Quadrennial Technology Review 2015

Chapter 7: Advancing Systems and Technologies to Produce Cleaner Fuels

Technology Assessments

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U.S. DEPARTMENT OF ENERGY

Hydrogen Production and Delivery

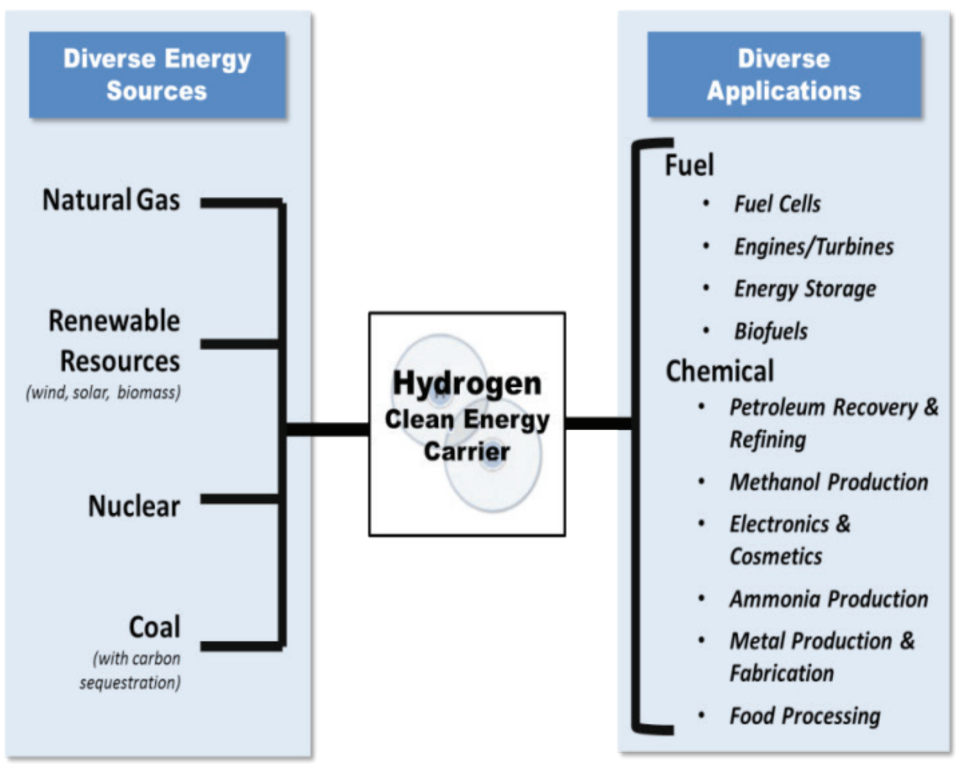
Chapter 7: Technology Assessments

Introduction to the Technology/System

Hydrogen Production and Delivery: Opportunities and Challenges

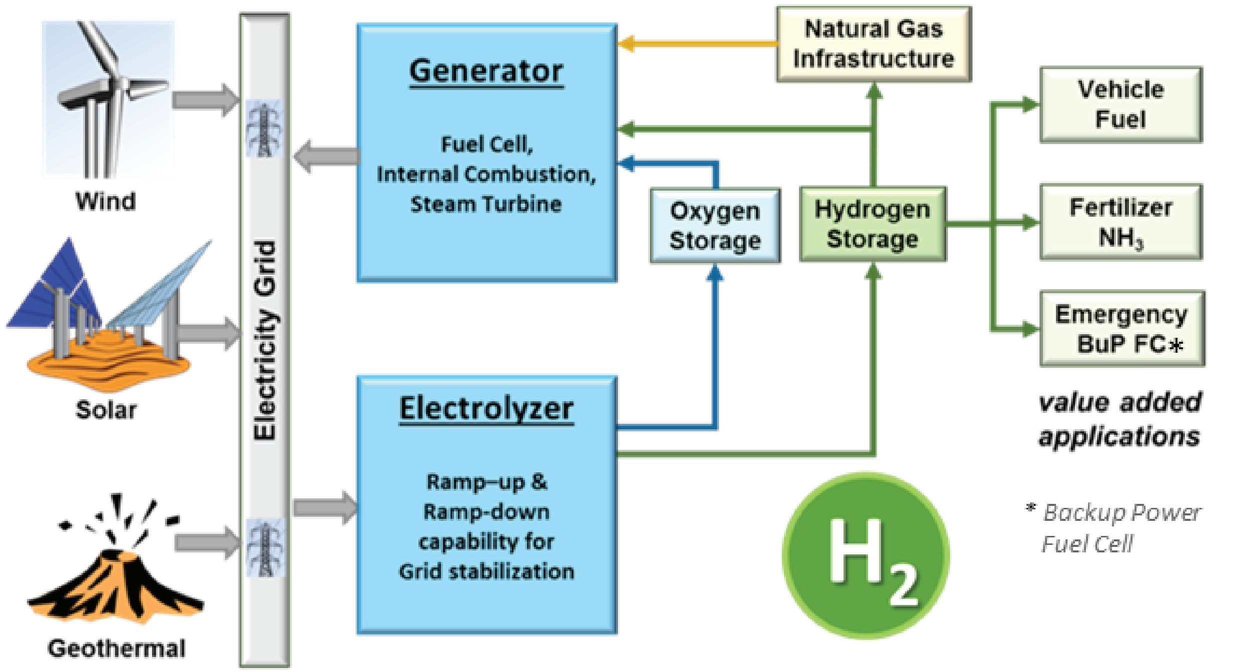
Hydrogen and hydrogen-rich fuels such as natural gas and biogas can be used in fuel cells to provide power and heat cleanly and efficiently in a wide range of transportation, stationary, and portable-power applications. Widespread deployment of hydrogen and fuel cell technologies offers a broad range of benefits for the environment, for our energy security, for our domestic economy, and for end-users. As a clean fuel in the energy sector, hydrogen can be used in highly efficient fuel cells for transportation and stationary power applications, in internal combustion engines (ICEs), and as an energy carrier and storage media in grid modernization and other applications.[1] In the United States, more than 8,000 fuel cell forklifts and more than 5,000 fuel cell backup power units have been deployed. In addition, light-duty fuel cell electric vehicles (FCEVs) are now becoming available for lease and for sale.[2] Hydrogen as a clean energy carrier can be produced using a variety of domestic resources, and utilized in diverse industrial applications, as illustrated in Figure 7.D.1.

Figure 7.D.1 Hydrogen offers important long-term value as a clean energy carrier.



Hydrogen can also potentially support grid modernization, functioning as an energy storage medium for renewable electricity, to be used as a fuel for a number of applications or to provide electricity at times of peak demand. This is illustrated in Figure 7.D.2.

Figure 7.D.2 Renewable Energy Integration Options with Hydrogen



The environmental and energy benefits of hydrogen and fuel cells in different industrial sectors are discussed in Chapters 3, 4, 7 and 8 of the QTR and their accompanying Technology Assessments and include the following:

- **Reduced Greenhouse Gas Emissions:** Due to their high efficiency and zero emissions at the point of use, hydrogen powered fuel cells have the potential to reduce life-cycle greenhouse gas emissions in many applications, including when natural gas reforming without CCUS is used as the source of hydrogen. Department of Energy (DOE)-funded analyses have shown that fuel cells have the potential to achieve the following impact on emissions in various applications. The extent of emissions reduction depends on the source of energy used to produce the hydrogen (e.g., biomass, coal, natural gas, nuclear, solar, wind, etc.) and the potential for CCUS at the point of production for fossil energy sources. The following analyses assume hydrogen from natural gas reforming without CCUS unless otherwise noted:
  - **Combined heat and power (CHP) systems:** The life cycle GHG emissions of distributed power generation using fuel cell based CHP systems powered by natural gas are over 50% less compared with the current the U.S. grid mix, taking into account the added thermal benefits of CHP. Even greater reductions in emissions are possible if the feedstock for hydrogen in the fuel cell system is biogas rather than natural gas.[3]
  - **Light-duty highway vehicles:** The well-to-wheels emissions of greenhouse gases from FCEVs are projected to be approximately 50% lower than those of advanced internal combustion engines (ICEs) fueled by gasoline in 2035. These calculations assume the use of central reforming of natural gas with CCUS for hydrogen production. The analyses assume that the technologies for hydrogen production by steam methane reforming (SMR) and delivery (pipelines) will be equivalent to those

available today, but project improvements in the fuel economy of both FCEVs and ICEs by 2035. FCEVs were projected to have a fuel economy of 79 miles per gallon gasoline equivalent (mpgge), while advanced ICEs were projected to have a fuel economy of 49 mpgge. Moreover, when hydrogen production is instead assumed to take place via wind electrolysis, the emissions reductions are over 80% greater than those of the advanced ICEs in 2035.[4]

- **Specialty vehicles:** Use of fuel cells to power forklifts reduces the greenhouse gas emissions associated with the fuel cycle by over 30%, where the incumbent technology is assumed to be battery-powered forklifts powered by energy from the U.S. grid.[5]
- **Transit buses:** Fuel cell buses have demonstrated more than 40% higher fuel economy than diesel internal combustion engine (ICE) buses and more than double the fuel economy of natural gas ICE buses;[6] these very high efficiency improvements could lead to substantial reductions in emissions, regardless of the hydrogen source.
- **Auxiliary power units (APUs):** Fuel cell APUs have demonstrated more than 60% reduction in emissions over truck engine idling-powered APUs.[7]

- **Reduced Oil Consumption:** Hydrogen fuel cells offer a virtually petroleum-free way to provide power for applications that are currently responsible for a large portion of the petroleum consumed in the United States today, such as automobiles, buses, backup generators, and auxiliary power generators. DOE analysis has shown that FCEVs using hydrogen can reduce oil consumption in the light-duty vehicle fleet by more than 95% when compared with today's gasoline internal combustion engine vehicles, by more than 85% when compared with advanced hybrid electric vehicles using gasoline or ethanol, and by more than 80% when compared with advanced plug-in hybrid electric vehicles.[8]
- **Reduced Air Pollution:** Hydrogen fuel cells emit negligible criteria air pollutants [i.e., carbon monoxide, nitrogen oxides (NOx), ozone, particulate matter (PM), sulfur dioxide, and lead], regardless of the fuel they use. When using hydrogen (as opposed to natural gas, propane, etc.), while there may be emissions at the site of the hydrogen production depending on the source, the fuel cells themselves emit only water.
- **Advancement of Renewable Power Using Hydrogen for Energy Storage and Transmission:** Hydrogen can be used as a medium for energy storage and transmission, which can facilitate the expansion of renewable power generation. Hydrogen can "store" electrical energy when it is produced through electrolysis using surplus electricity, when generation exceeds demand. This stored energy can be used for other high-value applications—such as CHP systems, passenger vehicles, and buses—or it can be converted back into grid electricity, using fuel cells or turbines, for "peak-power" when demand exceeds generation. Hydrogen can also be moved over long distances through pipelines—potentially at higher efficiency and less expense than conventional long-distance electricity transmission—enabling transmission of energy from renewable generation facilities in remote locations.
- **Highly Efficient Energy Conversion:** Hydrogen fuel cells directly convert the chemical energy in fuel into electricity, with very high efficiency and without combustion. Fuel cells using hydrogen can achieve nearly 60% electrical efficiency in vehicle systems (more than twice the efficiency of gasoline internal combustion engines). Moreover, in stationary applications, fuel cells can achieve 50-60% electrical efficiency, with the potential for over 80% overall efficiency in CHP systems where the thermal energy generated can also be made use of.[9]
- **High Reliability and Grid Support Capabilities:** Fuel cells can provide high-quality, reliable power for critical-load applications such as hospitals, data centers, and emergency shelters. They can also be monitored remotely, reducing maintenance time and cost, especially in isolated installations like telecommunications backup-power sites. Fuel cells can operate as stand-alone systems with an available fuel source, without any need to be connected to the grid; this can offer flexibility and energy security. Large-scale fuel cells can also provide grid support to help alleviate transmission issues nearer to the point of use. In addition, fuel cells can be used in smart grid or microgrid applications, providing

an alternative to, or an enhancement of, traditional electric power systems. Dispersed distributed generation can provide highly reliable electric power, and byproduct heat from fuel cells, offering additional benefits for space-, water-, or process-heating needs. High temperature fuel cells (such as molten carbonate or solid oxide fuel cells) offer good opportunities for combined heat and power applications. Compared to high temperature options (e.g. molten carbonate fuel cells, phosphoric acid fuel cells, or solid oxide fuel cells), lower temperature polymer electrolyte membrane (PEM) fuel cells (and electrolyzers) have rapid start-up times and offer peaking capabilities with good load-following characteristics for both the demand and supply side of power generation.

- **Suitability for Diverse Applications:** Fuel cells can provide power for a wide range of applications, such as consumer electronics (up to 100 W), homes (1–5 kW), backup power generators (1–5 kW), forklifts (5–20 kW), vehicles (50–125 kW), and centralized power generation (1–200 MW or more).
- **Opportunities for Economic Growth and Leadership in an Emerging High-Tech Sector:** The domestic hydrogen and fuel cell industry is poised to become a major high-tech sector, with the potential to help strengthen the domestic economy and provide high-skilled jobs in diverse areas, including manufacturing, installation, maintenance, and service. The United States has long been the world leader in hydrogen and fuel cell technologies, but worldwide interest and investment in these technologies are growing.

The environmental and energy benefits of hydrogen and fuel cells are particularly significant in the transportation sector. With over 15 quads of petroleum per year going to light-duty highway transportation, a significant energy security challenge is our transportation sector's heavy dependence on petroleum. With greenhouse gases (GHGs) and criteria pollutants being the other major concerns associated with petroleum use, FCEVs and low-carbon hydrogen can play an important role in our energy future. Analyses by the National Research Council,[10] California,[11] Japan's Ministry of Economy, Trade, and Industry,[12] and a consortium of international automakers and energy companies[13] have shown that a major GHG reduction target requires a portfolio that includes electric drives such as batteries and fuel cells and various fuels derived from low-carbon/carbon-neutral sources, including cellulosic biofuels, renewable electricity, and low-carbon hydrogen. Even when using natural gas-derived hydrogen without CCUS, the CO_2 reduction potential of an FCEV is expected to be at least 50% compared to a current internal combustion engine vehicle (ICEV) using gasoline. With hydrogen derived from sustainable, low-carbon sources, GHG reductions greater than 90% are achievable, as seen in the well-to-wheels analysis shown in Figure 7.D.3 (note that even compared with future advanced ICE vehicles, FCEVs offer GHG reductions of over 80%, as seen in the figure). Additional well-to-wheels analysis of hydrogen and fuel cells in the transportation sector is included in the QTR Chapter 8 and its FCEV Technology Assessment.

Figure 7.D.3, illustrates that significant reductions in GHG emissions can be achieved through the use of hydrogen fuel cells, making substantial gains toward the goal of 80% reduction in CO_2 emissions by 2050. The portfolio approach shown in Figure 7.D.4 assumes a significant introduction of FCEVs to the market, the maximum practical rate of improvements in ICEV efficiency (including hybrid electric vehicles), and large-scale use of biofuels.

Figure 7.D.3 GHG Emissions Reductions with Hydrogen FCEVs in Grams CO_2e per Mile[14]

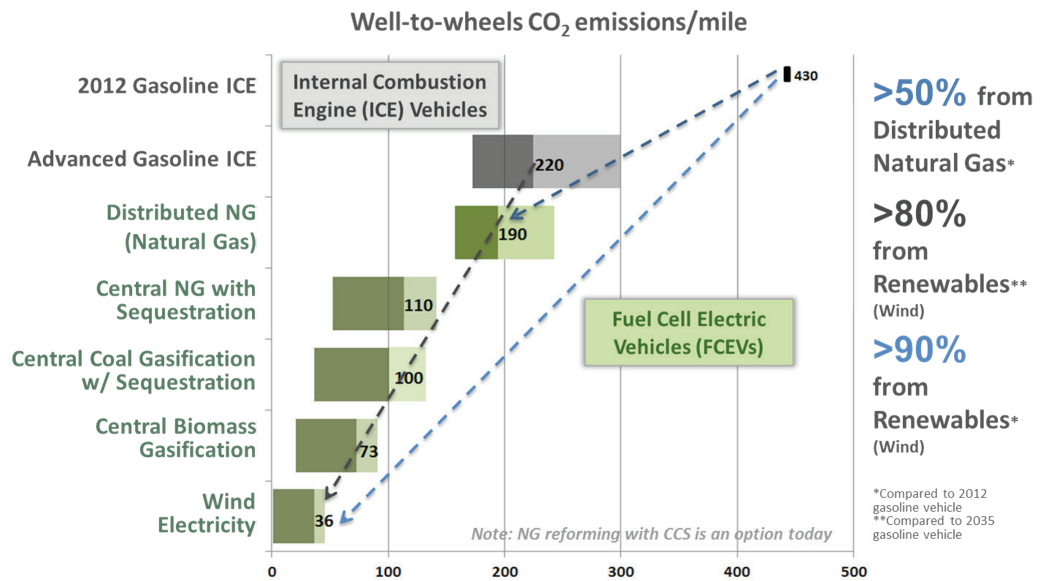
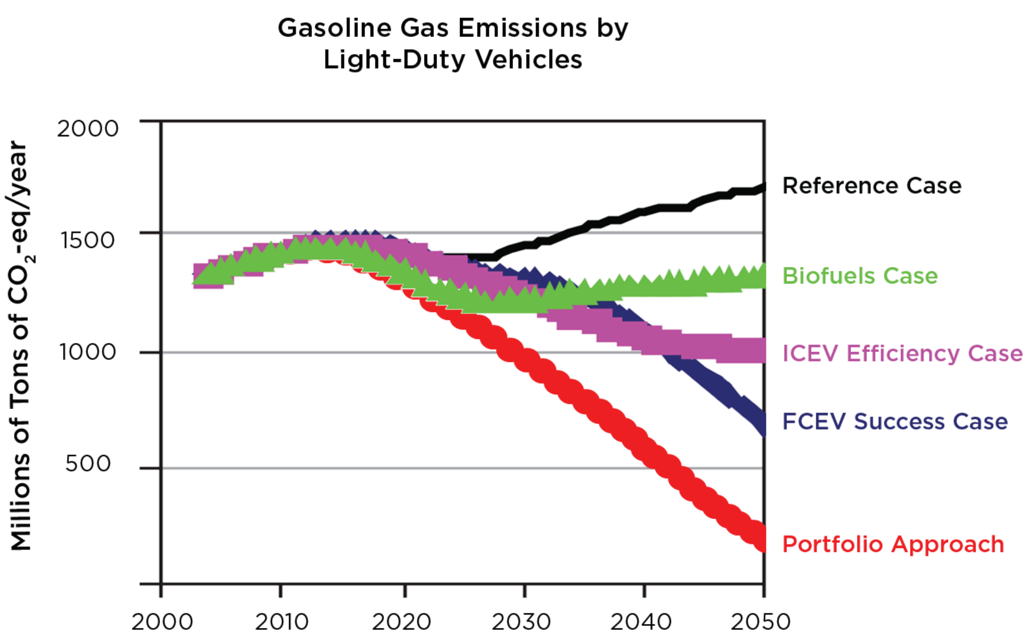
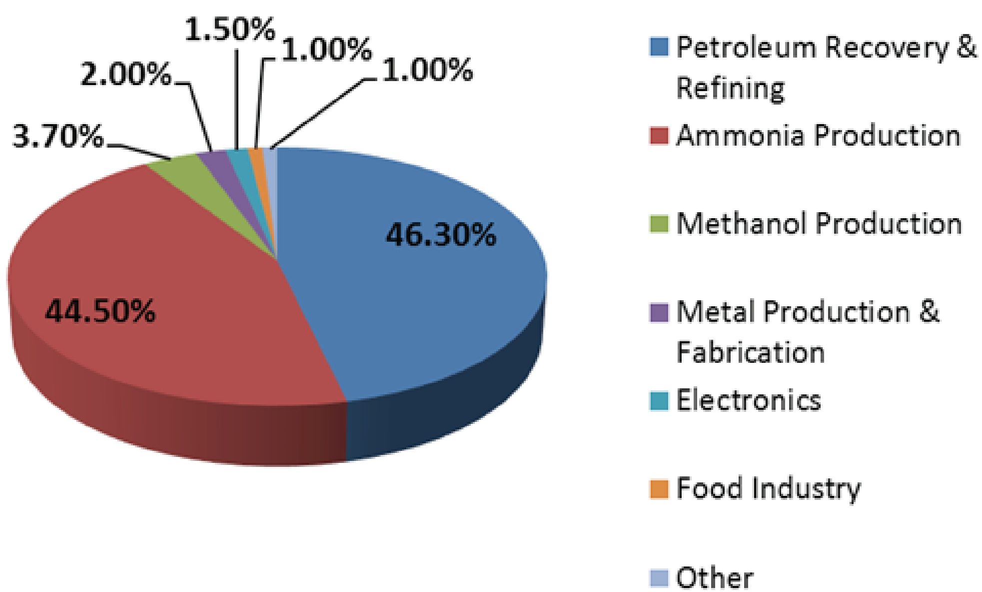


Figure 7.D.4 Achieving GHG emissions goals in a portfolio approach assuming a significant introduction of fuel cell electric vehicles (FCEVs) to the market, the maximum practical rate of improvements in internal combustion engine vehicle (ICEV) efficiency, and large-scale use of biofuels.[15]



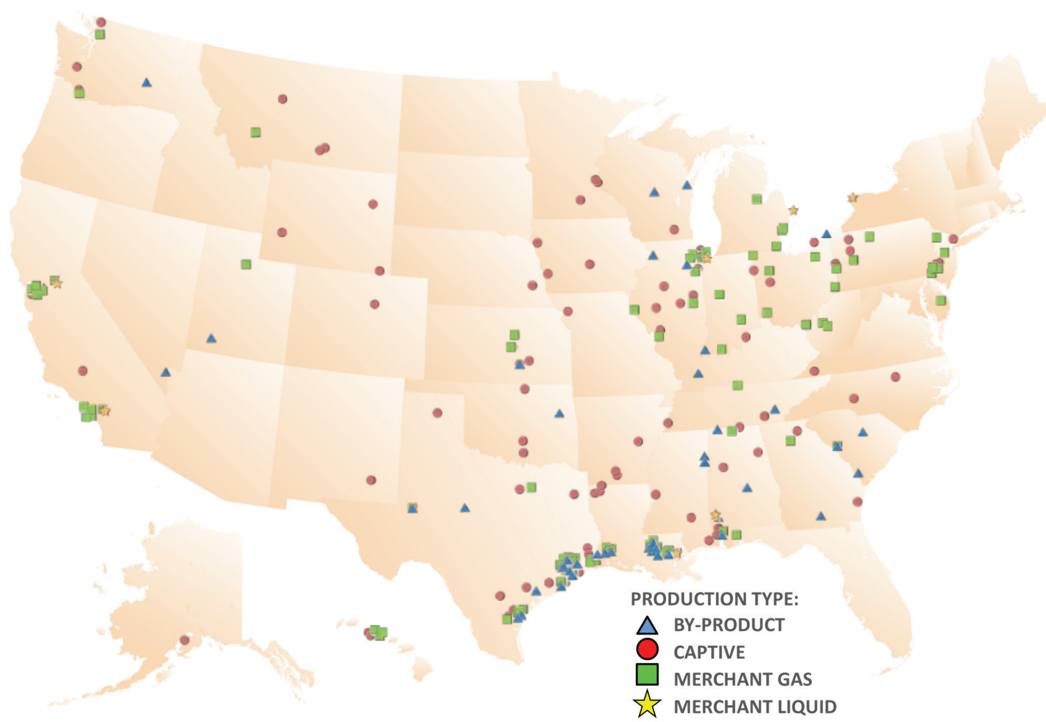
Although hydrogen and fuel cell technologies are not yet widespread in the transportation sector, hydrogen is already a well-established chemical commodity in various industrial sectors. Today, hydrogen is most commonly used as an industrial feedstock for refineries and ammonia production. The petroleum and fertilizer industries have produced and used hydrogen for decades, and worldwide demand is increasing. A more detailed breakdown of hydrogen consumption by industrial market is shown in Figure 7.D.5. The total U.S. hydrogen consumption, including imports, is over 10 million tonnes per year, and worldwide consumption is approximately 23 million tonnes per year.[16] The United States currently produces about 9 million tonnes annually, mainly from fossil fuels. This production volume is equivalent to just over 1 quadrillion BTUs per year (1% of U.S. energy consumption)—enough to power at least 40 million FCEVs for a year.

Figure 7.D.5 Hydrogen Consumption Market Share by Application[17]



The majority of the world's hydrogen is currently produced at or near the petroleum refineries and ammonia plants that require it as a chemical feedstock. In North America, hydrogen is most commonly produced using SMR of natural gas. According to the Hydrogen chapter in the 2012 *National Petroleum council (NPC) Future Transportation Fuels Study: Advancing Technology for America's Transportation Future* (referred from here on as "NPC report"),[18] large hydrogen production facilities (>18,000 kg/day) exist in nearly every state in the United States, as illustrated in Figure 7.D.6. In other countries, such as China and India, coal is the primary feedstock.[19] Carbon capture, use, and storage (CCUS) can be used in conjunction to lower or remove the carbon footprint of the hydrogen produced through the reforming of fossil feedstocks. However, this process is yet to be deployed at low cost and at scale.

Figure 7.D.6 Existing Centralized Hydrogen Production Facilities in the United States[20]



In the near term, the hydrogen production and delivery infrastructure demands of the emerging FCEV market need to be met. Leveraging the synergies between natural gas and hydrogen delivery infrastructure and existing hydrogen production capacity based on natural gas reforming can facilitate meeting these near-term needs. In the long term, realizing the full environmental and security benefits of hydrogen in the energy sector will be a challenge, requiring the research and development of a portfolio of safe, low-cost, low-carbon hydrogen production and delivery methods relying on domestic resources.

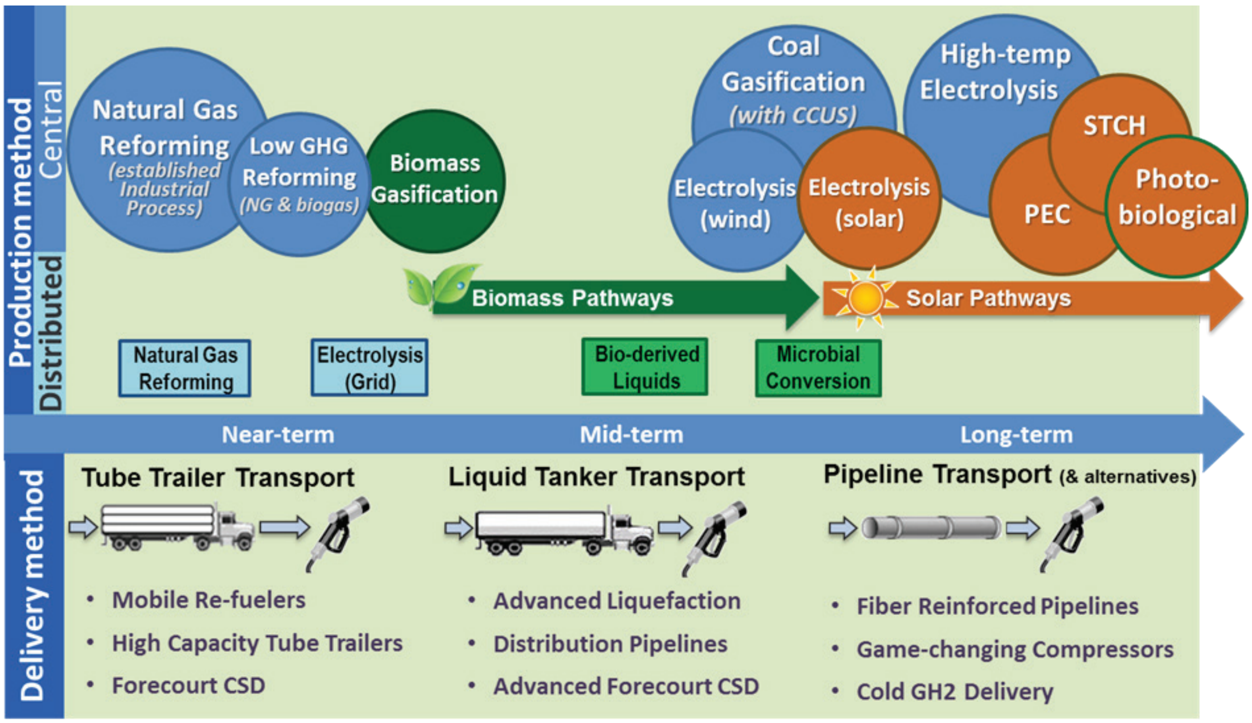
Technology Assessment And Potential

The Hydrogen Production and Delivery Portfolio

There is a broad portfolio of available hydrogen production and delivery technologies spanning a range of development stages and technology readiness, as illustrated in Figure 7.D.7. A small number of hydrogen production technologies are currently used commercially or are approaching commercial readiness. These include natural gas and biogas reforming, as well as electrolysis. Other technologies, particularly renewable production pathways such as solar water splitting, require more research, development, and demonstration (RD&D) prior to introduction as commercial technologies in the mid- to long-term.

Hydrogen for transportation fuel can be produced off-site at central facilities and transported to retail fueling stations or produced at the station through a wide variety of the pathways represented in Figure 7.D.7. When hydrogen is produced at the station, it is referred to as distributed or forecourt production. At the retail refueling station, prior to dispensing to the vehicle, hydrogen is compressed to high pressure for onboard storage.[21]

Figure 7.D.6 Many possible pathways for production and delivery of hydrogen exist. They vary in scale (semi-central to central production ranges from 50,000 to >500,000 kg/day, while distributed production is up to 1,500 kg/day) and time frame for development, as well as in potential cost and GHG emissions.[22]



The DOE's target for the cost of hydrogen production and delivery is \$4.00/gge by 2020.[23] Stochastic analyses accounting for the price of gasoline and the incremental ownership cost of an FCEV in comparison to a hybrid electric vehicle (HEV) indicated that hydrogen must cost <\$4/gge to produce and deliver for FCEVs to be cost-competitive with HEVs.[24] The incremental ownership cost accounted for vehicle depreciation, financing, maintenance, tires, repairs, insurance, registration costs, taxes, fees, and tax credits on a \$/mile basis. The 2020 \$4.00/gge cost target for hydrogen production and delivery has been apportioned to a \$2.00/gge target for the cost of hydrogen production and a \$2.00/gge target for the cost of hydrogen delivery.[25] For early markets, the interim target for dispensed hydrogen is <\$7.00/gge.[26]

Recent technology advancements have reduced the cost of distributed hydrogen at retail fueling stations to <\$4.50/gge (assuming high-volume production and widespread deployment). This applies to hydrogen produced by steam methane reforming (SMR) and dispensed at 700 bar, and is valid over a wide range of natural gas prices.[27] This meets the interim target of <\$7.00/gge, and at the lower end of the range of natural gas prices, hydrogen cost drops below the 2020 target of <\$4.00/gge. The mature SMR pathway is capable of meeting cost targets for hydrogen production, but this is not a sustainable, low-carbon option. CCUS is an option for reducing the greenhouse gas emissions associated with SMR. Ongoing demonstration projects (e.g., a DOE-sponsored project at a hydrogen production facility in Port Arthur, Texas) that capture and store CO_2 from SMR plants are proving the viability of this CCUS approach, but widespread commercial deployment will depend on improvements in the benefit-cost ratio through further RD&D. In the near term, low-carbon hydrogen can also be produced through reforming biogas (i.e., renewable natural gas), either through modified SMR, or using high temperature fuel cells, which can simultaneously generate power, heat, and hydrogen (typically called *combined heat, hydrogen, and power*, or CHHP) with a lower carbon footprint than natural gas SMR.[28] In the longer term, a portfolio of hydrogen production pathways will need to be deployed to meet the growing demand for sustainable, low-carbon hydrogen.

Hydrogen Production Pathways

There are many different pathways to produce hydrogen.[29] Numerous low-carbon pathways include reforming of biomass or fossil fuels such as natural gas and coal with CCUS; and the splitting of water using sustainable and/or renewable energy sources, such nuclear, wind, solar, geothermal, and hydro-electric power. Most of the hydrogen production technologies fall into three general categories: thermal, electrolytic, and photolytic.

Thermal Processes: These include reforming of natural gas or biofuels/biogas, gasification of coal and biomass, and thermochemical processes.[30] Reforming, the most widely deployed technology today, uses high-temperature steam (700°C–1000°C) to produce hydrogen from a carbon source such as methane. Sources can include natural gas, biogas generated from various biogenic renewable sources, and biomass.[31] Biomass gasification is a promising near-term technology that has not yet been commercialized at scale. Thermal reforming is suitable for both the central and distributed scale. Other emerging thermochemical processes use heat (500°C–2000°C) to drive a series of chemical reactions that produce hydrogen from water. Thermochemical water-splitting processes will be best suited for large-scale central production.

Electrolytic Processes: These processes produce hydrogen and oxygen from water using electricity in an electrolyzer.[32] Electrolyzers can range in size from small, appliance-size equipment well-suited for small-scale distributed hydrogen production, to large-scale, central production facilities. Hydrogen produced via electrolysis can result in minimal greenhouse gas emissions when low-carbon or zero-carbon electricity is used. Low-temperature electrolyzers are commercially available and in use at some hydrogen fueling stations. High-temperature electrolysis systems, typically operated at temperatures over 750°C with higher electrical efficiency compared with lower temperature electrolyzers, are applicable for use at nuclear reactors and solar thermal facilities, taking advantage of the high-grade heat generated by these technologies. There is growing interest, particularly in locations where emissions standards are in place (e.g., Europe, California, and others), for pairing water electrolysis with 'green' electricity as a way to utilize renewable electricity that otherwise would be curtailed during periods of low demand.

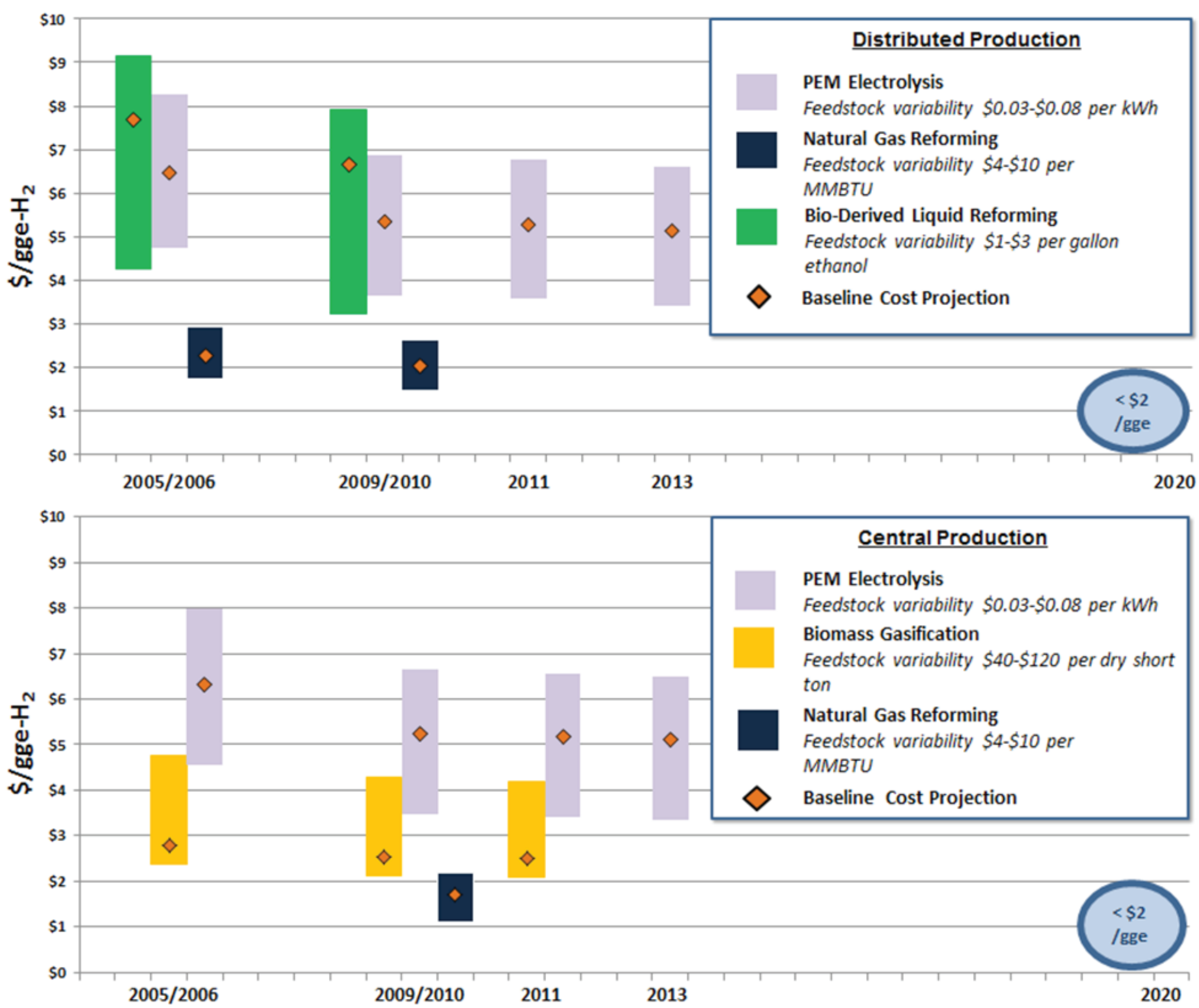
Photolytic Processes: Photolytic processes use the energy in sunlight to separate water into hydrogen and oxygen and can be further classified into two general categories: photoelectrochemical (PEC) and photobiological. In PEC hydrogen production, specialized semiconductor devices harness sunlight to split water.[33] In photobiological production, specialized microorganisms, such as green algae and cyanobacteria, use the energy from sunlight to produce hydrogen. In the future, these pathways have long-term potential for sustainable hydrogen production with low environmental impact, but they are in relatively early stages of research and development.[34]

Microbial Processes: Alternatively, hydrogen can also be produced through microbial biomass conversion processes, which do not require light, such as fermentation or microbial electrolysis cells. These microbes can consume organic matter such as corn stover or wastewater to produce hydrogen. This pathway could be suitable for central hydrogen production or even distributed production for waste stream feedstocks.

Ongoing RD&D is exploring the ways to accelerate development of all available hydrogen production pathways. The research focus includes demonstrating the viability of the longer term low-carbon pathways as well as continued cost reductions in all the near- to mid-term options. The hydrogen production-cost ranges for commercial and near-commercial pathways, at both central and distributed scales, are shown in Figure 7.D.8, which illustrates the reduction in costs in recent years resulting from the RD&D.[35] The analytical basis for the pathway-dependent cost ranges in the figure is the H2A analysis tool, a publically available spreadsheet tool that projects the high-volume cost of hydrogen production using capital, feedstock, and operation and maintenance (O&M) cost contributions levelized over the lifetime of the hydrogen production plant.[36] The hydrogen cost ranges shown for each pathway include a baseline cost projection (represented by a diamond symbol in the plot), along with a cost spread (represented by the vertical bars in the plot) reflecting variability in major feedstock pricing as well as uncertainties in capital cost estimates.[37]

As seen in Figure 7.D.8, RD&D is bringing down hydrogen production costs, which have dropped from a baseline of ~$2.30–$7.70 per kg across the pathways in 2005 to ~$2.00–$6.65 per kg by 2013. Natural gas hydrogen production technologies are well developed and the least expensive. Biomass gasification is also a mature technology, with the potential for producing relatively low-cost hydrogen, but the production cost is highly sensitive to the biomass feedstock pricing. Water electrolysis technologies have seen significant improvements since 2005, but the hydrogen production costs remain above the $2.00/kg target for hydrogen production because of the dominance of electricity pricing as a key cost driver.

Figure 7.D.8 Current Range of Hydrogen Production Costs (undispensed and untaxed, reported in $/gge including feedstock and capital cost variability assuming high-volume production and widespread commercialization)[38]



Independent of the hydrogen production pathway, improving process conversion efficiencies is critical to reducing the hydrogen cost. To date, feedstock-to-hydrogen energy conversion efficiencies exceeding 70% have been demonstrated for SMR, while ~46% has been achieved in biomass gasification.[39] Hydrogen can also be produced by coupling natural gas combined-cycle power plants with water electrolysis systems. Conversion efficiencies of ~32% have been achieved with this approach using commercial low-temperature electrolyzers (this efficiency calculation includes a ~67% electric-to-hydrogen electrolyzer efficiency, and a ~48% efficiency for the upstream natural gas combined-cycle power plant). Efficiencies greater than 50% are achievable using advanced high-temperature electrolyzers operating above 800ºC.[40] Higher conversion efficiency reduces feedstock requirements and lowers cost. Continued RD&D focused on improving efficiencies can reduce hydrogen costs in all the near- to long-term technologies.

In the near-term, current industrial hydrogen production capacity based largely on SMR of natural gas can potentially provide sufficient affordable hydrogen fuel for early-market FCEV deployment.[41] Going forward, demand growth would require increased capacity, with a priority on hydrogen production from renewable and/or low-carbon pathways. To meet this demand, the entire portfolio of low-carbon hydrogen production pathways will be needed, including emerging pathways such as microbial biomass conversion, photobiological production, and solar-based thermo- and photoelectrochemical water-splitting, which require additional RD&D to reach commercial readiness.

Technology advancements in conjunction with expanded market penetration of hydrogen and fuel cell technologies (resulting in industrial economies of scale) are expected to drive down costs for dispensed hydrogen in future scenarios. These scenarios include hydrogen production from the varied options in the technology portfolio. An interesting study presented in the *Hydrogen* chapter of the *NPC Report* uses Monte Carlo analysis to project fuel cost ratio comparisons of FCEVs with conventional gasoline vehicles out to 2050[18]. The analysis results, shown in Table 7.D.1, indicate that in some of the near-term cases considered, and in most of the longer-term cases, hydrogen compares favorably with gasoline on a per-mile basis (a fuel cost ratio <1). The greater efficiency of FCEVs over conventional gasoline counterparts is an important contributor to this result. Continued reductions in hydrogen production costs are also an important factor. Equally important will be reductions in the hydrogen delivery and dispensing costs.

Table 7.D.1 Fuel Cost Ratio Comparison (hydrogen $/mile versus gasoline $/mile) of FCEVs Compared with Conventional (non-hybrid) Gasoline Vehicles. For analysis inputs and assumptions, see the source document.[42]

Gasoline Prices	Hydrogen Price	FCEV Efficiency	2015	2020	2025	2030	2035	2040	2045	2050
AEO2010 High Oil Price Case	Low	High	0.6	0.4	0.4	0.3	0.3	0.3	0.3	0.3
		Low	1.0	0.6	0.6	0.5	0.5	0.5	0.5	0.5
	High	High	0.9	0.6	0.6	0.4	0.4	0.4	0.4	0.4
		Low	1.3	0.9	0.8	0.6	0.6	0.6	0.6	0.6
AEO2010 Reference Case	Low	High	0.9	0.6	0.6	0.5	0.4	0.4	0.4	0.4
		Low	1.3	1.0	0.9	0.7	0.7	0.6	0.6	0.6
	High	High	1.2	0.9	0.9	0.6	0.5	0.5	0.5	0.5
		Low	1.8	1.4	1.3	0.8	0.8	0.8	0.8	0.7
AEO2010 Low Oil Price Case	Low	High	1.3	1.0	1.0	0.8	0.8	0.8	0.8	0.8
		Low	2.0	1.6	1.6	1.2	1.2	1.2	1.2	1.2
	High	High	1.8	1.4	1.4	1.0	1.0	1.0	1.0	1.0
		Low	2.7	2.2	2.2	1.5	1.5	1.5	1.5	1.5
Average value by year			1.4	1.0	1.0	0.7	0.7	0.7	0.7	0.7
Overall Average			0.9							

Color Key	<1	1 - 1.2	>1.2

Notes: Gasoline price based on AEO2010 oil price scenarios.
Hydrogen price efficiecy based on centralized pathwya discussion in this chapter.
FCEV efficiency assumed to range from 2C to 3X of gasoline vehicle.

Hydrogen Delivery Pathways

As seen in Figure 7.D.7, a wide range of hydrogen delivery technologies are available to serve existing and emerging markets. Hydrogen delivery includes all of the infrastructure required to move and store hydrogen from the point of production to the vehicle. This includes transmission, distribution, and refueling station operations. There are three main transmission and distribution pathways: pipeline, tube trailer, and liquid tanker truck. The gaseous hydrogen transmission and distribution pathway is very similar to the pathway for natural gas transmission and distribution today. Pipelines can be made with steel or fiber-reinforced polymer (FRP) pipe and operate at 70 to 100 bar. Gaseous tube trailers carry hydrogen in large pressurized storage cylinders. These can be either steel cylinders at 180 bar or high-pressure composite cylinders, which can carry hydrogen at pressures as high as 500 bar. Typical steel tube trailers can carry approximately 280 kg, while the high-pressure tube trailers can carry close to 1000 kg. Geologic storage is used to store large capacities of hydrogen (thousands of tonnes) to buffer fluctuations in seasonal demand and supply disruptions.[43]

Distributing hydrogen as a liquid involves liquefaction. During this process, the hydrogen is cooled below -253°C (-423°F) using liquid nitrogen and a series of compression and expansion steps. The cryogenic liquid hydrogen is then stored in large, insulated tanks, loaded into delivery trucks, and transported to the point of use or stored in vacuum-jacketed tanks until it is used.

After on-site production or distribution to the point of use, the hydrogen goes through compression, storage, and dispensing (CSD) at the retail fueling station to serve the vehicle market. The hydrogen in light-duty FCEV tanks is pressurized to 700 bar in order to store the approximately 5 kg of hydrogen needed to enable a 300-mile vehicle range in today's FCEVs.[44, 45] At the station, the hydrogen is stored at 875–1000 bar and then precooled to -40°C. It must also be precooled during dispensing in order to achieve a 3- to 5-minute fill time without overheating the storage tank. Therefore, thermal management is a key consideration in cost-effective station design. The heavy-duty vehicle market operates similarly, except that the hydrogen onboard the vehicle is stored at 350 bar rather than 700 bar since larger vehicles are less constrained with respect to space, and lower-pressure vessels provide a cost and weight advantage.

In conjunction with the current industrial production capacity to support early-market FCEV deployments, significant hydrogen delivery infrastructure is in place today to serve the industrial market. There are more than 1,500 miles of hydrogen pipelines in the United States, primarily along the Gulf Coast. The Praxair salt dome cavern on the Gulf Coast is one of the largest hydrogen storage systems in the world, with 1.4 billion cubic feet of working storage.[46] California is the first state making significant investments in a hydrogen infrastructure for the light-duty vehicle market. They are working to achieve a target of 100 hydrogen refueling stations by 2020. Twenty-eight stations will be open by the end of 2015, with twenty-three more stations planned to open in 2016.[47]

High-pressure gaseous tube trailer delivery is the lowest cost delivery method to serve the near-term vehicle market. This is due to the decrease in compression required at the station when the gas is delivered at high pressure. Relatively small amounts of gaseous hydrogen can be transported short distances by high-pressure (up to 500 bar) tube trailers. A modern high-pressure tube trailer is capable of transporting nearly 1000 kg of hydrogen. Gaseous transmission and distribution through pipelines remains the lowest cost delivery option for large volumes of hydrogen. The high initial capital associated with this pathway constitutes a major barrier to the construction of new hydrogen pipelines.

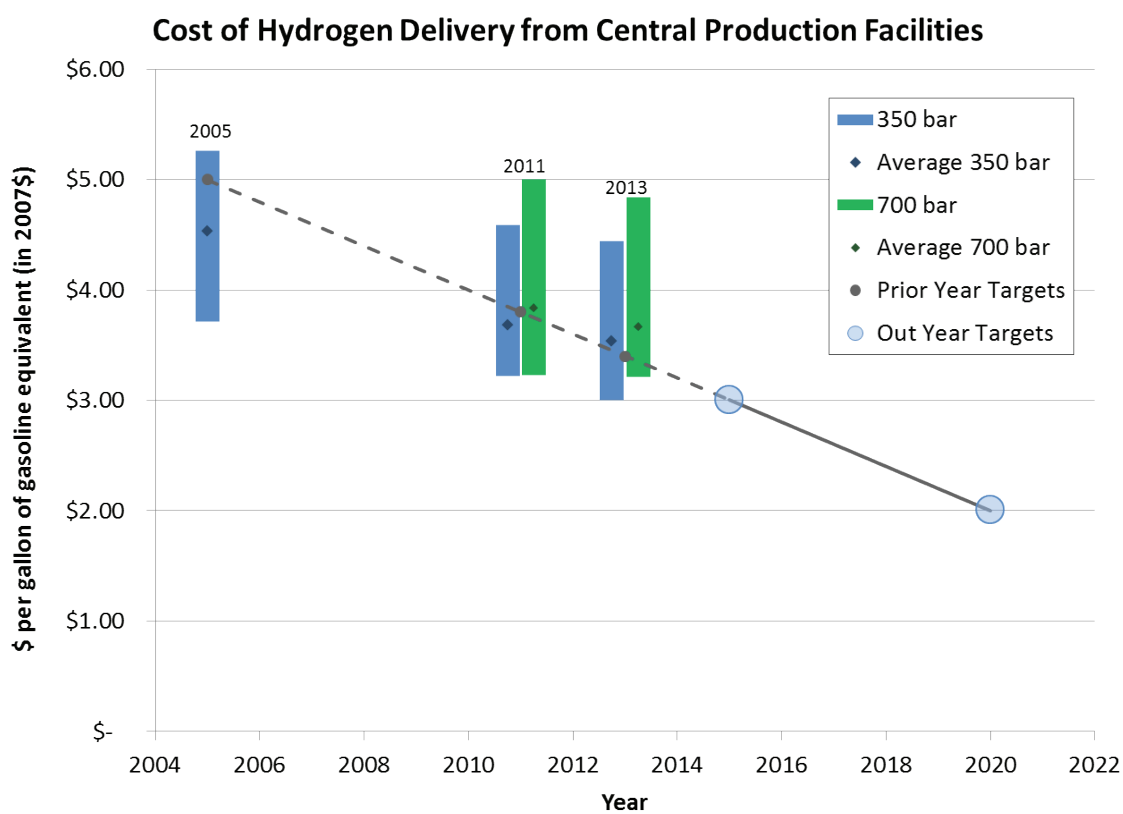
The liquid hydrogen pathway is a well-developed and competitive method of providing hydrogen molecules for high-demand applications that are beyond the reach of hydrogen pipeline supplies. It is more economical than gaseous trucking for high market demands (greater than 700 kg/day) and longer delivery distances because a liquid tanker truck with a capacity of approximately 4000 kg can transport more than four times the capacity of a 500-bar gaseous tube trailer. The nine existing liquefaction plants in North America vary in production size from 5,400 to 62,000 kg of hydrogen per day.

Table 7.D.2 Current Hydrogen Delivery Cost Status as a Function of Dispensed Gas Pressure and Delivery Pathway as Reported from HDSAM (to the nearest $0.05/gge)[48]

Dispensing pathways	Delivery costs ($/gge H_2 delivered and dispensed)	
	350 bar	700 bar
Pipeline	4.45	4.85
Pipeline – tube trailer	3.15	3.20
Tube trailer	3.00	3.30
Pipeline – liquid tanker	N/A	3.75
Liquid tanker	N/A	3.25

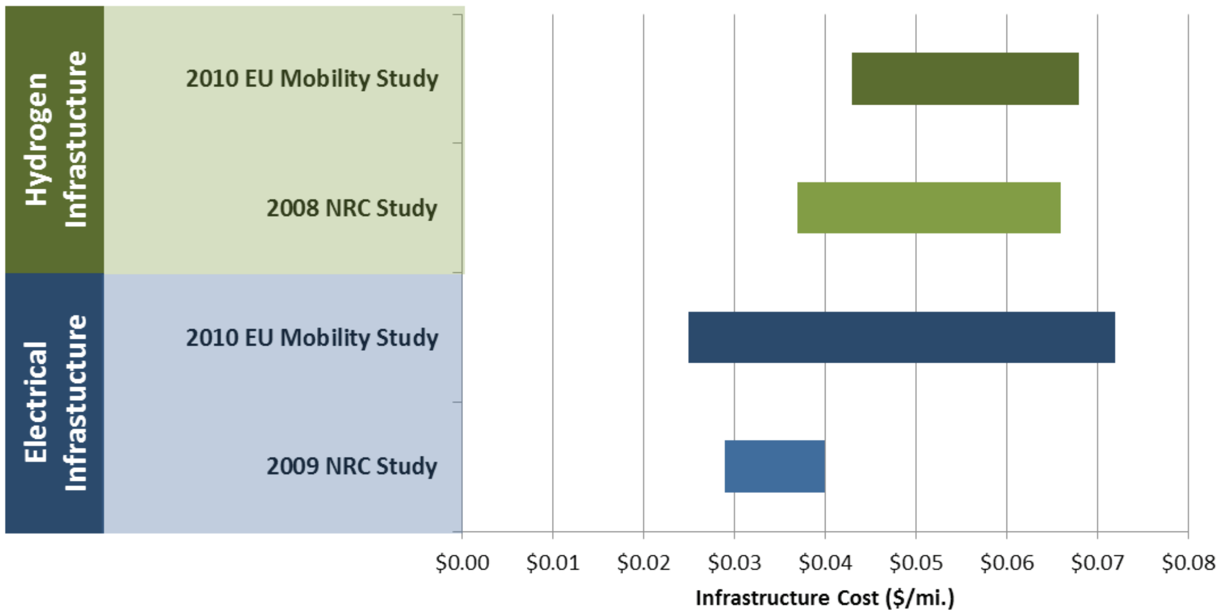
Table 7.D.2 shows the current costs for a range of hydrogen delivery pathways at high volume. Technology advances through RD&D over the past decade have resulted in considerable cost reductions in hydrogen delivery and dispensing, as seen in Figure 7.D.9.

Figure 7.D.9 Hydrogen Delivery Costs from Central Production. The cost statuses and targets of hydrogen delivery (transmission and distribution) have steadily declined since 2005. The ranges shown in this graph are based on simulations of three 350-bar scenarios, and five 700-bar scenarios. Cost statuses for prior years were based on the technology readiness levels during those years. Cost projections are based on DOE targets and feasibility assumptions from technical experts.[49]



The cost reductions evident in Figure 7.D.9 indicate that hydrogen delivery technologies are on track for meeting the $2/gge target in 2020, given the successes and progress in recent years. Additionally, it is important to note that the cost of hydrogen infrastructure is similar on a per-mile basis to electrical charging infrastructure for battery electric vehicles, as illustrated in Figure 7.D.10. As states implement zero-emission vehicle programs, hydrogen fuel cell vehicles are therefore positioned to be competitive with electric vehicles.

Figure 7.D.10 A number of external studies indicate that infrastructure costs for FCEVs and BEVs are comparable on a cost-per-mile basis.[50]

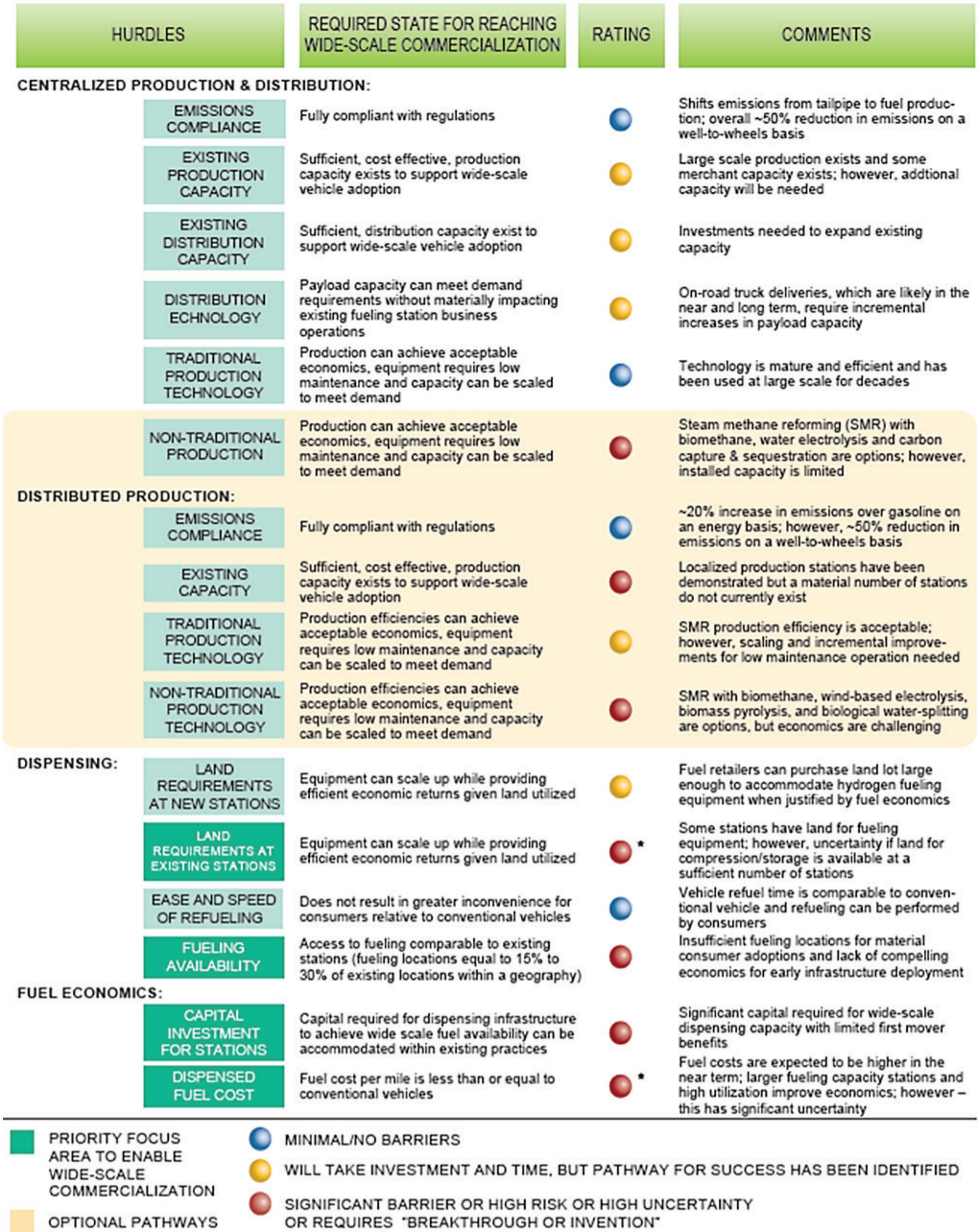


Status of Hydrogen Fuel Technology Challenges

The "Priorities for Technology Investments" chapter in the NPC report has summarized the status of technology hurdles for hydrogen fuel, based primarily on commercial and near-term technologies for hydrogen production and delivery. This summary, shown in Figure 7.D.11, indicates that although some significant technical barriers remain requiring substantial RD&D time and effort (particularly in distributed production and in dispensing), there are clearly near-term pathways for early roll-out of hydrogen fueling technologies with minimal to moderate challenges.

Figure 7.D.11 Summary of Hydrogen Fuel Hurdles[51]

Credit: National Petroleum Council



HURDLES	REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	RATING	COMMENTS
CENTRALIZED PRODUCTION & DISTRIBUTION:			
EMISSIONS COMPLIANCE	Fully compliant with regulations		Shifts emissions from tailpipe to fuel production; overall ~50% reduction in emissions on a well-to-wheels basis
EXISTING PRODUCTION CAPACITY	Sufficient, cost effective, production capacity exists to support wide-scale vehicle adoption		Large scale production exists and some merchant capacity exists; however, addtional capacity will be needed
EXISTING DISTRIBUTION CAPACITY	Sufficient, distribution capacity exist to support wide-scale vehicle adoption		Investments needed to expand existing capacity
DISTRIBUTION ECHNOLOGY	Payload capacity can meet demand requirements without materially impacting existing fueling station business operations		On-road truck deliveries, which are likely in the near and long term, require incremental increases in payload capacity
TRADITIONAL PRODUCTION TECHNOLOGY	Production can achieve acceptable economics, equipment requires low maintenance and capacity can be scaled to meet demand		Technology is mature and efficient and has been used at large scale for decades
NON-TRADITIONAL PRODUCTION	Production can achieve acceptable economics, equipment requires low maintenance and capacity can be scaled to meet demand		Steam methane reforming (SMR) with biomethane, water electrolysis and carbon capture & sequestration are options; however, installed capacity is limited
DISTRIBUTED PRODUCTION:			
EMISSIONS COMPLIANCE	Fully compliant with regulations		~20% increase in emissions over gasoline on an energy basis; however, ~50% reduction in emissions on a well-to-wheels basis
EXISTING CAPACITY	Sufficient, cost effective, production capacity exists to support wide-scale vehicle adoption		Localized production stations have been demonstrated but a material number of stations do not currently exist
TRADITIONAL PRODUCTION TECHNOLOGY	Production efficiencies can achieve acceptable economics, equipment requires low maintenance and capacity can be scaled to meet demand		SMR production efficiency is acceptable; however, scaling and incremental improvements for low maintenance operation needed
NON-TRADITIONAL PRODUCTION TECHNOLOGY	Production efficiencies can achieve acceptable economics, equipment requires low maintenance and capacity can be scaled to meet demand		SMR with biomethane, wind-based electrolysis, biomass pyrolysis, and biological water-splitting are options, but economics are challenging
DISPENSING:			
LAND REQUIREMENTS AT NEW STATIONS	Equipment can scale up while providing efficient economic returns given land utilized		Fuel retailers can purchase land lot large enough to accommodate hydrogen fueling equipment when justified by fuel economics
LAND REQUIREMENTS AT EXISTING STATIONS	Equipment can scale up while providing efficient economic returns given land utilized	*	Some stations have land for fueling equipment; however, uncertainty if land for compression/storage is available at a sufficient number of stations
EASE AND SPEED OF REFUELING	Does not result in greater inconvenience for consumers relative to conventional vehicles		Vehicle refuel time is comparable to conventional vehicle and refueling can be performed by consumers
FUELING AVAILABILITY	Access to fueling comparable to existing stations (fueling locations equal to 15% to 30% of existing locations within a geography)		Insufficient fueling locations for material consumer adoptions and lack of compelling economics for early infrastructure deployment
FUEL ECONOMICS:			
CAPITAL INVESTMENT FOR STATIONS	Capital required for dispensing infrastructure to achieve wide scale fuel availability can be accommodated within existing practices		Significant capital required for wide-scale dispensing capacity with limited first mover benefits
DISPENSED FUEL COST	Fuel cost per mile is less than or equal to conventional vehicles	*	Fuel costs are expected to be higher in the near term; larger fueling capacity stations and high utilization improve economics; however – this has significant uncertainty

PRIORITY FOCUS AREA TO ENABLE WIDE-SCALE COMMERCIALIZATION

OPTIONAL PATHWAYS

MINIMAL/NO BARRIERS

WILL TAKE INVESTMENT AND TIME, BUT PATHWAY FOR SUCCESS HAS BEEN IDENTIFIED

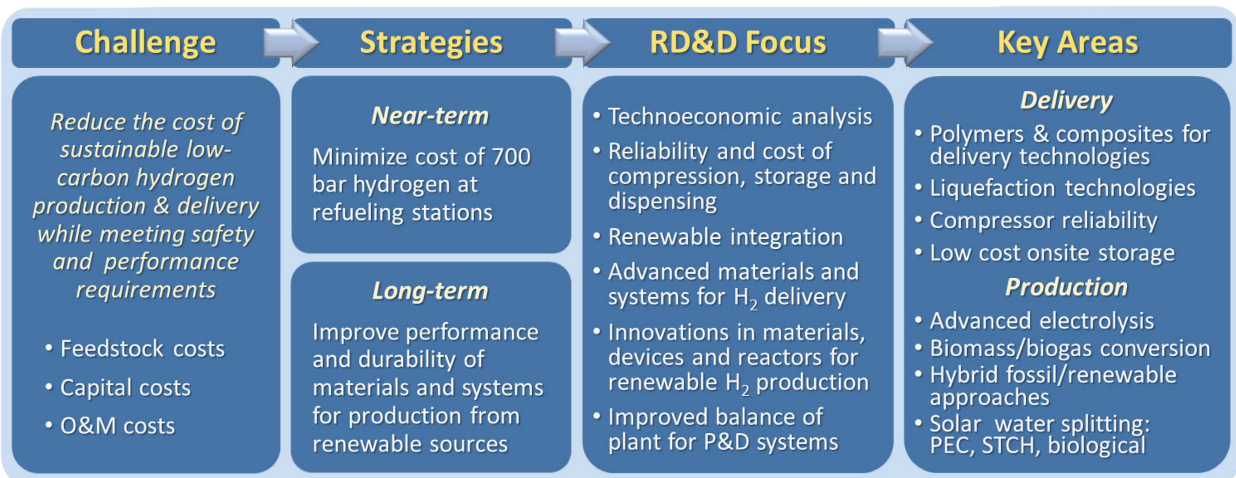
SIGNIFICANT BARRIER OR HIGH RISK OR HIGH UNCERTAINTY OR REQUIRES "BREAKTHROUGH OR INVENTION"

* Some authors assert that existing stations have the land required in the near term, and future stations can accommodate hydrogen fueling equipment in their designs, thereby changing these color codes from red to yellow. Under this scenario, current technology can meet near-term performance requirements, and as fuel demand develops and capacity utilization increases, fuel costs will be lower.

RD&D Needs and Priorities in the Hydrogen Production and Delivery Program

Cost reduction of at-scale technologies remains the key challenge in the production and delivery of hydrogen, particularly from low-carbon sources for use in fuel cell electric vehicles. The critical barriers and strategies for reducing the cost of hydrogen production and delivery are shown in Figure 7.D.12. Since high volume market penetration is an essential factor for any cost reduction, lowering the cost of hydrogen for 700 bar refueling to accelerate the introduction of FCEVs into the marketplace is an important near-term need. The RD&D priorities in this strategy rely on techno-economic analysis and modeling to identify refueling station equipment and processes with the largest contributions to refueling cost, along with cost mitigation approaches based on technology improvements. Broader RD&D priorities addressing longer term needs include lowering the cost of hydrogen from renewable and low-carbon sources through process and materials development.

Figure 7.D.12 Hydrogen Production and Delivery Research and Development Priorities[52]



Near-Term Pathway RD&D Needs and Priorities:

The thermal production processes such as bio-derived liquid reforming, coal gasification, and biomass gasification could achieve reduced capital costs through improved catalysts and low-cost separation and purification technologies. Electrolysis systems are another near-term hydrogen production pathway that requires additional research, with a focus on reducing costs and improving efficiency. Currently the feedstock cost (i.e., the electricity feedstock) is the most significant contributor to the hydrogen cost from this pathway. As a result, it is critical to focus on improving the process efficiency while reducing the capital cost. Development of load-following capability would provide more economical system operation during times of low demand. The cost of low-temperature electrolysis could be up to 10% lower if efficiency increased from 67% production efficiency to 74%. Please refer to Chapter 4 of the QTR for coal gasification cost and performance.

Long-Term Pathway RD&D Needs and Priorities:

The costs of all emerging production pathways need to be significantly reduced. As material costs and performance improvements are needed for most of these pathways, one promising area of RD&D with impacts on multiple pathways is high throughput/combinatorial approaches to enable rapid identification and development of promising materials systems as appropriate. Photoelectrochemical (PEC) production requires RD&D to develop materials with the appropriate band gap to both absorb sunlight and electrolyze water in a single device, while solar thermochemical (STCH) production pathways require identification and development of efficient and durable materials to design a cost-effective reactor system. Photobiological approaches require fundamental research in a number of areas such as direct water splitting using microalgae or cyanobacteria, and optimization of energy flows and electron flux. These pathways are supported through fundamental research on artificial solar-fuel generation technology. Research in this area is being performed at the DOE Energy Innovation Hub Joint Center for Artificial Photosynthesis (JCAP), which was established in 2010.[53] Microbial biomass conversion methods such as fermentation require research to improve hydrogen production yields and rates. Intra-DOE collaboration and coordination (e.g., between technology and science programs) and interagency collaboration and coordination (e.g., National Science Foundation, Department of Defense, National Institute of Standards and Technology) are an important aspect of RD&D in these areas.

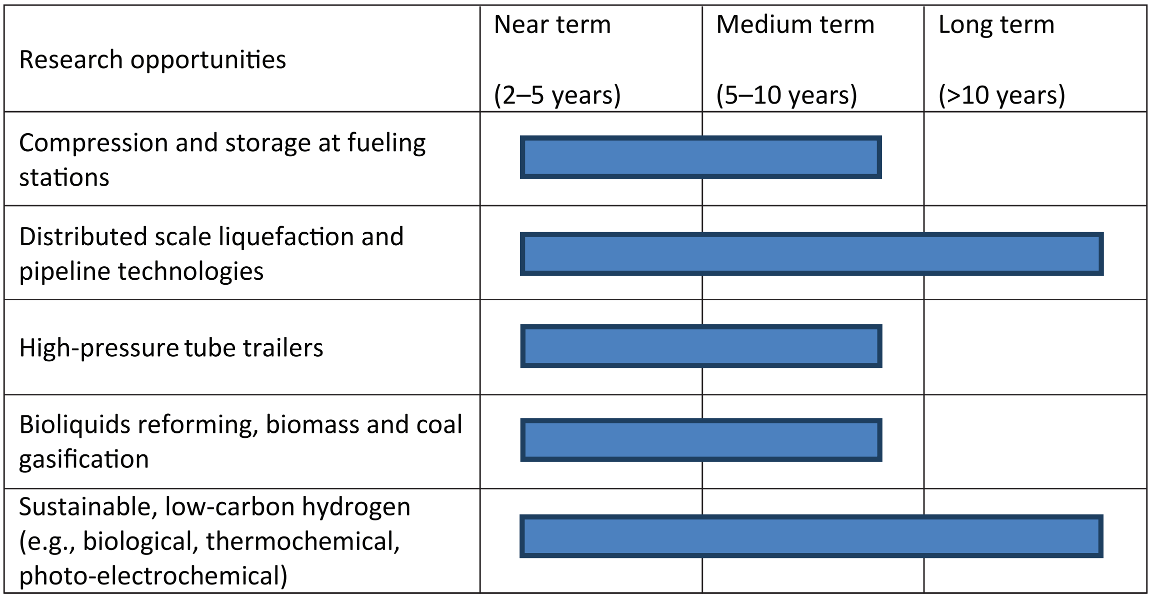
A high-temperature advanced nuclear reactor coupled with one of the high-temperature technologies (thermochemical cycles, electrolytic, and hybrid thermochemical/electrolytic) could achieve a thermal-to-hydrogen conversion efficiency of 45% to 55%. However, this technology requires further RD&D. Further RD&D is needed on the nuclear reactor (see Technology Assessment 4.J High Temperature Reactors) and there are critical challenges regarding the high temperature and design of corrosion resistant materials for the hydrogen generation system. System design development is still needed to study the hydrogen plant and its relationship to the reactor, including configuration options and operating conditions, system isolation issues, and intermediate heat transfer loop design. The QTR Chapter 4 on Power Technologies contains a discussion of the related nuclear energy RD&D as well as a number of related Technology Assessments.

Hydrogen Delivery Pathway RD&D Needs and Priorities:

Hydrogen's low volumetric density poses a challenge with respect to the costs of storage and delivery, necessitating further RD&D to improve the efficiency, cost, and reliability of compression, storage, and delivery technologies for 700-bar refueling. This can be achieved through researching new materials for high-pressure dynamic and static seals, developing new compression technologies such as linear motor, metal hydride, and thermal compressors, and demonstrating alternative refueling and control algorithms to lessen the burden on the station. Longer term priorities in delivery include developing advanced technologies for liquefaction, geologic storage, and pipelines and pipeline compressors. Issues such as hydrogen embrittlement and safety clearly must be addressed, and continued materials compatibility RD&D is essential. With successful technology development, hydrogen delivery costs could be reduced by more than 50% (2020 target is <$2/gge[54] versus today's cost of $3–$5/gge), which would enable economic competitiveness in the fuel cost of hydrogen FCEV with gasoline ICEs. For additional information regarding the status of forecourt technologies, please see the DOE Multi-year Research, Development, and Demonstration Plan.[55]

Figure 7.D.13 summarizes the near-, mid-, and long-term research priorities. For both production and delivery technology pathways, it is necessary to continue developing and testing innovative materials, components, and systems.

Figure 7.D.13 RD&D Timeline for Hydrogen Production and Delivery



Hydrogen is an energy carrier that can be produced from a wide variety of energy inputs and used in diverse applications, such as fuel cell electric vehicles for transportation and stationary fuel cells for heat and power. The major challenge is to reduce the cost of producing and delivering hydrogen from renewable and low-carbon sources using a portfolio of technologies that are scalable, and that meet industrial performance and safety requirements. To reduce costs, continued RD&D is needed to improve materials, systems, and scaled technologies for diverse hydrogen production and delivery options. Near-term cost reductions can be achieved by leveraging the synergies between natural gas and hydrogen delivery infrastructure and the existing hydrogen production capacity based on natural gas reforming. This is important to support the early market deployment of FCEVs, and to promote development and deployment of the hydrogen production and delivery technologies and infrastructure needed to sustain market growth. The longer term priority is to transition to the sustainable and low-carbon options for hydrogen production and delivery to fuel growing markets in the transportation, stationary heat and power, and energy storage sectors.

Program Considerations To Support RD&D

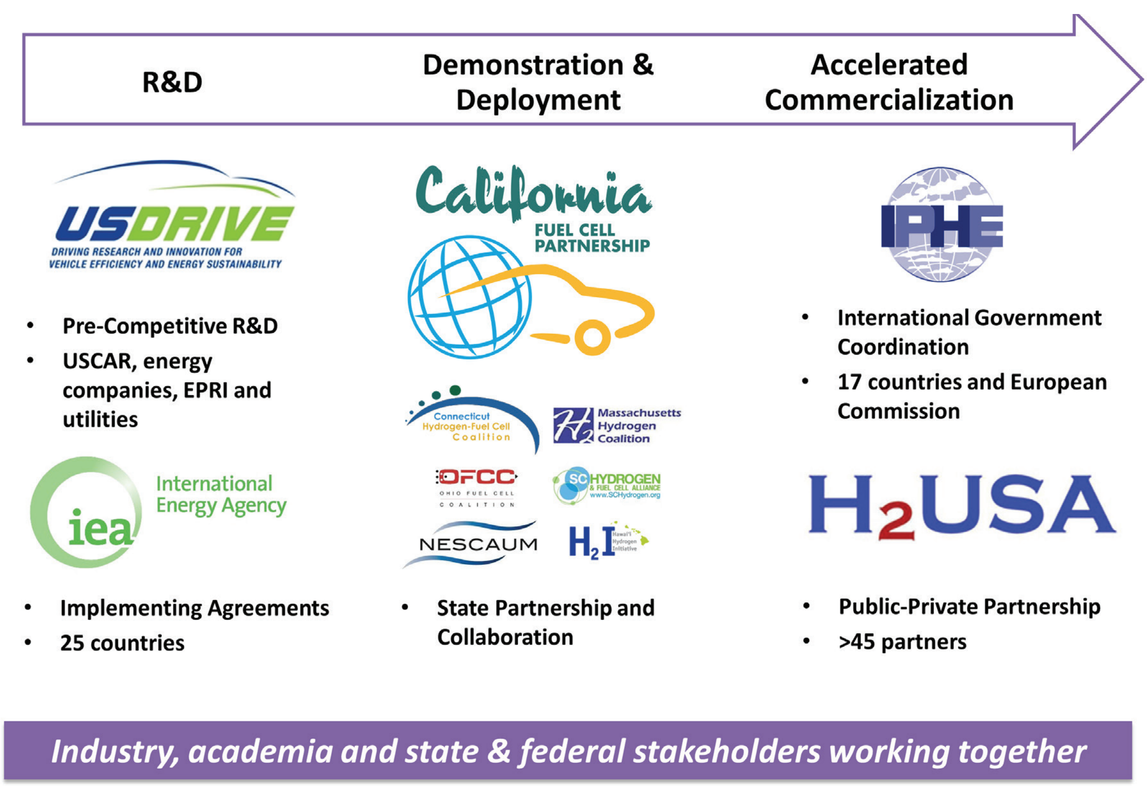
Public/Private Activities

While fuel cells are becoming competitive in some markets, the range of these markets can be greatly expanded with improvements in durability and performance and reductions in manufacturing cost, as well as advances in technologies for producing, delivering, and storing hydrogen. Successful entry into new markets, especially transportation, will also require overcoming certain institutional and economic barriers, such as the need for science-based codes and standards, the lack of public awareness and understanding of the technologies, and the high initial costs and lack of a supply base that many new technologies face in their critical early stages. Therefore, there is a clear need for government support in areas of hydrogen system development: (1) to ensure that the near term infrastructure, safety and public education issues vital to early-market roll outs are being addressed; and (2) to ensure that the longer-term, higher-risk RD&D vital to improved performance and lower cost is adequately sustained. With associated risks at this early stage in hydrogen fuel cell markets, industry is unlikely to commit all the needed resources.

To help identify government's most effective role in the support of hydrogen RD&D, the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) ,which was established under Section 807 of the Energy Policy Act of 2005 to provide technical and programmatic advice to the Energy Secretary on DOE's hydrogen research, development, and demonstration efforts, formed the Hydrogen Production Expert Panel (HPEP) Subcommittee in 2012. The HTAC Subcommittee Panel, comprised of experts from industry, academia, and national laboratories, was charged with providing recommendations to enable the widespread production of affordable, low-carbon hydrogen. Their key recommendations for the role of government in hydrogen-related technology development included: (1) providing incentives to accelerate the production of hydrogen for transportation applications with a particular focus on the steam reforming of natural gas, leveraging this abundant and low-cost domestic resource; (2) considering significant investments in hydrogen production and storage analyses and demonstrations; (3) developing a cohesive plan for all pertinent research and development programs to provide consistent and long-term guidance; and (4) establishing public-private partnerships and/or clusters to create well-defined plans for infrastructure roll-out, establishing appropriate incentives, and promoting uniform codes, standards, and safety regulations.

Consistent with and in response to the HTAC-HPEP recommendations, and driven by the need for continued efforts to support the growth of emerging hydrogen and fuel cell technologies and markets, the US DOE's Fuel Cell Technologies Office (FCTO) sponsors applied research programs in hydrogen production, delivery, storage, and utilization, and engages in numerous collaborative frameworks and public-private partnerships. Several of the most important collaborations are included in Figure 7.D.14. FCTO and the research priorities in its "Hydrogen Production and Delivery Program" are described in the following sections (note that research priorities for hydrogen storage and utilization are described separately in a Technology Assessment for QTR Chapter 8).

Figure 7.D.14 Multiple collaborations and partnerships have emerged in support of the RD&D of hydrogen and fuel cell technologies.

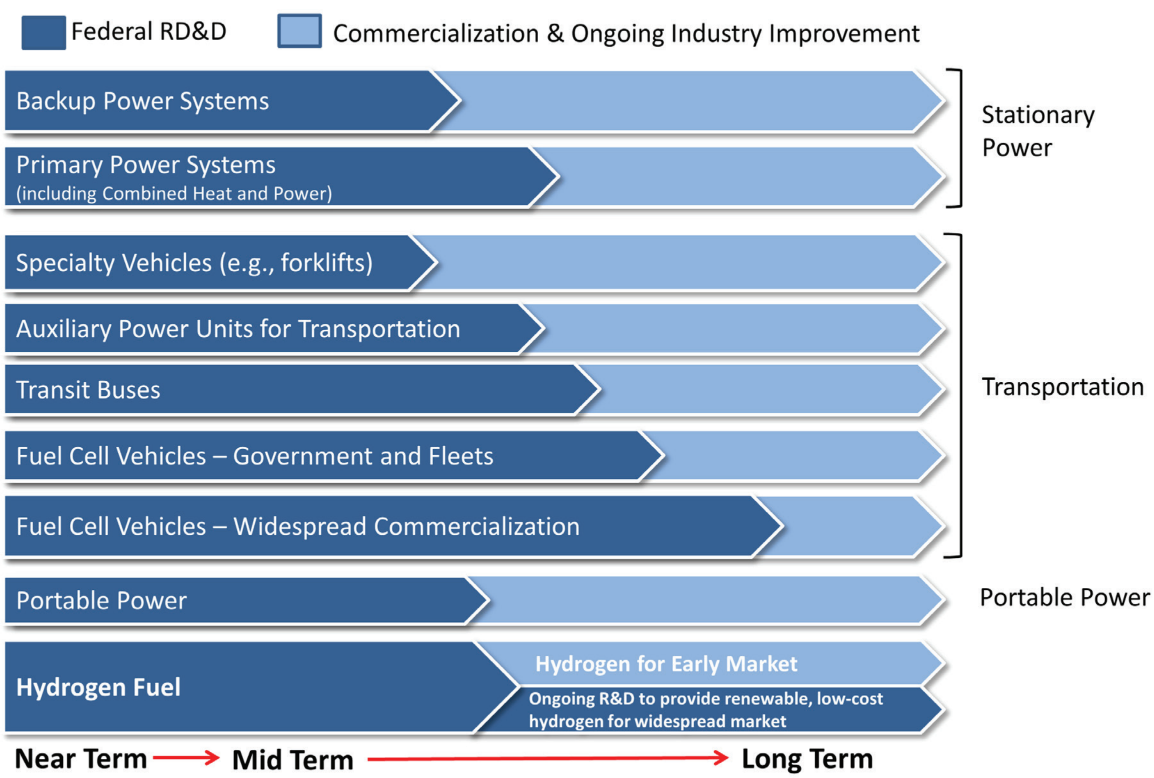


Fuel Cell Technologies Office

As part of the Transportation Sector of the Office of Energy Efficiency and Renewable Energy, DOE's Fuel Cell Technologies Office (FCTO) is tasked with supporting the national goals to decrease net oil imports by 50% by 2020, and to reduce greenhouse gas emissions by 17% by 2020 and by more than 80% by 2050. Hydrogen and fuel cell technologies have the potential to be a major player in meeting these goals. When hydrogen is generated from renewable feedstock, FCEVs have potential for over 90% lower CO_2e emissions than conventional IC engines. However, critical barriers must be addressed for the widespread commercialization of hydrogen and fuel cell technologies that would enable such reductions in GHG emissions and help to reduce dependency on foreign oil.

The mission of the FCTO, as established by Congressional directive, is to enable the research, development, and demonstration of hydrogen and fuel cell technologies and thereby enable their widespread commercialization. Federal RD&D thrusts are shown below in Figure 7.D.15 in relation to ongoing industry commercialization efforts.

Figure 7.D.15 Federal Role in Fuel Cell and Hydrogen RD&D – Pursuing Advances in Hydrogen and Fuel Cell Technologies in the Early Stages of Development for a Variety of Applications[56]



FCTO strategies and programmatic decisions are informed by rigorous techno-economic analysis over the entire portfolio of hydrogen and fuel cell technologies, with assumptions and inputs vetted through extensive stakeholder review. The FCTO sub-programs listed below support RD&D to address the key barriers identified through the stakeholder engagement process:

- The Production and Delivery sub-program supports RD&D to enable low-cost production of hydrogen from renewable resources, along with low-cost, reliable delivery and dispensing to vehicles.
- The Fuel Cells and Storage sub-programs focus on enabling low-cost fuel cells and on-board hydrogen storage that are safe and meet customers' driving range expectations.
- The Manufacturing sub-program ensures that lab scale innovations can be generated at industrial scales cost-effectively.
- The Safety, Codes, and Standards sub-program generates scientific bases that enable the development of codes and standards for hydrogen fuel cells; these bases include the regular publication of technical references and quantitative models, along with engagement with the codes and standards community.
- The Technology Validation and Market Transformation sub-programs address barriers to market acceptance of fuel cell technologies by demonstrating their performance in real-world environments; with insights gained during such work used to guide future RD&D.
- The Systems Analysis sub-program studies the economic and environmental impacts of fuel cell pathways from cradle-to-grave to identify barriers and thereby guide future RD&D.

Additional efforts at FCTO focus on outreach to address gaps in public knowledge and awareness of hydrogen and fuel cell technologies. Integrating education and public outreach in the transition from hydrogen and fuel cell RD&D to deployment is needed to transform the marketplace and ultimately lead to long-term market adoption and acceptance.

Additional References

The following list includes key program plans from the U.S. Department of Energy's Fuel Cell Technologies Office, as well as some of the important peer-reviewed technology reports referenced in this Technology Assessment that have informed P&D strategies and priorities. These provide much more detail on RD&D opportunities than could be provided here:

- U.S. Department of Energy, Fuel Cell Technologies Office, Multi-Year Research, Development, and Demonstration Plan, 2012, http://energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22
- U.S. Department of Energy, Hydrogen and Fuel Cells Program Plan, 2011, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/program_plan2011.pdf
- Hydrogen Pathways: Updated Cost, Well-to-Wheels Energy Use and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios (2013) - http://www.nrel.gov/docs/fy14osti/60528.pdf
- Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs (2014) - http://www.hydrogen.energy.gov/pdfs/58564.pdf
- Report of the Hydrogen Production Expert Panel: A Subcommittee of the Hydrogen & Fuel Cell Technical Advisory Committee (2013) - http://www.hydrogen.energy.gov/pdfs/hpep_report_2013.pdf
- Cost of Ownership and Well-to-Wheels Carbon Emissions/Oil Use of Alternative Fuels and Advanced Light-duty Vehicle Technologies – Energy for Sustainable Development 17 (2013) 626-641 - http://www.sciencedirect.com/science/journal/09730826/17

A number of key FCTO Peer-Reviewed Technology Records[57] are referenced in this Technology Assessment. Relevant Records include:

- Early Market Hydrogen Cost Target Calculation (#14013)
- Hydrogen Production Status 2006–2013 (#14005)
- Hydrogen Delivery Cost Projections—2013 (#13013)
- Hydrogen Production Cost Using Low-Cost Natural Gas (#12024)
- Hydrogen Threshold Cost Calculation (#11007)
- Hydrogen Production and Delivery Cost Apportionment (#12001)
- Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles (#13005)

Case Studies

PEM Electrolysis Case Study

Industry-vetted techno-economic case studies of H_2 production costs via polymer electrolyte membrane (PEM) electrolysis, completed in 2014, found that electricity cost, electrolyzer efficiency, and capital cost were the major cost contributors for the pathway.[58] These cases modeled representative PEM electrolyzer systems based on input from several key industry collaborators with commercial experience. Four cases were analyzed, comprising two technology years: Current (2013) and Future (2025); and two production capacities: Distributed Forecourt (1,500 kg/day) and Centralized (50,000 kg/day), and used H2A, a hydrogen production and delivery economic analysis model, which is available as a spreadsheet tool.[59] The process to evaluate the cases began with soliciting relevant, detailed information from the companies followed by synthesizing and amalgamating the data into base parameters for cases. The base parameters and sensitivity limits were vetted by the companies, and the data was then used to populate the four H2A cases, which were run to project the hydrogen price.

The results of the Distributed Forecourt and Centralized case studies, shown in Figure 7.D.16, indicated a current range of projected high volume untaxed cost of hydrogen production PEM electrolysis of ~$5/kg, with costs reduced to ~$4/kg in the future (2025) case. These results were documented in a DOE Hydrogen and Fuel Cells Program Record.[60] Improvements in efficiency and capital costs were assumed between the current and future costs, resulting in an overall reduction in production cost, despite a projected increase in the cost of electricity. Cost breakdowns for PEM electrolysis, excluding the feedstock costs, are shown in Figure 7.D.17. Further improvements in efficiency, decreases in capital costs, and significant reductions in electricity price will be needed to reach DOE long-term targets of <$2/kg H_2 produced. However, in regions where electricity prices are low, PEM electrolysis could be a viable regional solution for low-cost hydrogen production in the near term. High-temperature and high-pressure electrolysis presents another option for increasing performance and reducing cost by lowering forecourt compression costs.[61]

Table 7.D.16 PEM Electrolysis H_2 Production Cost Contributions (2007$/gge) for Four Cases[62]

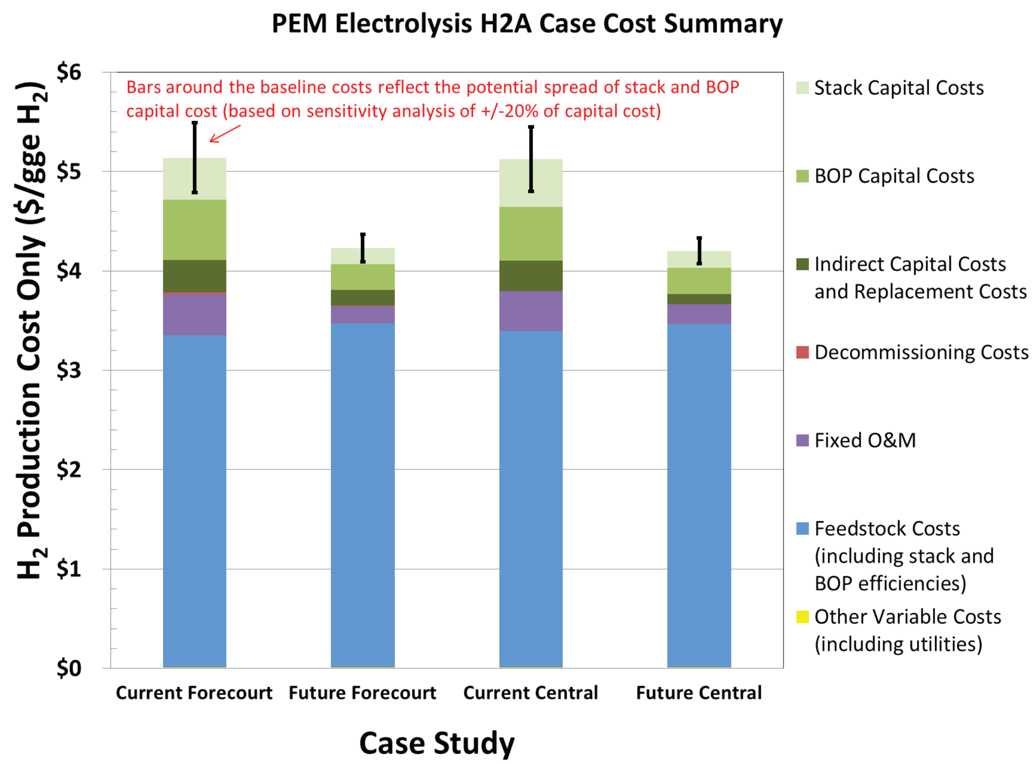
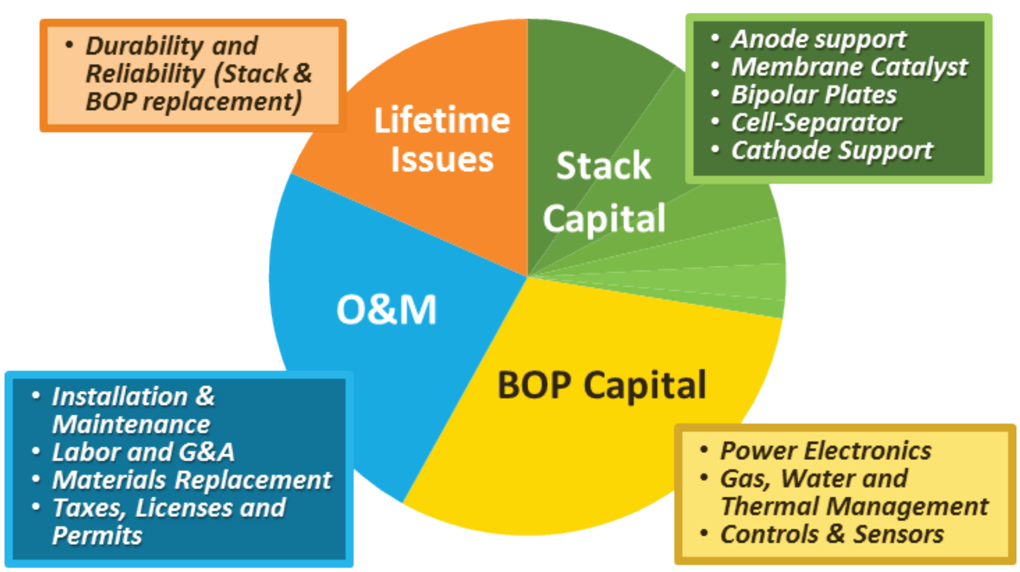


Table 7.D.17 Cost Breakdowns for PEM Electrolysis, excluding electricity feedstock costs[63]



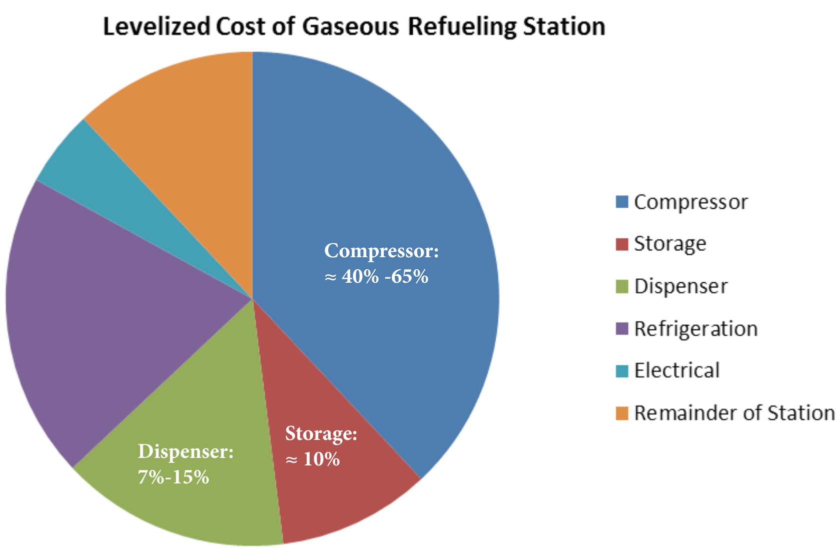
Notably, DOE-industry cost-shared electrolysis RD&D has resulted in a greater than 80% reduction in electrolyzer stack cost since 2001 through design optimization and manufacturing innovations that have reduced costs to less than $400/kW. Other improvements include a greater than 75% reduction in stack part count since 2006 with 50% reduction in manufacturing labor, and a greater than 40% reduction in cell stack cost for a large active area (>500 cm^2) electrolysis cell design compared to the 2011 baseline, primarily due to bipolar plate innovations.

Forecourt Costs Case Study

Techno-economic analysis has indicated that the refueling station makes a significant contribution to the levelized cost of hydrogen delivery and dispensing. Reliable performance of a refueling station is also critical to a positive customer experience with fuel cell electric vehicles. The primary contributors to a gaseous refueling station's cost are the compressor, storage, and dispenser (Figure 7.D.18).[64] Compressors today see excessive downtime and maintenance requirements, insufficient capacities, and high capital costs. Research is therefore focused on novel compression technologies and improvement in common points of failure (such as seals). Conventional storage vessels face risks of hydrogen embrittlement, high capital cost, and significant setback distances. Research today is focused on developing high-strength storage vessels. Focus areas include integration of steel with external layers to design novel composites, and design of vessels that can be stored underground. Dispenser units are challenged by insufficient reliability and high capital costs. Research is focused on characterizing the performance of hoses in realistic fueling conditions during accelerated life testing. Additional research will also focus on improving the reliability of communications with vehicles to ensure complete fills.

The primary cost driver for liquid stations is the high-pressure pump. While reductions in pump cost would improve the economics of these stations, the stations are unlikely to be economical until their utilization rates also improve. Liquid stations today lose significant volumes of hydrogen through vaporization because the stations are under-utilized.

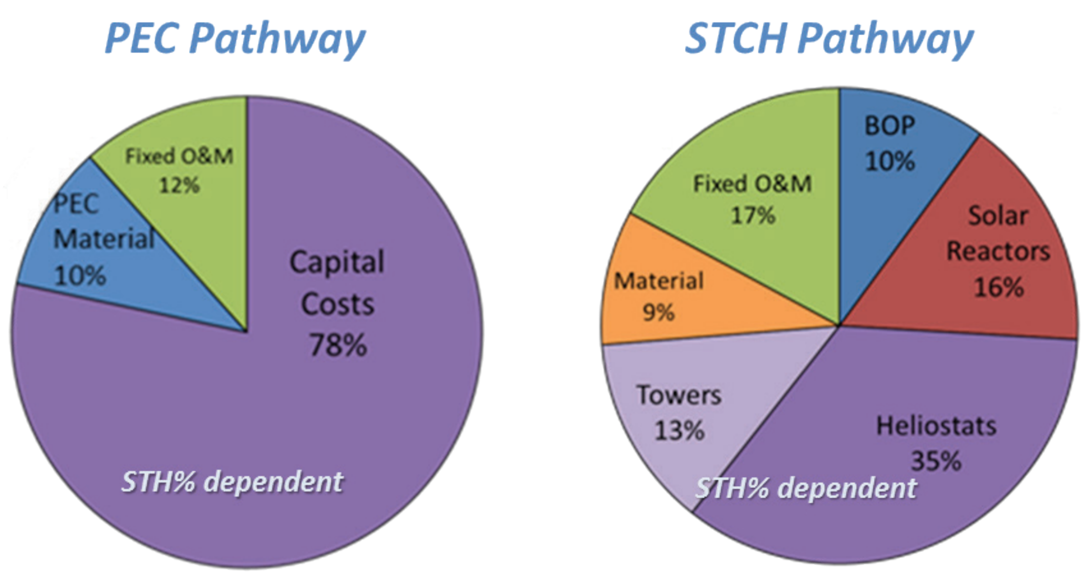
Table 7.D.18 Contributions to Levelized Costs of Gaseous Hydrogen Refueling Stations[65]



Emerging Hydrogen Production Technologies

While some technologies for producing hydrogen are mature, hydrogen production from low- or zero-carbon resources is currently not economically competitive. A portfolio of near- and longer-term technology options will be needed to address the cost challenges and enable market acceptance. Emerging solar-hydrogen production pathways hold promise for sustainable, large-scale production of hydrogen from renewable sources, but the costs of all these pathways need to be significantly reduced. Boundary techno-economic studies have been performed to identify the key cost drivers,[66] shown in Figure 7.D.19, for the photoelectrochemical (PEC) and solar thermochemical (STCH) pathways, clearly indicating that performance improvements and materials cost reductions are needed to achieve cost-competitiveness in these pathways. PEC production requires RD&D to develop materials with the appropriate band gap to both absorb sunlight and electrolyze water in a single device, while the STCH production pathway requires identification and development of efficient and durable materials to design a cost-effective reactor system. To guide RD&D priorities, FCTO utilizes top-down and bottom-up techno-economic analyses to set technical and economic targets for key components in each of the emerging production pathways, with the goal of ultimately enabling hydrogen production at a cost of <$2.00/gge. Solar-to-hydrogen (STH) efficiency has been identified as a key cost driver, with analysis indicating that STH efficiencies >20% will be needed to reduce capital costs in both PEC and STCH pathways (including heliostat capital costs for STCH) in order to meet the hydrogen cost target.

Table 7.D.19 Contributions to Levelized Costs of Hydrogen Production by PEC and STCH Pathways[67]



Endnotes

1 For more information, see the "Hydrogen" chapter in the "NPC Future Transportation Fuels Study: Advancing Technology for America's Transportation Future (2012)" (http://www.npc.org/reports/FTF-report-080112/Chapter_15-Hydrogen.pdf); the NREL report "Hydrogen Pathways: Updated Cost, Well-to-Wheels Energy Use and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios (2013)" (http://www.nrel.gov/docs/fy14osti/60528.pdf); and the "Report of the Hydrogen Production Expert Panel: A Subcommittee of the Hydrogen & Fuel Cell Technical Advisory Committee (2013)", (http://www.hydrogen.energy.gov/pdfs/hpep_report_2013.pdf).

2 Public announcements by Hyundai, Toyota and others, with confirmation by the California Air Resources Board (in correspondence between Catherine Dunwoody and Tien Nguyen of the DOE Fuel Cell Technologies Office).

3 Assumes molten carbonate fuel cells and phosphoric acid fuel cells (PAFC) with 40-45% electrical efficiency. The GHG estimate includes the emissions associated with natural gas recovery, steam methane reforming to produce hydrogen, conditioning of the hydrogen for use in fuel cells, and the emissions associated with distributed energy production. The analysis was performed using GREET 1.8c, and is detailed in: www.hydrogen.energy.gov/pdfs/review10/an012_wang_2010_o_web.pdf

4 U.S. Department of Energy, Fuel Cell Technologies Office Program Record #13005 (revision #1), "Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles", http://www.hydrogen.energy.gov/pdfs/13005_well_to_wheels_ghg_oil_ldvs.pdf. The analysis included only the fuel cycle. It did not include the life-cycle effects of vehicle manufacturing and infrastructure construction/decommissioning. The range of emissions for FCEVs is based on a range of pathways for producing hydrogen, with hydrogen from distributed reforming of natural gas resulting in the most emissions, to hydrogen from biomass gasification resulting in the least.

5 L.L Gaines, et al., Argonne National Laboratory, October 2008, "Full Fuel-Cycle Comparison of Forklift Propulsion Systems", http://energy.gov/sites/prod/files/2014/03/f11/forklift_anl_esd.pdf. Result cited for battery-powered lift trucks assumes batteries are charged using electricity from conventional combustion-based generators, and that fuel cell powered lift trucks are powered by hydrogen generated from steam reforming of methane or from coke oven gas. The upstream emissions for hydrogen include those associated with the recovery, processing and transportation of the natural gas, hydrogen compression and delivery via pipeline.

6 U.S. Department of Energy, Fuel Cell Technologies Office, 2010 Annual Progress Report, Technology Validation: Fuel Cell Bus Evaluations, http://hydrogen.energy.gov/pdfs/progress10/viii_7_eudy.pdf. Figures based on evaluation of data collected in FY2010 from current-generation Fuel Cell Bus demonstrations at three transit agencies; fuel economy was compared on a per diesel gallon equivalent basis.

7 L.L. Gaines and C. Hartman, Center for Transportation Research, Argonne National Laboratory, November 2008, "Energy Use and Emissions Comparison of Idling Reduction Options for Heavy-Duty Diesel Trucks", http://trrjournalonline.trb.org/doi/10.3141/2123-02. Lacking validated experimental data at this time, it was assumed that fuel cell APUs would consume 0.2 gallon/hr, the same as the conventional APU in Gaines' study (current modeling suggests fuel cell APUs would consume even less). This would result in overall CO_2 emissions comparable to those of a diesel ICE APU. Actual CO_2 emissions by fuel cell APUs are likely to be lower, and improvements in the efficiency of diesel reformers and fuel cells will result in further reductions.

8 U.S. Department of Energy, Fuel Cell Technologies Office Program Record #13005 (revision #1), "Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles", http://www.hydrogen.energy.gov/pdfs/13005_well_to_wheels_ghg_oil_ldvs.pdf. The ranges of oil consumption reductions cited all assume that hydrogen from centralized biomass gasification is used; since this is the most petroleum-intensive pathway for hydrogen production, potential reductions from other pathways will be even greater. Analysis assumed average projected grid mix in 2030 for all electricity used.

9 The "efficiency" refers to the electricity generated by the fuel cell or internal combustion engine with respect to the lower heating value of the hydrogen or gasoline being consumed. Source: www.hydrogen.energy.gov/pdfs/doe_fuelcell_factsheet.pdf

10 National Academies report, 2008, "Transitions to Alternative Transportation Technologies—A Focus on Hydrogen", http://www.nap.edu/openbook.php?record_id=12222.

11 California Fuel Cell Partnership, 2014, "Air, Climate, Energy, Water, and Security", http://cafcp.org/sites/files/W2W-2014_Final.pdf

12 Agency for Natural Resources and Energy, June 2014, "Summary of the Strategic Road Map for Hydrogen and Fuel Cells", http://www.meti.go.jp/english/press/2014/pdf/0624_04a.pdf

13 "A portfolio of power-trains for Europe: a fact-based analysis", http://www.fch.europa.eu/sites/default/files/Power_trains_for_Europe_0.pdf

14 U.S. Department of Energy, Fuel Cell Technologies Office Program Record #13005 (revision #1), "Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles", http://www.hydrogen.energy.gov/pdfs/13005_well_to_wheels_ghg_oil_ldvs.pdf.

15 Adapted from National Academies report, 2008, "Transitions to Alternative Transportation Technologies—A Focus on Hydrogen", http://www.nap.edu/openbook.php?record_id=12222.

16 U.S. Department of Energy, Fuel Cell Technologies Office Program Record #12014, "Current U.S. Hydrogen Production", http://www.hydrogen.energy.gov/pdfs/12014_current_us_hydrogen_production.pdf

17 Graphic prepared by DOE based on data found in: "Global Hydrogen Generation Market by Merchant & Captive Type, Distributed & Centralized Generation, Application & Technology – Trends & Forecasts (2011-2016)", www.marketsandmarkets.com

18 National Petroleum Council, August 2012, "NPC Future Transportation Fuels Study: Advancing Technology for America's Transportation Future", Chapter 15: Hydrogen, http://www.npc.org/reports/FTF-report-080112/Chapter_15-Hydrogen.pdf. From the "Hydrogen" chapter in the NPC Report: "Large hydrogen production facilities (>18,000 kg/day) exist in nearly every state, supplying approximately 1,000 locations with bulk hydrogen."

[19] Estimated emissions from hydrogen production in China exceed 150 million tons per year.

[20] Reproduced with permission from National Petroleum Council, August 2012, "NPC Future Transportation Fuels Study: Advancing Technology for America's Transportation Future", Chapter 15: Hydrogen, http://www.npc.org/FTF-80112.html. From the "Hydrogen" chapter in the NPC Report: "Large hydrogen production facilities (>18,000 kg/day) exist in nearly every state, supplying approximately 1,000 locations with bulk hydrogen."

[21] To achieve a range comparable to commercial gasoline vehicles, FCEV tanks are filled to a pressure of 700 bar to provide 5.6 kg of hydrogen within the volume available. When range is not critical to the application, or larger volumes are available (such as onboard a bus), 350-bar storage systems may be used. Lower pressure systems offer improved reliability and cost benefits over the high-pressure systems. Note that 1 kg of hydrogen has approximately the same energy as 1 gallon of gasoline, i.e., 1 gasoline gallon equivalent (gge). See: Fuel Cell Technologies Office Program Record #13010, "Onboard Type IV Compressed Hydrogen Storage Systems – Current Performance and Cost", http://www.hydrogen.energy.gov/pdfs/13010_onboard_storage_performance_cost.pdf

[22] E. Miller, U.S. Department of Energy Hydrogen and Fuel Cells Program Annual Merit Review, 2015, "Hydrogen Production & Delivery Program Plenary Presentation", http://www.hydrogen.energy.gov/pdfs/review15/pd000_miller_2015_o.pdf

[23] U.S. Department of Energy, Fuel Cell Technologies Office Program Record #11007, "Hydrogen Threshold Cost Calculation ", http://www.hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.pdf , including a base case analysis using an untaxed gasoline price of $3.13/gallon.

[24] Cost targets include the onboard efficiency benefits of FCEVs, as described in the Fuel Cell Technologies Office Program Record #13006, "Life-Cycle Costs of Mid-size Light-Duty Vehicles", http://www.hydrogen.energy.gov/pdfs/13006_ldv_life_cycle_costs.pdf

[25] U.S. Department of Energy, Fuel Cell Technologies Office, 2012. Program Record # 12001, "H_2 Production and Delivery Cost Apportionment," http://www.hydrogen.energy.gov/pdfs/12001_h2_pd_cost_apportionment.pdf

[26] For additional details, please see Fuel Cell Technologies Office Program Record #14013: http://www.hydrogen.energy.gov/pdfs/14013_hydrogen_early_market_cost_target.pdf

[27] U.S. Department of Energy, Fuel Cell Technologies Office, 2012. Program Record # 12024, "Hydrogen Production Cost Using Low-Cost Natural Gas", http://www.hydrogen.energy.gov/pdfs/12024_h2_production_cost_natural_gas.pdf

[28] For more information on CHHP, see Chapter 4 of the QTR, "Advancing Clean Energy Power Technologies".

[29] For more information on hydrogen production pathways, see the USDrive Hydrogen Production Technical Team Roadmap (2013) (http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/hptt_roadmap_june2013.pdf); and the 2013 NREL "Hydrogen Pathways Report" (http://www.nrel.gov/docs/fy14osti/60528.pdf).

[30] For more information on gasification, see the Biofuels sections in this chapter, and Chapter 6 on Power Generation.

[31] U.S. Department of Energy, National Renewable Energy Laboratory, January 2013. Biogas and Fuel Cells Workshop Summary Report, http://energy.gov/eere/fuelcells/downloads/biogas-and-fuel-cells-workshop-summary-report-proceedings-biogas-and-fuel

[32] U.S. Department of Energy, Fuel Cell Technologies Office, July 2014. 2014 Electrolytic Hydrogen Production Summary Report, http://energy.gov/sites/prod/files/2014/08/f18/fcto_2014_electrolytic_hydrogen_production_workshop_summary_report.pdf

[33] For more information, see: http://energy.gov/eere/fuelcells/photoelectrochemical-working-group

[34] U.S. Department of Energy, Fuel Cell Technologies Office, November 2013. 2013 Biological Hydrogen Workshop Summary Report, http://energy.gov/eere/fuelcells/downloads/2013-biological-hydrogen-production-workshop-summary-report

[35] Analysis using the H2A Hydrogen Production Models (http://www.hydrogen.energy.gov/h2a_prod_studies.html), including high-volume production assumptions; Ranges reflect variability in major feedstock pricing as well as a bounded range for capital cost estimates, as described in the Fuel Cell Technologies Office Program Record #14005, "Hydrogen Production Status 2006-2013", http://www.hydrogen.energy.gov/pdfs/14005_hydrogen_production_status_2006-2013.pdf

[36] The H2A Hydrogen Production models are publicly available, along with supporting documentation describing their structures and assumptions: http://www.hydrogen.energy.gov/h2a_production.html

[37] The pathway-dependent feedstock price ranges used in the analysis of the Low- and High-cost projections are consistent with documented reports relevant to each pathway major feedstock. The Low-cost projections use the low-end feedstock price with the baseline capital cost estimate in the H2A analysis, while the High-cost projections use the high-end feedstock price and the escalated capital cost including a pathway-specific uncertainty factor. Based on industry feedback, capital cost uncertainties are typically modeled as a 30% escalation factor over the baseline capital cost estimate for most pathways, though a higher escalation factor was used for biomass gasification based on the results of an independent review.

[38] Fuel Cell Technologies Office Program Record #14005, 2014 http://www.hydrogen.energy.gov/pdfs/14005_hydrogen_production_status_2006-2013.pdf

[39] See the 2013 NREL "Hydrogen Pathways Report", http://www.nrel.gov/docs/fy14osti/60528.pdf

[40] International Atomic Energy Agency. "Nuclear Hydrogen Production Technology", http://www.iaea.org/About/Policy/GC/GC57/GC57InfDocuments/English/gc57inf-2-att1_en.pdf

[41] The amount of hydrogen fuel required in the near term can be extrapolated from the California Air Resources Board's Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development (June 2014). For additional information, see NREL's 2013 resource assessment for hydrogen production (http://www.nrel.gov/docs/fy13osti/55626.pdf), the National Hydrogen Association's 2010 market report (www.ttcorp.com/pdf/marketReport.pdf), and/or the IEA's North American Roadmap workshop (http://www.iea.org/media/workshops/2014/hydrogenroadmap/7doeericmiller.pdf). Additional public hydrogen fueling stations will, however, be required to meet vehicle demand.

[42] Reproduced with permission from the National Petroleum Council, August 2012, "NPC Future Transportation Fuels Study: Advancing Technology for America's Transportation Future", Chapter 15: Hydrogen, http://www.npc.org/reports/FTF-report-080112/Chapter_15-Hydrogen.pd. From the "Hydrogen" chapter in the NPC Report: "Large hydrogen production facilities (>18,000 kg/day) exist in nearly every state, supplying approximately 1,000 locations with bulk hydrogen."

[43] See the 2014 SNL report "Geologic storage of hydrogen: Scaling up to meet city transportation demands", http://www.sciencedirect.com/science/article/pii/S0360319914021223

[44] Fuel economies for all fuel/vehicle systems were determined using ANL's Autonomie modeling system, see: http://www.autonomie.net

[45] U.S. Department of Energy, Fuel Cell Technologies Office Program Record # 13010, July 2013, "On-Board Type IV Compressed Hydrogen Storage Systems – Current Performance and Cost", http://www.hydrogen.energy.gov/pdfs/13010_onboard_storage_performance_cost.pdf

[46] R. Watme, October 2010, Renewable Resources for Fuel Cells – Workshop, "Large Scale Hydrogen Storage in Salt Caverns", http://cafcp.org/sites/files/3_Watwe_LargeScaleHydrogenStorageCaverns.pdf

[47] Information throughout this paragraph is from DOT, industry sources, market research firms, and other sources (source: EERE Fuel Cell Technologies Office - Tien Nguyen)

[48] Adapted from U.S. Department of Energy, Fuel Cell Technologies Office Program Record # 13013, December 2013. http://www.hydrogen.energy.gov/pdfs/13013_h2_delivery_cost_central.pdf

[49] U.S. Department of Energy, Fuel Cell Technologies Office Program Record # 13013, December 2013. http://www.hydrogen.energy.gov/pdfs/13013_h2_delivery_cost_central.pdf

[50] Graphic was developed by DOE based on data found in the following sources: 1. NRC study Transitions to Alternative Transportation Technologies-A Focus on Hydrogen (http://www.nap.edu/openbook.php?record_id=12222); 2. NRC study Transitions to Alternative Transportation Technologies-Plug-In Hybrid Electric Vehicles (http://www.nap.edu/catalog/12826/transitions-to-alternative-transportation-technologies--plug-in-hybrid-electric-vehicles); and 3. EU Mobility study A Portfolio of Power-Trains for Europe: A Fact-Based Analysis (http://www.eesi.org/files/europe_vehicles.pdf);

[51] Reproduced with permission from the National Petroleum Council, August 2012, "NPC Future Transportation Fuels Study: Advancing Technology for America's Transportation Future", Chapter 15: Hydrogen, http://www.npc.org/reports/FTF-report-080112/Chapter_15-Hydrogen.pdf. From the "Hydrogen" chapter in the NPC Report: "Large hydrogen production facilities (>18,000 kg/day) exist in nearly every state, supplying approximately 1,000 locations with bulk hydrogen."

[52] E. Miller, U.S. Department of Energy Hydrogen and Fuel Cells Program Annual Merit Review, 2015, "Hydrogen Production & Delivery Program Plenary Presentation", http://www.hydrogen.energy.gov/pdfs/review15/pd000_miller_2015_o.pdf

[53] For more information on JCAP, please visit http://solarfuelshub.org/about/

[54] U.S. Department of Energy, Fuel Cell Technologies Office, 2012. Multi-Year Research, Development, and Demonstration Plan, 2012 update, http://energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

[55] See the 2015 Delivery Section, http://energy.gov/sites/prod/files/2015/06/f22/fcto_myrdd_delivery.pdf

[56] U.S. Department of Energy, Fuel Cell Technologies Office, Multi-Year Research, Development, and Demonstration Plan, 2012, http://energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

[57] Fuel Cell Technology Office Program Records are available at http://www.hydrogen.energy.gov/program_records.html

[58] Case studies available at http://www.hydrogen.energy.gov/h2a_prod_studies.html. Supporting documents available at http://www.hydrogen.energy.gov/h2a_production_documentation.html.

[59] The H2A Hydrogen Production models and case studies, including the studies of PEM Electrolysis, are publicly available, along with supporting documentation describing their structures and assumptions: http://www.hydrogen.energy.gov/h2a_production.html

[60] DOE Hydrogen and Fuel Cells Program Record #14004, Hydrogen Cost from PEM Electrolysis available at http://hydrogen.energy.gov/pdfs/14004_h2_production_cost_pem_electrolysis.pdf

[61] C. Mittelsteadt, et al., Giner, Inc., June 2015, 2015, Annual Merit Review, "High Temperature, High Pressure Electrolysis", http://www.hydrogen.energy.gov/pdfs/review15/pd117_mittelsteadt_2015_o.pdf

[62] U.S. Department of Energy, Fuel Cell Technologies Office Program Record #14004, July 2014, http://www.hydrogen.energy.gov/pdfs/14004_h2_production_cost_pem_electrolysis.pdf

[63] U.S. Department of Energy, Fuel Cell Technologies Office Program Record #14004, July 2014, http://www.hydrogen.energy.gov/pdfs/14004_h2_production_cost_pem_electrolysis.pdf

[64] For additional information on compression, storage, and dispensing research areas, see presentation slides from the 2nd International Hydrogen Infrastructure Challenges Workshop (http://energy.gov/sites/prod/files/2015/03/f20/fcto_webinarslides_2nd_international_h2_infrastructure_

challenges_031015.pdf) or NREL's Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs report (http://www.nrel.gov/docs/fy14osti/58564.pdf)

[65] G. Parks, R. Boyd, J. Cornish, and R. Remick, U.S. National Renewable Energy Laboratory, U.S. Department of Energy Hydrogen and Fuel Cells Program, 2014, "Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs", http://www.nrel.gov/docs/fy14osti/58564.pdf

[66] Techno-economic case studies for hydrogen production pathways, including the emerging pathways can be found at http://www.hydrogen.energy.gov/h2a_prod_studies.html

[67] Graphics were developed by DOE based on data found in the techno-economic case studies found at http://www.hydrogen.energy.gov/h2a_prod_studies.html

Acronyms

$/gge	Dollars per gallon of gasoline equivalent
$/kW	Dollars per kilowatt
$/kg	Dollars per kilogram
APU	Auxiliary power unit
BEV	Battery electric vehicle
Btu	British thermal unit
CCUS	Carbon capture utilization and storage
CHHP	Combined heat, hydrogen and power
CHP	Combined heat and power
CO_2e	Co_2-equivalent global warming potential
CSD	Compression, storage and dispensing
DOE	U.S. Department of Energy
FCEV	Fuel cell electric vehicle
FCTO	U.S. Department of Energy Fuel Cell Technologies Office
FRP	Fiber-reinforced polymer
gge	Gallon of gasoline equivalent
GHG	Greenhouse gas
HDSAM	Hydrogen Delivery Scenario Analysis Model
HPEP	Hydrogen Production Expert Panel Subcommittee
HTAC	Hydrogen and Fuel Cell Technical Advisory Committee
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
JCAP	Joint Center for Artificial Photosynthesis
kg	Kilogram

kW	Kilowatt
mpgge	Miles per gallon of gasoline equivalent
MW	Megawatt
NOx	Nitrogen oxides
NPC	National Petroleum Council
O&M	Operations and maintenance
P&D	Production and delivery
PEC	Photoelectrochemical
PEM	Polymer electrolyte membrane
PM	Particulate matter
QTR	Quadrennial Technology Review
Quad	Quadrillion British thermal units
RD&D	Research, development, and demonstration
SMR	Steam methane reforming
STCH	Solar thermochemical
STH	Solar-to-hydrogen efficiency
W	Watt

Glossary

Auxiliary power unit	A device on a vehicle (truck, airplane, etc.) that provides power to start engines, run support equipment, or serve as backup power.
Biogenic	Produced by biological processes of living organisms.
British thermal unit	The quantity of heat required to raise the temperature of one pound of liquid water by one degree Fahrenheit.
Carbon capture and storage	The process of capturing waste carbon dioxide from a source, such as fossil fuel power plants, and storing it where it will not enter the atmosphere.
Catalyst	A molecule or material that accelerates the rate of a chemical reaction without undergoing a permanent change itself. Catalysts exist either in the same phase (homogeneous) or a different phase (heterogeneous) relative to the reactant.

Co_2 equivalent	A measure used to compare the emissions from various greenhouse gases based upon their global warming potential in units that are equivalent to that of carbon dioxide (CO_2).
Combined heat and power	A power generating unit designed to produce both electricity and heat from a fuel source, increasing system efficiency.
Compressed natural gas	Natural gas compressed to a pressure at or above 200–248 bar (i.e., 2,900–3,600 pounds per square inch) and stored in high-pressure containers. It is used as a fuel for natural gas-powered vehicles.
Electrolysis	A process that uses electricity to split water into hydrogen and oxygen.
Fuel cell	A device that produces electricity through an electrochemical process, usually from hydrogen or from methane, with oxygen, etc.
Hybrid electric vehicles	A vehicle in which a power plant (e.g., internal combustion engine or fuel cell) powers an electric propulsion system, either exclusively or in parallel with a mechanical drivetrain.
Kilowatt	One thousand watts (also kW)
Life cycle	All stages of a product's life, from raw materials extraction to manufacturing, use, and final disposal or recycling.
Megawatt	One million watts of electricity (also MW)
Molten carbonate fuel cell	A type of fuel cell that contains a molten carbonate electrolyte. Carbonate ions (CO3-2) are transported from the cathode to the anode. Operating temperatures are typically near 650°C.
Phosphoric acid fuel cell	A type of fuel cell in which the electrolyte consists of concentrated phosphoric acid (H3PO4). Protons (H+) are transported from the anode to the cathode. The operating temperature range is generally 160°C–220°C.
Photoelectrochemical water splitting	A process where hydrogen is produced from water using sunlight and specialized semiconductors called photoelectrochemical materials, which use light energy to directly dissociate water molecules into hydrogen and oxygen.
Polymer electrolyte membrane fuel cell	A type of acid-based fuel cell in which the transport of protons (H+) from the anode to the cathode is through a solid, aqueous membrane impregnated with an appropriate acid. The electrolyte is a called a polymer electrolyte membrane. The fuel cells typically run at low temperatures (<100°C).
Quads	Quadrillion British thermal units
Solar thermochemical hydrogen	A thermochemical process for extracting hydrogen from water using concentrated sunlight as the heat source.

Solid oxide fuel cell	A type of fuel cell in which the electrolyte is a solid, nonporous metal oxide with temperatures of operation typically 800°C–1000°C.
Steam methane reforming	A method for producing hydrogen, carbon monoxide, or other useful products by reacting high-temperature steam with natural gas.
Thermochemical	The chemistry of heat and heat-assisted chemical reactions.
Watt	The Système International (SI) unit of power, defined as one joule per second.