural gas or methane into hydrogen and carbon dioxide. On the other hand, the majority of emissions due to electrolysis come from producing electricity—not the hydrogen directly—using a variety of primary energy sources individually or in some combination including fossil fuels, biomass, wind, solar, or nuclear power. Hydrogen can be produced on-site or at a centralized facility. Centralized production typically offers greater efficiency through increased scale, for the price of increased cost and emissions associated with transporting the fuel. All the pathways include energy to compress, pump, store, and deliver hydrogen at various stages.

Each combination of energy sources, chemical conversion processes, production facility scale and location, and distribution method results in different energy consumption and emissions impacts. Several studies have compared the greenhouse gas emissions impacts of various hydrogen production pathways.[8] One conclusion from these studies is that the share of overall production of hydrogen from renewable sources is the dominant factor in determining fuel cell vehicles' contribution to deep carbon emission reductions. A second finding is that liquefaction of hydrogen, though useful in storing and transporting hydrogen, can greatly reduce its life-cycle climate benefits if the energy used for liquefaction is not from renewable sources.

Figure 3 shows the life-cycle, or well-to-wheel, greenhouse gas emissions impact of several hydrogen production pathways for an average fuel cell vehicle, and compares them with average conventional and hybrid gasoline-powered vehicles. The figure compares the greenhouse gas emissions impact in carbon dioxide equivalent (CO_2e) emissions including the on-vehicle efficiency differences of the vehicles. The vehicle efficiency values are taken from the conventional, hybrid, and fuel cell models, using U.S. test certification values from the 2017 Honda models in Figure 2. The "upstream" fuel carbon intensity emission estimates are from the California Low Carbon Fuel Standard. The finer details, and impacts, of a multitude of additional pathways can be found at California's Low Carbon Fuel Standard pathways list. As shown in the figure, fuel cell vehicles using hydrogen from all production pathways can have clear carbon reduction benefits versus the baseline 2017 gasoline vehicle. Most pathways also have carbon reduction benefits versus the baseline hybrid. For example, the pathway

8 Robert Edwards, Heinz Hass, Jean-François Larivé, Laura Lonza, Heiko Maas, David Rickeard, "Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context" (2014), http://iet.jrc.ec.europa.eu/about-jec/sites/iet.jrc.ec.europa.eu.about-jec/files/documents/wtw_report_v4a_march_2014_final.pdf and California Air Resources Board, "LCFS Pathway Certified Carbon Intensities" (2017), https://www.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm

shown in Figure 3 as 0% renewable natural gas delivers a 53% reduction over the 2017 gasoline baseline and a 17% reduction from the gasoline hybrid.

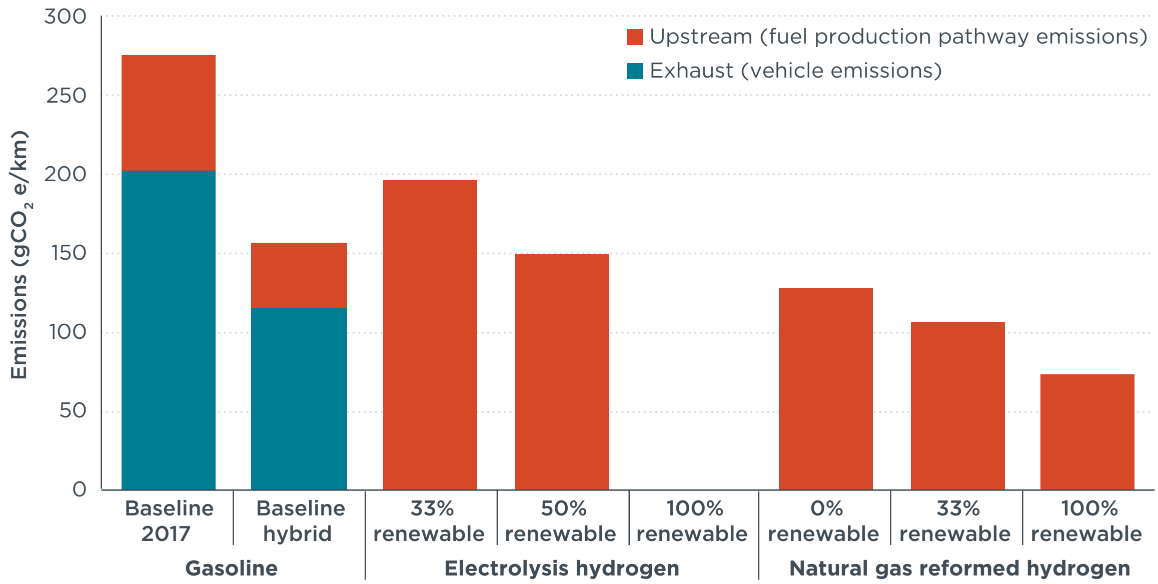

Figure 3. Hydrogen fuel cell vehicle CO_2e versus conventional and hybrid gasoline vehicles.

Upstream emissions of hydrogen are for on-site, gaseous hydrogen production only. U.S. average grid electricity is assumed in the electrolysis pathways. The reformed natural gas pathways assume a constant value for emissions due to natural gas/methane fuel use, but a variable value for production of the natural gas. The upstream emission estimates shown for hydrogen and gasoline are from the California Low Carbon Fuel Standards' modified GREET 2.0 model on a per megajoule, per gallon, or per kilogram basis. These emission factors are scaled to account for the impact of the fuel efficiency of each vehicle (see Figure 2).

Figure 3 also illustrates the relative impact of more renewably sourced hydrogen on life-cycle emissions of hydrogen when used in fuel cell vehicles. One-hundred percent renewable natural gas includes biomass sources of methane, which reduce the feedstock emissions of the natural gas. Japan, for example, is using renewable methane from sewage fields to provide enough hydrogen to fully run a single station. The greater the reliance on renewables for hydrogen production, the greater the CO_2 benefit associated with increased hydrogen use in fuel cell vehicles.

Over time, conventional vehicles are likely to get more efficient as regulatory standards around the world continue to tighten. Fuel cell vehicles have and will continue to increase in efficiency over time as well. However, in the early stages of fuel cell vehicle markets, annual efficiency improvements will not match those of conventional vehicles, because most research and design changes are focused on increased durability, better performance, and reduced costs.

Compared to today's major users of hydrogen, namely industrial gas consumers, hydrogen for transport is used in relatively small amounts, at several small dispensaries spread over a relatively wide geographical area. Whereas industrial hydrogen typically is transported in large quantities via truck and pipeline to individual centralized customers, hydrogen fueling stations for vehicles are comparatively small. At these small scales, gaseous hydrogen is more economical than liquid, particularly because liquefaction requires a substantial amount of electrical energy. For this reason, Figure 3 shows the emissions associated with gaseous hydrogen only. However, liquid hydrogen is much denser than gaseous, so fueling stations relying on liquid hydrogen can store more fuel and reduce delivery frequency. Also, cryogenic storage at stations may use less costly equipment, mainly by avoiding tube trailers and compressors, especially on a per-kilogram of hydrogen basis. Thus, liquid hydrogen delivery/storage has the potential to enable larger stations, with improved business cases for these stations, assuming greater volumes of dispensed hydrogen as more fuel cell vehicles are deployed. Of course, the energy required to liquefy hydrogen would need to be from increasingly renewable sources such as solar, wind, and nuclear; otherwise, upstream emissions would increase.

Hydrogen production costs vary with process and scale. The NRC projects that retail hydrogen prices will decrease from $10 per kilogram or higher in 2017 to about $4 to $6 per kilogram in the approximate 2025 time frame, factoring in both increased volume and a shift to more renewable and lower-carbon sources.[9] The NRC study indicates the importance of the shift to higher volume fuel cell vehicle usage for lower cost hydrogen production and lower per-kilogram markups for taxes and business profits: $6 per kilogram may be possible with 1 million fuel cell vehicles, and around $4 per kilogram with 5 million fuel cell vehicles. Other, more detailed, studies offer similar findings.[10] For example, the steam-methane reforming process could deliver hydrogen from natural gas at about $4 per kilogram, including delivery and dispensation. Electrolysis-derived hydrogen ultimately could come down to $3 to $6 per kilogram, depending on electricity prices and the facility scale: larger, centralized electrolysis occupies the lower end of the cost range, and distributed hydrogen plants take the higher end of the range. Biomethane sources, such as landfill gas, potentially could be blended into such sources at minimal additional cost, depending on availability, but otherwise renewable sources of hydrogen would increase hydrogen costs.

A basic calculation of the fueling costs, on a per-kilometer basis, puts hydrogen prices into context for a potential fuel cell vehicle consumer. A future hydrogen price of $4 per kilogram is equivalent to about 3.7 cents per kilometer for the Mirai or Clarity models assessed above. A hydrogen cost of about $10 per kilogram results in a cost per kilometer that is 2.5 times greater. Comparable nonhybrids cost about 5.8 to 6.9 cents per kilometer to fuel, based on 80 cents per liter ($3 per gallon) gasoline, meaning the fuel cell vehicles are 37%–47% less expensive per kilometer to fuel at the expected future price of hydrogen. Hybrid vehicles like the Honda Accord and Toyota Camry, at 80 cents per liter gasoline, cost about 4.3 cents per kilometer, which is about 16% higher fuel cost per kilometer than the fuel cell vehicle at $4 per kilogram hydrogen. Owing to fuel cell vehicles' substantially higher energy efficiency, this basic calculation shows how fuel cell vehicles offer substantial consumer fuel savings, even as combustion vehicles get more efficient. This remains true as long as the price of

9 National Research Council, "Transitions to alternative vehicles and fuels" (2013). http://www.nap.edu/catalog.php?record_id=18264

10 See, for example: Joan Ogden et al., "The Hydrogen Fuel Pathway," chapter 3 in Sustainable Transportation Energy Pathways: A Research Summary for Decision Makers. (Institute of Transportation Studies: University of California, Davis, 2011). https://its.ucdavis.edu/research/publications/ and Joan Ogden et al., "Making the Transition to Light-duty Electric-drive Vehicles in the U.S.: Costs in Perspective to 2035" (2016), https://its.ucdavis.edu/research/publications/

hydrogen is roughly $4 per kilogram, or more generally stays within 30%–40% of the price-per-unit energy of gasoline excluding fuel taxes.

There is also the potential to develop synergy between renewable electricity and renewable, lower cost hydrogen.[11] When renewable electricity supply exceeds demand (e.g., when there is excess solar during the day, or excess wind through the evening), hydrogen could be produced at a much lower cost. Hydrogen production offers the ability to absorb and store renewable electricity, thereby enhancing the uptake of renewables on the grid.[12] As a result, hydrogen fueling stations could provide energy storage and revenue for grid utilities. In general, for renewable energy-powered electrolysis, the cost of renewable electricity would need to fall below conventional retail or industrial electricity prices for renewable hydrogen to be cost-competitive.

HYDROGEN INFRASTRUCTURE NETWORK DEVELOPMENT

Hydrogen infrastructure networks continue to be developed in areas where vehicle manufacturers, hydrogen providers, and governments share an interest in paving the way for greater fuel cell vehicle deployment. A recent analysis by the U.S. Department of Energy[13] provides the global statistics for the overall state of hydrogen infrastructure development. By the end of 2016, at least 150 hydrogen stations had been built or funded around the world, with more than 50 each in California, Germany, and Japan. Numerous companies worldwide provide equipment and construct the stations. These include Air Products, Linde, Air Liquide, Shell, Total, and several others.

Most of the existing hydrogen infrastructure was developed in the past several years. In most cases, station developers have sought to estimate local fuel cell vehicle deployment numbers as a means to forecast fuel demand. Below we review progress in key markets, based on data from government ministries and hydrogen associations in each region.

United States. Based on data from the U.S. Department of Energy's Alternative Fuel Data Center, through mid-2017, the United States had 62 operational hydrogen fueling stations. Of these, 38 stations are public and 24 are private. An additional 25 stations are in planning stages, with 18 for public use. California has the most developed hydrogen fueling network within the United States with 31 public retail stations. Much of the U.S. hydrogen infrastructure activity is focused on the implementation of the California Zero-Emission Vehicle regulation, adopted by California and nine other U.S. states to promote fuel cell vehicle technology. With 50 stations funded in 2017 and the 2018 projection of 67 stations, the California network could support around 20,000 fuel cell vehicles. The initial stations focused on the leading market of Los Angeles, but the stations now are covering many major markets and connecting corridors in

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11 The Hydrogen and Fuel Cell Technical Advisory Committee (HTAC), "2015 HTAC Annual Report" (2015), https://www.hydrogen.energy.gov/htac_reports.html and "H2@ Scale" (2017), U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, Fuel Cell Technologies Office, https://energy.gov/eere/fuelcells/h2-scale

12 Graham Cooley, "Building a hydrogen refueling infrastructure in the UK," presentation at H2FC Hannover, 2017, http://www.h2fc-fair.com/hm17/exhibitors/itm.html

13 U.S. Department of Energy, "Insights from hydrogen refueling station manufacturing competitiveness analysis" (2016). https://energy.gov/eere/analysis/downloads/insights-hydrogen-refueling-station-manufacturing-competitiveness-analysis

the state. More than 120 total retail hydrogen stations may be available by 2025 to support up to 60,000 fuel cell vehicles, as newer stations are expected to have higher delivery capacities.[14] Automakers project a somewhat lower trajectory of 13,000 fuel cell vehicles by 2019 and 43,600 by 2022.[15] California's hydrogen station development involves many companies, including Shell, Linde, FirstElement Fuel, Air Liquide, Air Products and Chemicals Inc, and ITM Power. Universities and municipalities also have been involved as host sites for stations. As previously mentioned, California also has several fuel cell bus projects, and these provide additional opportunities for hydrogen production and sales.

Outside of California, the other public stations in early 2017 were in Connecticut, Massachusetts, and South Carolina. Air Liquide and Toyota are planning to support the development of 12 fueling stations in the northeast United States. The Northeast Electrochemical Energy Storage Cluster (NEESC) has estimated that more than 100 stations would be needed across the northeast to accommodate more than 10,000 new fuel cell vehicles by 2025.[16] In addition, the Nikola Motor Company has indicated that it aims to have dozens of hydrogen stations nationally within several years, and that hundreds would eventually be needed on the way to a national highway network for its prospective long-haul tractor-trailers.

Japan. Japan has among the more ambitious plans for a transition to hydrogen for its vehicle fleet, as part of broader efforts to transition all of Japan's energy sectors to hydrogen. Nearly achieving its goal of 100 stations, there were about 90 active stations in Japan by August 2017. More than one-third of these stations are mobile, which is to say, tube trailers. The first deployment was focused on four major metropolitan areas (Tokyo, Aichi, Osaka, Fukuoka), and a corridor connecting them. Per the government plans to meet fuel cell vehicles' fueling demand, the fueling network could approximately double in size in time for the 2020 summer Olympics, and double again 5 years later. The Ministry of Economy, Trade and Industry has goals of 1% of 2020 sales, and 3% of 2030 sales of automobiles being fuel cell vehicles. Based on this trajectory, the market would surpass 100,000 fuel cell vehicle sales per year in the mid-2020s, up from about 1,000 at the end of 2016. This would amount to about 800,000 cumulative fuel cell vehicles by 2030. To support this growth, Japan expects to have 160 hydrogen stations in operation by 2020, 320 by 2025, and 900 by 2030. At the regional level, the Tokyo Metropolitan Government has established a roadmap with the goal of deploying 35 hydrogen stations, 6,000 fuel cell passenger vehicles, and at least 100 fuel cell buses, along with 150,000 residential fuel cell systems, by the 2020 Tokyo Olympics.

As with other ambitious plans, this level of infrastructure development necessitates rapid investment and coordination of many stakeholders including fuel and equipment providers. The government plans to create a hydrogen society much broader than

14 California Fuel Cell Partnership, "2014 Update: Hydrogen Progress, Priorities and Opportunities (HyPPO) Report. A California Road Map: The Commercialization of Hydrogen Fuel Cell Vehicles." http://cafcp.org/sites/default/files/Roadmap-Progress-Report2014-FINAL.pdf

15 California Air Resources Board, "2016 Annual Evaluation of Hydrogen Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development." California Environmental Protection Agency. https://www.arb.ca.gov/msprog/zevprog/ab8/ab8_report_2016.pdf

16 Northeast Electrochemical Energy Storage Cluster & H2USA, "2017 Northeast Regional Hydrogen Economy Fuel Cell Electric Vehicle Fleet Deployment Plan." http://h2usa.org/sites/default/files/2017_Regional_H2_Fleet.pdf

simply transportation to help achieve economies of scale and other benefits of expanded hydrogen use throughout the economy.

Germany. Germany has 23 hydrogen fueling stations in operation, most of which are located near major urban areas,[17] with several connectors in between. An additional 25 stations are under construction, and include further connector and destination stations. By the end of 2017, about 60 will be operational. The National Organization Hydrogen and Fuel Cell Technology (NOW) coordinated Germany's National Innovation Programme (NIP) to establish 50 stations with 118 million euros. The Clean Energy Partnership convened public and private stakeholders to create this initial network. H2Mobility, a consortium of Air Liquide, Daimler, Linde, OMV, Shell, and Total, is planning and constructing this network. The consortium plans to have 100 stations by 2019, with roughly 10 stations each in Hamburg, Berlin, Rhine-Ruhr, Frankfurt, Stuttgart, and Munich metropolitan areas, and the remaining 40 as connectors and destination stations. This infrastructure backbone supports both light-duty and light commercial fuel cell vehicles, with the additional stations expected to grow with the vehicle market.

After these early markets, the German government's goal is for 400 stations to cover the entire country by 2025. A second NIP worth 350 million euros will help fund the network expansion. To complement the nationwide strategy and better optimize funding, H2Mobility has opened up funds to bidders presenting the best business cases to help reduce costs. Beginning with the existing infrastructure in 2017, H2Mobility would need to construct more than 50 stations per year to reach 400 by 2025. At that level of density, the infrastructure would provide station access less than 10 minutes away for most German residents.[18] To achieve this, H2Mobility is reducing costs by combining hydrogen with existing fossil fuel stations, and using standardized storage, compressors (700 bar), and other equipment across the network, as in other markets around the world.

United Kingdom. The UK has 15 hydrogen stations in operation in 2017, and at least five more in the planning stages. Infrastructure development is a public-private partnership among the national and local governments, and fuel cell, industrial gases, energy, and auto industry companies. The UK H2Mobility consortium has provided estimates for hydrogen infrastructure to match fuel cell vehicle goals through 2030. An initial set of 65 stations is estimated to be able to support the development of an early market of 10,000 fuel cell vehicles by 2020.[19] Subsequent station construction depends on the demand for hydrogen. The group projects that approximately 1,100 stations, with a public investment of 400 million pounds, would sufficiently cover the country's fuel cell vehicle growth to a total of 1.6 million fuel cell vehicles by 2030.

Rest of Europe. Denmark has 11 stations, with one additional station planned. Considering its size and population density, Denmark is one of the more complete hydrogen networks. Sweden has four stations, and Norway six. Together, the hydrogen-promoting organizations from each country have united under the Scandinavian

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17 Ludwig Bölkow Systemtechnik. Hydrogen Filling Stations Worldwide. https://www.netinform.de/H2/H2Stations/Default.aspx

18 Nikolas Iwan, "Our mission: Hydrogen Infrastructure in Germany," video from H2FC Hannover (2017). https://www.h2fc-fair.com/hm17/exhibitors/h2mobility.html

19 UK H2 Mobility. UK H_2 Mobility: Phase 1 Results. Retrieved from http://www.ukh2mobility.co.uk/wp-content/uploads/2013/08/UKH2-Mobility-Phase-1-Results-April-2013.pdf, April 2013

Hydrogen Highway Partnership. Most of these hydrogen installations are meant to serve fuel cell buses, as well as cars. We estimate that each of these countries still has less than 50 fuel cell cars each, as fuel cell vehicle model availability is very limited. There also is a relatively small number of fuel cell vehicles and hydrogen stations throughout the rest of Europe, including Austria, France, the Netherlands, and Switzerland. For example, 60 fuel cell range-extender Renault Kangoo vans are being deployed in 2017 to use France's and the United Kingdom's hydrogen networks. Various European governments continue to make statements regarding fuel cell buses, with announcements that would increase fuel cell buses in Europe to 600–1,000 by 2020.

Rest of Asia. Like Japan, Korea is an interesting case because one of the first commercially available fuel cell passenger vehicles (i.e., Hyundai Tucson ix35) is produced by a Korean manufacturer. Based on the country's geographic size and the locations of its eight stations in operation, a driver there could traverse the entire nation solely on hydrogen fuel. Korea plans to have 500 stations by 2030.[20] As in other countries, government-industry partnerships are being used to locate, fund, and deploy the fueling infrastructure. China currently has four hydrogen fueling stations, and one mobile fueling station.[21] The most recent goals from the Chinese government indicate more than 100 stations in the 2020 time frame, with the initial network intended to support primarily about 5,000 public vehicles (e.g., buses and taxis).[22]

Global summary. Many governments and industry partners have initiated plans to roll out hydrogen infrastructure networks to help spur the fuel cell vehicle market. These plans indicate that major sustained vehicle deployment and infrastructure investments will be needed over the next 10–15 years. By the end of 2016 there were about 4,000 fuel cell cars, plus several hundred fuel cell buses, with more than 150 hydrogen stations. Considering all that, a Hydrogen Council report[23] indicates that the combined tally of goals and announcements by governments could reach about 3,000 total hydrogen stations and support a total of 2 million hydrogen fuel cell vehicles in the 2025 time frame. The same report estimates that government plans for 2,000 hydrogen stations in Europe, 800 in Asia, and 600 in the United States would be enough to help enable the fuel cell vehicle market with a self-sustaining hydrogen fueling infrastructure.

Figure 4 plots the number of hydrogen stations (horizontal axis) and the number of fuel cell vehicles (vertical axis) in select jurisdictions. We use a log-log scale because the data vary so greatly, and to show the general trends of the market projections and goals across several orders of magnitude. The variation is in part due to differences in population density and early adopter locations in each region, the various strategies

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20 Yong-Gun Shul, "Hydrogen and Fuel Cells in Korea" presented at the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) Steering Committee meeting, December 2014, Rome, Italy. http://www.iphe.net/docs/Meetings/SC22/Meeting/Korea_SC22.pdf and Jong Won Kim, "Recent Achievements in Hydrogen and Fuel Cells in Korea" presented at the International Hydrogen Energy Development Forum 2013, Fukuoka, Japan. http://hydrogenius.kyushu-u.ac.jp/cie/event/ihdf2013/pdf/2-3kim.pdf

21 China Hydrogen Energy Network, 燃料电池是未来10年重要投资方向 ["Fuel cells are an important investment direction for the next 10 years"], (2017). http://www.china-hydrogen.org/observation/2017-05-19/6192_3.html

22 Ouyang Ming Gao, ["Technology roadmap for energy-saving and new energy vehicles"], (2016). http://www.autolightweight.com/article-2272-1.html and Ministry of Industry and Information Technology (MIIT) of the People's Republic of China, ["Made in China 2025"], (2015). http://www.miit.gov.cn/n1146285/n1146352/n3054355/n3057585/n3057589/c3617217/content.html

23 Hydrogen Council, "How hydrogen empowers the energy transition" (2017). http://hydrogeneurope.eu/wp-content/uploads/2017/01/20170109-HYDROGEN-COUNCIL-Vision-document-FINAL-HR.pdf

used to predict fuel cell vehicle deployment and hydrogen station locations, and general uncertainty about how the market emerges. Through 2016, the early deployment of stations and vehicles for seven markets is shown in the bottom left, with countries labeled. The points to the upper right reflect projections from national and regional planning efforts, fleet modeling analyses, and government or industry goals from California, Germany, Japan, United Kingdom, and the northeastern United States. The California and Japan markets are the foremost 2016 markets with roughly 2,000 vehicles and 50–80 built or planned stations each. In these markets, the first 100 stations are estimated to support about 10,000–40,000 fuel cell vehicles. Moving to the upper right of Figure 4, the data suggest that the first 1,000 hydrogen stations in leading markets around the world could support the first 1 million to 2 million global fuel cell vehicles. As the graph implies, the average station capacity is expected to grow: A 100-station network can support about 100–400 vehicles per station, whereas a 1,000-station network could support 1,000–2,000 vehicles per station. In the early rollout of fuel cell vehicles, a broad geographic distribution of small stations is necessary to access the initially small market. As the market grows, more economical, higher capacity stations are possible and each station serves more vehicles.

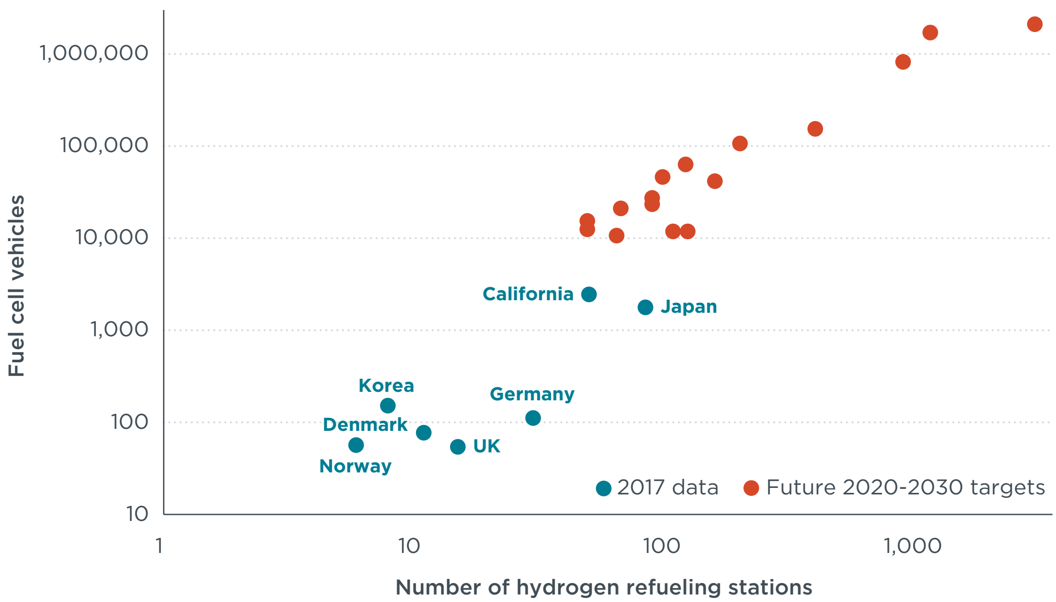

Figure 4. Summary of current hydrogen refueling station deployment, and government and industry projections and goals for initial hydrogen station and fuel cell vehicle deployment through 2025.

We refer to the future targets in Figure 4 as illustrative, because markets are still in their infancy. The various countries have greatly differing circumstances, so it would be difficult to draw definitive conclusions from the relationship or precise numbers for the 2020–2030 time frame. Additionally, it is highly uncertain to what extent automakers will remain committed to, or potentially strengthen, their investments toward these goals. As previously discussed, there are only a few light-duty fuel cell vehicle models so far, a handful of low-production buses, and several dozen public hydrogen stations per major vehicle market. Many of the markets will see different approaches in terms of commercial freight vehicles and buses, both of which could have potential for fleet uptake with centralized refueling. Such developments could greatly affect hydrogen availability and demand, as compared to focusing on light-duty vehicle developments.

HYDROGEN STATION PLACEMENT AND DESIGN

Each of the nascent fuel cell vehicle markets previously assessed continues to work on its early hydrogen station placement. There is no clear guidebook for how to roll out alternative fuels into a dominant incumbent market where gasoline and diesel are widespread, with tens of thousands of fueling stations.

A conceptual approach has been proposed for infrastructure planning that could be applied to all early hydrogen fueling networks. The first component of this concept is clustering. Here, stations are clustered together within a limited geographic area predicted to include potential early adopters. In this way, the early market benefits from reliable and convenient access to stations, which ideally supports a majority of trips. This serves early adopters and is a cost-efficient way of using limited funding for hydrogen infrastructure where it is most likely to be of higher use. Of course, driving outside the cluster is hindered by lack of access to fuel. Hence, the second key component is to connect clusters by placing stations to strategically create a corridor system, or “hydrogen highway,” through which fuel cell vehicle drivers can travel more widely than the initial cluster. The benefit of this design is broad coverage and access to many more locations, enabling drivers to move freely about the network. Even though lower daily usage is likely, such corridor stations are widely viewed as a prerequisite for most prospective owners, even for relatively infrequent trips that take drivers outside their home area. Both basic tactics have complementary benefits and are thus being widely developed in combination.

The early market cluster is typically located in a city or community with a high percentage of potential early technology adopters. Such areas typically have been identified by consortia of automakers and public-private partnerships that find common cause to share resources, as in the case of optimally placing publicly funded hydrogen stations. These regions in which station clusters are located are sometimes referred to as lighthouse communities. In the case of California, the Los Angeles metro area has long been targeted as a lighthouse community due to its many potential early technology adopters. The auto industry and government experts within the California Fuel Cell Partnership helped steer this as a priority. As a result, most of California’s hydrogen stations have been intended for communities throughout the San Francisco Bay Area and Los Angeles area, with Irvine, Torrance, and Santa Monica as cluster communities within the Los Angeles metropolitan area. In Japan, Tokyo, Aichi, Osaka, and Fukuoka have similarly been the targeted metropolitan areas. Due to the potentially high number of users and frequency of fueling, cluster networks generally require stations capable of handling a growing number of vehicles with increased hydrogen capacity.

Corridors help to extend the effective fuel cell vehicle driving range beyond areas served by the early clusters. Intercity stations are generally placed at connector communities. These stations link nearby clusters and help to plant seeds for new clusters. In Germany, about 60 of the first 100 stations are in six major metro areas, and the remaining 40 are connectors and destination stations. Similarly, the four initial clusters in Japan were connected via a major corridor highway. These may have fewer regular customers but possibly large fill-up amounts, as customers typically arrive from a relatively long distance away from the initial fill-up. Consequently, connector stations generally have different specifications with regard to capacity, fuel source, number of pumps, and so on.

Destination stations offer a third important aspect in the design and development of a fueling network. These stations are located at popular sites, for example longer-distance weekend destinations, that may not be considered lighthouse communities in their own right. As with connector stations, destination stations may eventually seed new markets, as nearby residents can purchase and fuel a fuel cell vehicle.

Choosing the specific location of stations, within clusters and on connecting roadways, offers its own challenges. One method is to locate cluster stations nearer to the homes or workplaces of the anticipated early adopters. Another theory recommends locating these stations along commonly travelled routes or commutes of early adopters. This latter option potentially could lead to stations that are outside the cluster itself, and is more dependent upon accurate daily traffic data. Locating sufficient infrastructure near homes is an ideal solution, but may only serve a small group initially, whereas locating stations along commuter routes is an important complementary solution for a large group of potential customers. In this way, both strategies can coexist and be part of a phased plan to convince the greatest number of people to purchase fuel cell vehicles with the least number of stations. Early stations can be selected for both their proximity to customer homes and proximity to a commuter route. An additional approach, used in tandem with the other methods in Japan and China, uses mobile stations. Compared to the other network design strategies, mobile stations allow for additional network flexibility and reconfiguration. They even can be used to experiment with new locations.

An important attribute in early station placement is coverage, which generally is determined by convenience, or proximity to a station, and network reliability (e.g., maintaining fuel availability if one station is out of service). Research indicates that current fossil fuel station networks are overbuilt in terms of convenience and reliability and that hydrogen networks can achieve comparable coverage with only 10%–30% as many locations as existing gasoline stations.[24] Population density, region size, and existing fossil fuel infrastructure all affect the minimum level of hydrogen infrastructure required.

The major early fuel cell markets all tend to have national laboratory- and university-developed tools to help advise on optimal hydrogen station placement. For example, California has used the Spatially & Temporally Resolved Energy & Environment Tool (STREET) to calculate the number, location, and rollout timing of stations using automaker fuel cell vehicle deployment projections, minimum travel time to stations (e.g., less than 6 minutes), travel and fuel delivery routes, existing gas stations, and vehicle owner density. The tool's resulting plan was for the equivalent of 5%–7% of existing gas stations to offer hydrogen, although travel times of less than 4 minutes were found in some clusters if only 1% of stations offered hydrogen. Taking industry input into consideration, the final results had 45 cluster stations and 23 connector and seed stations. California also uses tools like California Hydrogen Infrastructure Tool (CHIT) and California Hydrogen Accounting Tool (CHAT) to help assess and fill gaps in coverage, convenience, and redundancy to determine where the network can be improved with future network additions.

24 Joan Ogden, Christopher Yang, Michael Nicholas, Lewis Fulton, "The Hydrogen Transition" (2014). https://its.ucdavis.edu/research/publications/

The UK H2Mobility consortium plays a key role in developing the UK hydrogen network. Per its 2013 roadmap, the UK has a strategy, similar to California's, where major population centers contain the highest density of stations, with supporting stations sporadically located along major longer-distance travel routes. A total of 65 planned stations would create sufficient coverage to start the early market. Multiple early stations within single clusters increase reliability among early-adopting communities. The expectation is that a total of 330 stations nationwide would provide 50% coverage, and 1,150 stations would cover 100%. Although that number of stations represents only about 14% of the total number of fossil fuel stations in the country, the total network would provide close-to-home access to at least two stations for more than 80% of the population.

Germany and Japan, too, structure their networks based on early market locations connected by major thoroughfares. Germany's plan, like the UK's, is to create the fuel cell vehicle market first by building the minimal infrastructure needed, specifically, 100 stations, with 10 each in six major metropolitan areas, and 40 connectors and destinations. Subsequent build-out rates will depend on how the market develops. After the first 60 stations become operational in Germany by the end of 2017, more will be funded and installed based on open solicitations for compelling business cases. Similarly, the four initial clusters in Japan were connected by sufficient corridor hydrogen stations early on in the deployment plan. However, one difference in Japan is that the country is committed to hydrogen, not just as a transportation fuel, but also as an increasing stationary fuel source that is more integrated into the economy.

Because virtually all technical hurdles have been overcome, and many standards of technology and safety already exist, these aspects of hydrogen station and network design are no longer a barrier. SAE standards J2600, J2601, and J2719 are available for fueling connection devices, fueling dispensation, and fuel quality; and they have been demonstrated in the United States and in Germany. As an example of the benefits of standardization, California uses the Hydrogen Station Equipment Performance (HyStEP) device, which saves automakers the expense of evaluating each station built. HyStEP carries out tests to measure adherence to J2601. SAE J2719 helps to ensure the fuel quality is consistent and free of contaminants. The European Union has requirements for hydrogen infrastructure, including that vehicle connectors comply with International Organization for Standardization (ISO) 17268, that hydrogen fueling stations comply with ISO/TS 20100, and that hydrogen fuel quality complies with ISO 14782-2. Regarding standards for safety, California has adopted standards from the National Fire Protection Association *Hydrogen Technologies Code*, which were effective for statewide application in 2015. Since then, the California Governor's Office of Business and Economic Development created a Hydrogen Station Permit Guidebook with best practices for station developers.

The remaining questions of standardization are related to creating a consistent and user-friendly customer experience, such as the ability to accept universal payment. Such standards can encourage faster fuel cell vehicle adoption by minimizing changes to consumer behavior, and can reduce costs using uniform testing, design, and approval procedures. For context, a counterexample of note is the frustration that many electric vehicle users experience when charge types and payment methods restrict the use of some infrastructure to specific customers. The Netherlands, for example, offers electric vehicle charging interoperability across charging stations, and this helps drivers seamlessly use the network with just one payment type. This provides a constructive example to improve the driver experience as hydrogen infrastructure is incrementally built out.

HYDROGEN STATION FUNDING

The previous sections focused on developments related to the number of hydrogen stations needed to support fuel cell vehicles, and how different regions have approached their early deployment. As indicated above, several hundred hydrogen stations are being planned by governments around the world. Based on those planning efforts, about 1,000 hydrogen stations globally could support the initial 1 million to 2 million fuel cell vehicles across the major Asian, European, and North American markets in the 2025 time frame. This would be a step toward more comprehensive hydrogen infrastructure deployment. This section addresses several questions related to hydrogen station costs and how they are typically funded.

Hydrogen station costs. Many of the initial hydrogen stations were deployed at about $2 million to $3 million per station. Most government and industry consortium estimates suggest that average cost will drop over time to more like $1 million per station and eventually lower yet. Figure 5 summarizes costs from several studies that model the cost of hydrogen stations based on a number of parameters, including factors such as the scale/capacity and the hydrogen distribution and storage mechanisms. As shown, larger stations, with larger daily throughput of hydrogen, have higher overall cost; however, they tend to have lower cost per kilogram of hydrogen delivered. For context with the above discussion of hydrogen fuel price, the studies shown equate to $6 to $13 per kilogram of delivered hydrogen. Comparing a variety of studies by the National Renewable Energy Laboratory, U.S. Department of Energy, and University of California, Davis (previously cited), both gaseous and liquid hydrogen stations have the potential to reduce costs from $1.5 million to $2 million to approximately $1 million, and potentially as low as $0.5 million for relatively small stations.

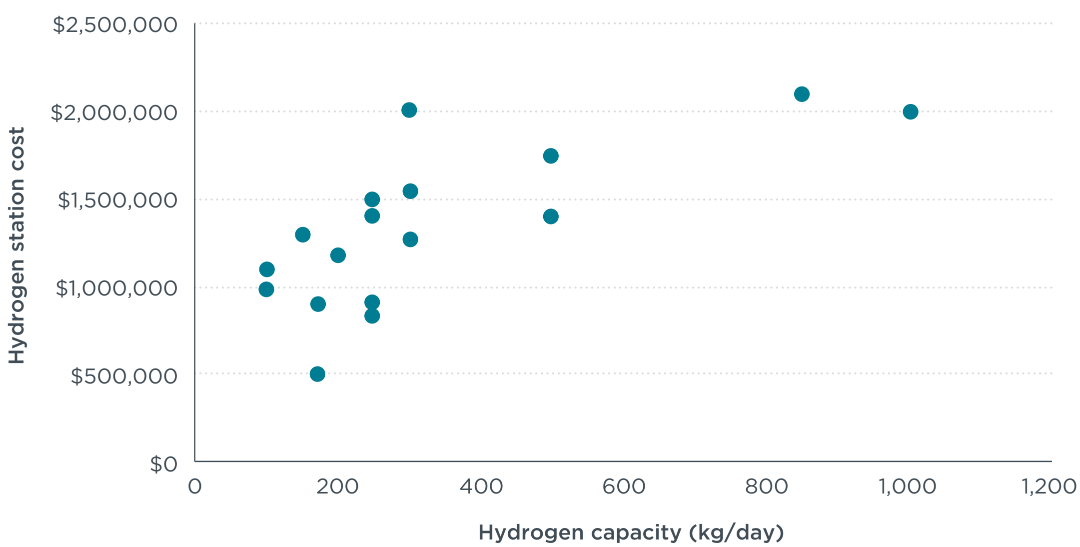

Figure 5. Modeled hydrogen station cost for varying hydrogen daily volume.

The reports provide approximate ranges and time frames for their station cost estimates. The variation in hydrogen station costs, at least in part, is due to the early state of the hydrogen market and uncertainties about how and when the station component costs will drop with the progression to hundreds of stations in the future. Cost reductions can be expected as demand for hydrogen increases and hydrogen station component suppliers and station developers innovate and move toward greater volume. Suppliers appear to largely focus on reducing costs and increasing the performance of compressors, storage tanks, and other station equipment. The growing experience among station developers will lower barriers and reduce time and cost for new stations to be added to the network.

The question of hydrogen delivery and storage, primarily whether hydrogen is delivered and stored in gaseous or liquid form, has a variety of impacts on station cost. Gaseous hydrogen has higher component costs for compression and high-pressure cascade equipment, as well as running costs to sufficiently compress for dispensation. Liquid hydrogen stations have larger costs for liquid storage, pumping, and evaporation, but relatively lower costs for dispensation, compression, and delivery (at high daily volumes).

Broader considerations are also key to reducing hydrogen station costs over time. As previously discussed, optimized station and network design can reduce the total number of stations needed within the overall hydrogen network. Planning hydrogen station sites for possible future expansion in daily hydrogen throughput can also reduce system-level cost. Standardization simplifies testing and approval, permits station scalability, and harmonizes customer experience.

Funding mechanisms. To support the transition to more fuel cell vehicles, some governments are investing public funds for the rollout of the initial hydrogen stations when fuel cell vehicle deployment is low and highly uncertain, as indicated in reports previously cited. In addition to this, automakers with early fuel cell models in the market are directly covering the fuel costs of the hydrogen for several years after the initial lease or purchase of their fuel cell vehicles.

As the first few dozen hydrogen stations are being deployed in major markets, cost sharing between government and industry on the next stations is more common for the in-development stations, and many governments are trying to steer investments more toward commercially viable business cases over the longer term. California, Germany, Japan, and the United Kingdom have taken similar approaches to the funding of their early hydrogen networks.

At this time, California is the leading edge of the U.S. fuel cell market. It has been estimated that it could cost about $5 billion overall to cover the initial U.S. hydrogen network for the first 4 million fuel cell vehicles in the 2025–2030 time frame.[25] This would include an initial strategy of clustering lighthouse communities and linking them to each other and popular destinations with connectors. Most of the first such investments are through public grants in California. The California Energy Commission is a major grantor, and its solicitations have offered up to 85% of the initial capital expense plus another $300,000 for operation and maintenance for several years. Companies apply for the grants, and they own and operate the stations. The California

25 Joan Ogden, Christopher Yang, Michael Nicholas, Lewis Fulton, "The Hydrogen Transition" (2014). https://its.ucdavis.edu/research/publications/

legislature has authorized funding of up to $20 million per year until the first 100 hydrogen stations are built. Other funding sources also support the hydrogen stations. The state's Low Carbon Fuel Standard program provides additional fiscal incentive for fuel providers to sell hydrogen, based on the fuel's low carbon intensity. California, along with other zero-emission vehicle (ZEV)-adopting states, also offers fuel cell vehicle purchase rebates, which further supports the market.

The Japanese government financially supports the hydrogen infrastructure build-out with support for stations, on the price of hydrogen, and at vehicle purchase. Japan funds stations up to two-thirds of initial capital expense. It also subsidizes hydrogen fuel in order to reduce the price to $10 per kilogram, because early station fuel revenues are unlikely to offset costs for at least several years. Japan also has both federal and local subsidies for the purchase of new fuel cell vehicles. Thus, as California does, Japan is using public expenditure to increase supply of, as well as demand for, hydrogen.

Germany offers to cover half the initial outlay for hydrogen stations through two phases of its National Innovation Programme (NIP). The first NIP funding totaled 700 million euros through 2016, which was partially used to build the first 20 stations. The second NIP commits at least 250 million euros through 2026, matched by equal funding from private industry. Several associated projects strive to reduce fuel production costs for renewable electrolysis, aiming for less than 4 euros per kilogram in 2021. The NIP work is managed by the Clean Energy Partnership, a public-private partnership which has set up the H2Mobility consortium of companies to plan the network and construct stations. H2Mobility estimates that a network of 1,000 stations would cost Germany 1 billion to 2 billion euros. The German implementation of the European Union's Fuel Quality Directive could play a role similar to that of the California Low Carbon Fuel Standard in putting a value on low-carbon hydrogen as a transportation fuel.

In the United Kingdom, the UK H2Mobility consortium comprises many of the same members as in Germany. The UK government has funded the network planning phase of the hydrogen infrastructure development. In 2017, the consortium is well into the building and expansion phases, primarily funded by the consortium member companies. The UK H2Mobility estimates 62 million pounds will be needed before 2020, and the resulting network will largely be able to cover its own operating and maintenance costs shortly thereafter. The UK's Office of Low Emission Vehicles has announced a new 23-million-pound fund that will match successful proposals for hydrogen infrastructure build-out. A total of 418 million pounds is projected to be able to cover the complete network and would break even by 2030.

Business case for private station ownership. As indicated by the California, Japan, Germany, and United Kingdom cases, major public funding sources have been critical for the initial growth phase, and these infrastructure projects transition to public-private sharing of the costs. As of 2017, there are only several thousand fuel cell vehicles, fueled by a few hundred hydrogen stations, throughout the world. At such low volume, the use of stations is low and they are not yet profitable. Many jurisdictions are considering ways to steer the next-generation hydrogen stations toward a clearer business case, considering the cost reductions associated with moving to higher volume.

Governments are likely to play a role in spurring business investments in hydrogen for the foreseeable future beyond simply providing funding. By requiring standardized collection of data from hydrogen fueling stations, governments can help inform future government and industry-based stations. Governments can use fuel cell vehicle demand data, based on their vehicle and fuel policy development plans, to demonstrate to investors the financial opportunities of supporting the initial capital costs. Governments and industry can continue to improve their network cost estimates through coverage requirements analysis, including such things as location of early adopters, common traffic flows, etc.; providing a platform to share experiences on the hydrogen networks; assessing costs of modifying stations for higher capacities; and identifying target markets to expand coverage.

Governments are generally trying to develop grant solicitations and requests for public funding that encourage new business models. Germany provides one example. After Germany's first 60 stations are operational, by the end of 2017, there will be open funding applications for groups to submit the most compelling business cases. Winning bids will make the best business case based on hydrogen demand and station cost, which depends on the uptake of fuel cell vehicles. By doing so, H2Mobility is helping to initiate the transition from the stations being part of the public infrastructure to being businesses.

Another potential way to reduce market barriers is through standardization. Standardization can allow for more versatility for more use by different vehicle types from different vehicle manufacturers. Again, the counterexample is seen in plug-in electric vehicle charging's lack of standardization, where a system of different public charging plug types, protocols, and payment systems limits the use the charging network by drivers. Hydrogen stations can be outfitted with both standard 350-bar (5,000 pounds per square inch, or psi) and 700-bar (10,000 psi) pumps and dispensers to expand their utility to both commercial and passenger vehicles of those types.

It could also be important to encourage business models that are more versatile for uncertain growth in different fuel cell vehicle applications. Stations that are used to their full capacity will make it easier to maintain financing and eventually will become fully commercialized and self-funding. Hydrogen providers could potentially move toward higher daily hydrogen demand if they can have multiple fuel cell applications including cars, buses, and heavy-duty vehicles at the station, but this requires alignment of the various driver preferences. "Return-to-base" vehicles, such as buses, taxis, and some commercial vehicles, can offer predictable hydrogen demand at centralized facilities, which is an important factor for developing hydrogen stations as a business. Combined use across vehicle types can help complete a business model with more hydrogen revenue and less sustained government funding. Having such a combined-use model could take more planning and permitting for the multiple private and commercial uses, but helps enable higher utilization faster.

Alternatives continue to emerge in terms of the hydrogen station footprint and its revenue streams. Existing gasoline and diesel stations can lease space to hydrogen station developers, generating income for themselves, as well as potentially reducing costs for the hydrogen providers relative to developing entirely new fuel station sites. Many of the early stations are indeed located at existing gas stations. Some groups have begun to explore whether there might be value in supplementing hydrogen stations with electrolysis and storage to include ancillary energy services. Ideally, future business cases will better exploit hydrogen's versatility as an energy carrier. Through electrolysis or direct electrochemical conversion, hydrogen can store over-generated wind and solar power. The hydrogen can then be used as a transport fuel, in stationary fuel cells, or in natural gas plants to create electricity. This could enable more renewable hydrogen, and potentially at a lower cost, to improve the business case for hydrogen.

IMPLICATIONS

This paper compiles information on the development of hydrogen fueling infrastructure to power fuel cell vehicles at the very early market stage in 2017. The compilation includes research on hydrogen infrastructure deployment, energy pathways, and hydrogen infrastructure planning. We offer several high-level reflections.

Fuel cell vehicle technology is progressing, opening up greater possibilities for low-carbon transport. Reductions in fuel cell cost, volume, and mass, and hydrogen storage cost have greatly contributed to enabling the initial fuel cell market entrants in California, Japan, Korea, and Europe. Fuel cell vehicle efficiency advantages, the ability to produce hydrogen from renewable sources, and fuel cell vehicles' long-range and quick-fueling capability make hydrogen fuel cells a promising long-term option for a decarbonized transport sector. The use of hydrogen fuel cells for heavy-duty applications is relatively unexplored but could be especially promising as a zero-emission prospect where plug-in batteries will be more difficult.

Uncertainty about when low-cost hydrogen from renewable-energy sources will emerge is a key challenge for fuel cell vehicles. The cheapest source of hydrogen is natural gas, but renewable hydrogen pathways are necessary for fuel cells to become a prominent part of long-term climate stabilization scenarios. Hydrogen fuel that has a higher cost per energy unit than gasoline or diesel provides only a limited opportunity for an attractive consumer proposition. Greater investment into fuel pathways that demonstrate the ability to deliver renewable hydrogen to market at less than the cost of fueling a conventional, or hybrid, vehicle is a key to enabling the market. Government fuel standards programs that provide incentives to low carbon sources of hydrogen can assist in reaching this goal. Another promising opportunity is to explore synergies where temporary oversupply of solar and wind electricity can create opportunities for more inexpensive hydrogen.

Industry will need to bear a greater burden of hydrogen infrastructure investments over time. To address the public need for zero-emission solutions and the uncertainty about fuel cell market growth, the first few hundred hydrogen stations have been primarily publicly funded. As the market emerges in the tens, and eventually hundreds, of thousands of fuel cell vehicles, governments investing in hydrogen infrastructure will continue shifting to strategic cost-shared stations with industry that encourage and help develop commercially viable business models. Government plans in a number of jurisdictions are underway that could provide hundreds of millions of dollars to cover the first thousand hydrogen stations. Ideally public investments would continue to use competitive cost-sharing models to help develop and refine the best business cases for these stations.

The multifaceted nature of developing hydrogen infrastructure underscores the need for public-private consortia with regular collaboration. Such consortia play important roles in the deployment of hydrogen infrastructure in high-potential fuel cell vehicle markets like California, Germany, Japan, and the United Kingdom. Among vehicle manufacturers, hydrogen suppliers, energy companies, and government agencies, such consortia play a key role in planning the infrastructure rollout, standardization, learning from early station and market developments, and helping to identify and troubleshoot barriers in the transition. Furthermore, coordination across passenger vehicle markets, freight, and fuel cell bus applications appears to be an important opportunity for low urban emissions and higher daily throughput at early hydrogen stations.

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