CHAPTER FIFTEEN

HYDROGEN

EXECUTIVE SUMMARY

Fuel cell electric vehicles (FCEVs) and the use of hydrogen as a transportation fuel have been pursued by government, academia, and industry for over a generation because of their potential to improve energy security, reduce greenhouse gas (GHG) emissions, and spur economic growth. Hydrogen-fueled FCEVs are a promising technology option for the U.S. light-duty (LD) vehicle fleet for the following reasons:

- FCEV driving performance is comparable to conventional vehicles.
- Hydrogen is currently produced primarily from domestic natural gas using mature technology.
- Hydrogen is an energy carrier and can be produced from a diverse set of energy resources.
- FCEVs significantly reduce GHG emissions.
- Cost of driving on a per-mile basis can be comparable to that of conventional vehicles.

Major auto manufacturers, fuel and industrial gas providers, and governments have made material investments in this area. These investments have resulted in significant progress towards the commercial viability of FCEVs and hydrogen as a consumer fuel; however, vehicle and infrastructure challenges remain. The status of FCEVs and infrastructure is summarized in Table 15-1.

The key findings of this analysis are:

Pathway Benefits

- Compared to today's conventional LD vehicles, GHG emissions can be reduced ~50% on a well-to-wheels basis by the deployment of FCEVs operating on hydrogen produced from natural gas.
  - Further reduction is possible using lower carbon feedstocks or carbon capture and sequestration.
  - Current FCEVs have two to three times the efficiency of comparable conventional vehicles on a tank-to-wheels basis.
- FCEV technology is applicable across all LD vehicle segments.
  - Operating performance (acceleration, range, etc.) of FCEVs is comparable to that of conventional vehicles.
- Hydrogen production via steam methane reforming of domestic natural gas is currently the most competitive process for hydrogen production in the United States and is expected to be the major source of hydrogen production near- to mid-term.
  - Steam methane reforming is the baseline against which other hydrogen production technologies will compete.
  - Domestic natural gas resources can support hydrogen production for a material segment of the transportation sector.
- As compared to other fuels, hydrogen dispensed fuel costs are less sensitive to changes in feedstock commodity costs because capital infrastructure costs and taxes make up a greater proportion of the final fuel cost.

Price and Market Considerations

- Upon commercial introduction, FCEVs are expected to cost ~1.4 times more than a comparable gasoline internal combustion engine (ICE)

Fuel Cell Electric Vehicle Status		
Technology Benefits	**Recent Achievements**	**Near-Term Focus Areas**
☑ Vehicle Efficiency	☑ Acceleration (Stack Power)	■ Durability & Degradation
☑ Zero Tailpipe Emissions	☑ Refueling Time	■ Cost
☑ Low Noise	☑ Interior Space	
☑ Low Vibration	☑ Sustained High Power	
	☑ Freeze start	
	☑ Driving Range	
Hydrogen Fueling Infrastructure Status		
Technology Benefits	**Recent Achievements**	**Near-Term Focus Areas**
☑ Domestic Feedstock	☑ Distribution	■ Fuel Cost
☑ Large Scale Production	☑ Dispensing	■ Fueling Network
☑ Low GHG Emissions		■ On-site Compression
		■ On-site Storage
□ Better than conventional	□ Parity with conventional	■ Not yet at parity with conventional

Table 15-1. *Technology Achievements Summary*

vehicle; these prices may come down over time and be cost competitive with other LD vehicle options. Ongoing effort will be needed to lower the cost of subsequent generations of vehicles.

- On a cost-per-mile basis, hydrogen fuel for an FCEV can be comparable to gasoline for a conventional vehicle.
  - The modeled price of dispensed hydrogen (fully taxed) is \$9–\$12 per kilogram (kg) in the near term and \$6–\$7 per kg in the long term.
  - One kg of hydrogen in an FCEV is equivalent to two to three gallons of gasoline in a conventional vehicle on a miles-driven basis.
- Unsubsidized economic viability can only be reached when sufficient FCEVs are deployed within a geographic region.
- Leveraging of existing hydrogen capacity at centralized production facilities is the most economical option for early fueling infrastructure deployment.
  - Additional hydrogen production capacity will be needed upon mass commercialization of FCEVs.
- Many automotive manufacturers (General Motors, Ford, Toyota, Honda, Nissan, Daimler, and Hyundai) are planning commercial introduction of FCEVs by 2015 in targeted geographies (e.g., United States, Germany, Japan, and South Korea).

Ongoing Challenges

- Fuel cell durability (life) improvements by a factor of two are needed to be comparable to today's conventional vehicles, based on publicly available fleet demonstration data.
  - Commercial durability targets have been demonstrated in laboratory environments and these improvements will be incorporated into next generation vehicles.
- An early market value proposition for FCEVs is needed because the first generations of commercial FCEVs are not expected to be cost competitive with conventional vehicles.
- As is the case for most fueling infrastructure business models, the economic viability for hydrogen fueling infrastructure is significantly dependent

on scale of fueling capacity and utilization of installed fueling capacity (i.e., leveraging economies of scale).

- Technology advancements in compression and on-site storage are needed and can provide reductions in capital costs, operating costs, and land requirements. They can also improve station reliability.

Significant and sustained investments by industry and government are required for this pathway to achieve commercial success.

INTRODUCTION

This chapter begins with a summary of current global hydrogen activities and a high-level overview of the technologies and pathways through which hydrogen can be used as a fuel for transportation. These technologies and pathways are then prioritized to focus the discussion and analysis on areas with the potential to spur economic growth, reduce GHG emissions, and increase energy security. The high priority technologies and pathways are discussed in detail from both the vehicle and fuel supply perspectives to highlight the current status, challenges, and opportunities. Cost analyses are included to quantify early market transition challenges and long-term economic potential.

This chapter also provides a basis for the integrated analyses in Part 1 of this report. FCEV and hydrogen fuel characteristics are quantified using the findings in this chapter and are then competed with other propulsion options using a market model. The contribution of FCEVs and hydrogen fuel to GHG emissions reduction, petroleum displacement, fuel feedstock diversity, and economics is then quantified across a range of cases.

Key Facts

- A fuel cell:
  - Is an electrochemical device that converts chemical energy from a fuel to electric energy (no combustion)—a discussion on how a fuel cell works is provided in Appendix 15A at the end of this chapter.
  - Is more than twice as efficient as a gasoline (internal combustion) engine.
  - Can be used in an electric vehicle (FCEV) where hydrogen fuel is supplied to a fuel cell stack to produce electricity and water (zero tailpipe emissions).
- Hydrogen:
  - Is one of the most abundant elements on earth; however, it is rarely found in its pure form (<1%) and is commonly combined with other elements such as carbon and oxygen and must be isolated for use as a fuel.
  - Is typically measured by weight (kilograms) where 1 kg of hydrogen has approximately the same energy content as 1 gallon of gasoline.
  - Is a gas except at extremely cold temperatures (-253°C).
  - Is colorless, odorless, tasteless, nontoxic.

CURRENT HYDROGEN ACTIVITIES

International Hydrogen Initiatives

The United States has historically been a global leader in technology development. This has also been the case for hydrogen and fuel cell technologies and their application in the transportation sector. More recently, other countries have recognized the promise of these technologies and have made strategic investments and commitments to support the development and deployment of hydrogen technologies over the long term.

Japan, Germany, and South Korea have signaled their intentions to move towards commercial introduction of hydrogen fueled vehicles and infrastructure in the near future, with government providing coordination and funding support for early movers in industry (see Table 15-2). Collectively, these countries, along with the European Union (and Member States), have committed approximately $4 billion for FCEV and fueling infrastructure research, development, and deployment activities.

Japan

Japanese industry (auto, energy, and suppliers), government, and academia are targeting commercial introduction of FCEVs in 2015. The Japanese government has announced plans to begin the deployment of hydrogen vehicles and infrastructure. Government, industry, and academia have a role and activities include developing technologies,

Country	Before 2015*	After 2015*	
	Target FCEV Deployments		Target Hydrogen Fueling Stations
Japan	300	100K (2015)† 2M (2025)	1,000
Germany	1,300	10K (2015) 600K (2020)	500–1,000 (2020)
South Korea	500	10K (2015) 100K (2020)	160 (2020)
United States‡	1,400	53K (2017)	–

* Fuel Cell & Hydrogen Energy Association – FCEV Global Race Presentation.

† JHCF International Roundtable and Seminar, March 2011.

‡ California Fuel Cell Partnership, Progress and 2011 Actions for Bringing Fuel Cell Vehicles to the Early Commercial Market in California, February 2011.

Table 15-2. *International Commercial Deployment Programs*

revising regulations, and creating sustainable business models and base infrastructure (100 stations) before 2015. Initial infrastructure will focus on four key metropolitan areas (Tokyo, Nagoya, Osaka, and Fukuoka) and connections between them. Toyota has separately announced its intention to commercialize fuel cell vehicles by 2015.[1] Honda has built low-volume production lines for FCEVs, systems, and stacks. Thirteen Japanese companies, led by JX Nippon Oil, have formed an alliance with an intention to supply hydrogen to fuel cell vehicles by 2015.[2]

Germany

A collection of key players including commercial gas suppliers, car companies, energy companies, and government agencies signed a non-binding Memorandum of Understanding in 2009 to evaluate the commercialization of fuel cell vehicles and a hydrogen refueling network around 2015 (see Table 15-3). The group is lead by NOW (German subsidy office for electric mobility).

The group has targeted installation of up to 1,000 hydrogen fueling stations and deployment of 600,000 hydrogen fueled vehicles by 2020; however, the exact number of stations that will be built by 2015 has not been announced because the group has not reached final agreement. In late 2009, the German government announced plans to invest $1.1 billion for early vehicle and infrastructure deployment.[3] In addition, the German government's 2009 Economic Stimulus package includes funding to expand hydrogen infrastructure, with an earmark to establish 10–25 hydrogen fueling stations by 2015. Leveraging funding support from government, Daimler and Linde announced plans in June 2010 to install 20 hydrogen fueling stations

1 Alan Ohnsman, "Toyota Plans 'Limited' Consumer Sales of Fuel-Cell Cars by 2015," Bloomberg, January 14, 2009, www.bloomberg.com/apps/news?pid=newsarchive&sid=aKdSR3OInOa8&refer=home.

2 Green Car Website, "Japanese Carmakers Unite Behind Hydrogen Fuel Cell Vehicles," January 2011.

3 Green Car Congress, "Germany Launches H2 Mobility Initiative to Expand Infrastructure for Refueling Hydrogen Vehicles," September 2009.

German MOU Signatories		
Royal Dutch Shell	NOW	Daimler
Total	Linde	Opel
ENI	Air Products	Toyota
OMV	Air Liquide	Nissan
EnBW	Siemens	BMW
Vattenfall	Intelligent Energy	

Source: Electric Cars Report, "Hyundai-Kia Joins Fuel-Cell Partnership in Germany," *Automobile Magazine,* February 25, 2011, http://electriccarsreport.com/2011/02/hyundai-kia-joins-fuel-cell-partnership-in-germany/.

Table 15-3. *German Memorandum of Understanding Signatories* in Germany beginning in 2012.[4] Further, NOW is studying what legislation would enable a larger scale roll out of hydrogen refueling infrastructure by 2015.

South Korea

Leading South Korean auto manufacturers, Hyundai Kia Motors and GM Daewoo, are leading the effort to partner with government for the deployment of FCEVs and hydrogen fueling infrastructure. In their 2010 "Green Vehicle Deployment Roadmap," the South Korean government is aiming to operate over 160 hydrogen fueling stations throughout the country by 2020 and invest $330 million for early vehicle and infrastructure deployment.[5] In the same roadmap, the government announced plans to subsidize FCEVs at a level of $3,000/vehicle. As of 2011, approximately ten stations have been built and two additional stations are planned in South Korea by partnerships that include government, universities, industrial gas providers, utilities, and oil and gas companies.[6] There are currently 100 FCEVs operating in a government test program with plans of further expansion in the near future. The auto industry is working with government to develop plans for the deployment of fueling infrastructure to support the deployment of these vehicles. South Korea has announced a goal to supply 20% of the world stationary and transportation fuel cells by 2025, leading to 560,000 projected new jobs.[7]

United States Hydrogen Initiatives

For decades, the U.S. government has made significant investments in research (with over $1.7 billion between 2004 and 2010) for development and demonstration of a portfolio of technologies for transportation applications that include hydrogen and fuel cells. Federal investments have supplemented industry investments and the United States is currently considered a global leader in hydrogen and fuel cell technology development. U.S. Department of Energy (DOE) support for hydrogen fueled passenger cars and hydrogen fueling infrastructure began in the early 1990s, but has varied considerably over this time period. Even through cycles of high and low funding support, the domestic program continues to make solid and steady progress toward the technical milestones established by the DOE for commercial viability. No federal targets have been announced for the deployment of FCEVs and fueling infrastructure.

The DOE Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project,[8] which ended in 2011, has significantly advanced the world's understanding of hydrogen fueled vehicles and infrastructure. This public/private cost share project contributed towards improvements in many areas such as fuel cell stack durability, FCEV range/efficiency, and infrastructure readiness. The project began in 2004 and included the deployment of over 180 FCEVs and 25 hydrogen fueling stations. The station types ranged from delivered hydrogen to on-site hydrogen production using natural gas reformation and water electrolysis from grid and solar electricity. The program resulted in 3.6 million miles driven by FCEVs, 37,000 fuelings and over 150,000 kg of hydrogen produced or dispensed.

DOE's hydrogen efforts focus on precompetitive technology development and the public disclosure of the advancements. As industry progresses towards commercialization, research and advancements are being made increasingly through proprietary technology development activities.

From 2009 to 2012, federal support for hydrogen and FCEVs has declined significantly. Although majority of 2009 to 2012 funding is targeted to transportation sector technologies, a greater percentage of federal hydrogen fuel cell initiatives now stress non-transportation applications than prior to 2009. Congressional testimony by the Secretary of Energy and proposed funding reductions (to zero in 2010) in the DOE Hydrogen and Fuel Cells Program suggests that the current administration views hydrogen and FCEVs as a high-risk long-term technology.[9]

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4 Marketwire, "Linde and Daimler press ahead with development of infrastructure for fuel-cell vehicles," June 1, 2011.

5 Fuel Cell Today, "2010 Survey of Korea," 2010.

6 TUV SUD Industrie Service (website), "Hydrogen Filling Stations Worldwide," http://H2stations.org.

7 International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), "2010 Hydrogen and Fuel Cell Global Commercialization & Development Update," November 2010, http://www.iphe.net/docs/IPHE-FINAL-SON-press-quality.pdf.

8 National Renewable Energy Laboratory (website), Hydrogen & Fuel Cells Research,"Hydrogen Fuel Cell Electric Vehicle Learning Demonstration," July 23, 2012, http://www.nrel.gov/hydrogen/proj_learning_demo.html.

9 U.S. Department of Energy (website), Hydrogen and Fuel Cells Program: "Budget," http://www.hydrogen.energy.gov/budget.html.

As of early 2012, 56 hydrogen fueling stations were operating in the United States, with 20 of these stations located in California.[10] California is playing a significant role in developing the next generation of commercial fueling stations. In late 2010, the California Energy Commission awarded incentives for 10 new stations that are expected to be operational by late 2012. California is developing plans to fund additional stations.[11] A survey of auto manufacturers suggest FCEV deployment to reach >50,000 total units by 2017.[12] Additionally, regional efforts are also underway to develop hydrogen fueling networks on the U.S. East Coast[13] and in Hawaii.[14]

PATHWAY PRIORITIZATION AND RATINGS

Both physical infrastructure and vehicles must be considered when evaluating the potential introduction and adoption of the use of hydrogen as a transportation fuel. Figure 15-1 shows the applicable market segments and highlights those that are the focus of this chapter and that should be priorities in order to accelerate the development of hydrogen as an alternative fuel.

Pathways Prioritization Discussion

A detailed discussion on the prioritization of each pathway evaluated is included in Appendix 15B at the end of this chapter and summarized below.

Vehicles

- Hydrogen ICE Light-Duty Vehicles. Although no material technology challenges exist, this pathway does not use hydrogen fuel as efficiently as FCEVs. Most automobile manufacturers are not pursing hydrogen ICE technology for LD vehicles. Therefore, this is not a priority pathway.
- Hydrogen ICE Medium-/Heavy-Duty Vehicles. Although no material technology challenges exist, this pathway does not use hydrogen fuel as efficiently as FCEVs. Additionally, the fuel usage for this market segment is not as significant as that for LD vehicles. Therefore, this is not a priority pathway.
- FCEV Light-Duty Vehicles. Technical challenges associated with FCEVs exist; however, FCEVs present an opportunity for efficient use of hydrogen fuel. According to the Energy Information Administration's (EIA) Annual Energy Outlook 2010 (AEO2010), the LD vehicle market represents over 50% of transportation GHG emissions and transportation energy in the United States. The use of FCEVs in this market could have a significant and positive impact on emissions and energy security. Therefore, this is a priority pathway.
- FCEV Medium-/Heavy-Duty Vehicles. While this pathway can have a role in impacting emissions and energy security, the fuel usage for this market segment is not as significant as that for LD vehicles. The successful deployment of fueling infrastructure in this segment could help enable the deployment of FCEVs for the LD vehicle market; however, it is not discussed in detail in the body of this document.

Infrastructure

- Centralized Hydrogen Production Pathway. This is currently the most common and efficient method to produce hydrogen. Potential exists to leverage existing infrastructure to provide hydrogen fuel for early deployment. Therefore, this is a priority pathway.
- Distributed Hydrogen Production Pathway. Although not as common as the centralized production pathway, distributed hydrogen production has been successfully demonstrated and has the potential to be scalable and economically competitive with alternative pathways. Therefore, this is a priority pathway.
- Home Fueling. Successful advancements could revolutionize the fueling in vehicles; however, this technology is in the early stages of development and other pathways have significantly lower technology challenges. Therefore, this is not a priority pathway.

10 U.S. Department of Energy (website), "Alternative Fueling Station Counts by State," July 30, 2012, http://www.afdc.energy.gov/afdc/fuels/stations_counts.html.

11 South Coast Air Quality Management District (AQMD), "Board Meeting Date: December 3, 2012: Agenda No. 11," November 24, 2010, http://www.aqmd.gov/hb/2010/December/101211a.htm.

12 California Air Resources Board Hearing on "Advanced Clean Cars Regulations" in January 2012.

13 Robert Friedland, "Sun Hydro Fueling Stations," Proton presentation, May 18, 2011, http://www.hfc2011.com/wp-content/uploads/2011/06/HFC2011_RobertFrieland.pdf.

14 Sonia Isotov, "Hawaii Helping U.S. in Worldwide Fuel Cell Race," *Maui Now,* June 14, 2011, http://mauinow.com/2011/06/14/hawaii-helping-keep-u-s-in-worldwide-fuel-cell-race/.

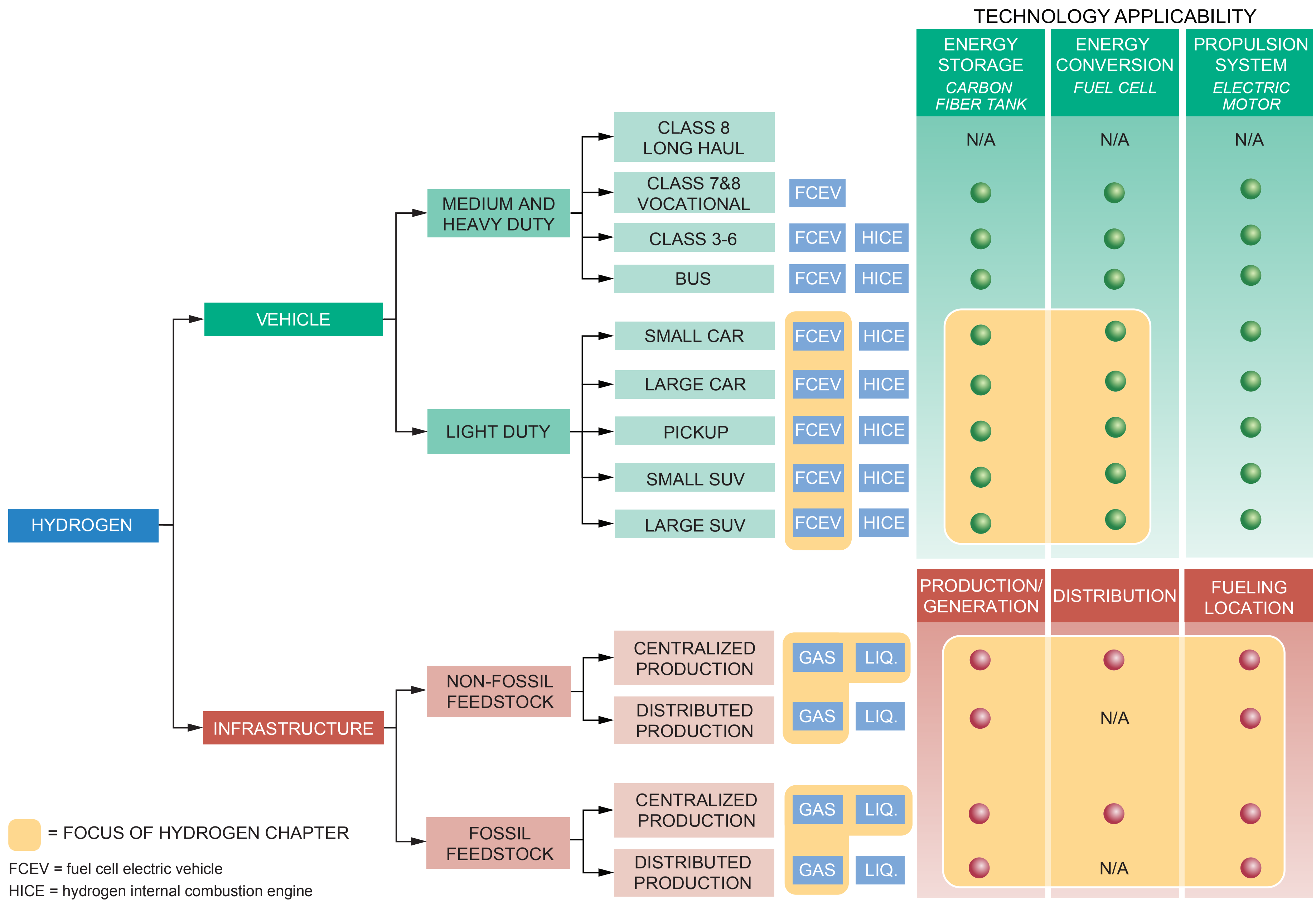


Figure 15-1. *Discussion Focus Areas*

- Combined Heat, Power, and Hydrogen Pathway. This pathway optimizes efficiencies for the production of heat, power, and hydrogen and can result in lower cost hydrogen; however, scalability is limited and this solution is only applicable in niche locations. Therefore, this is not a priority pathway.

Readiness Ratings for Current Technologies

The status of each technology pathway considered a priority for further analysis has been evaluated. Key criteria for FCEVs and hydrogen fueling infrastructure have been rated and shown below (see Figure 15-2 and Figure 15-3).

The ratings developed for this technology status evaluation convey the state of technology development at the writing of this report, considering a variety of metrics for wide-scale commercialization of FCEVs using hydrogen as a transportation fuel. The ratings are not meant to evaluate whether hydrogen and fuel cell technologies are sufficiently advanced to begin a process of market entry in the near term, but rather are intended to convey the areas where investments in technology advancement need to be focused to enable wide-scale commercialization. In some instances, the state of the technologies involved have not been sufficiently developed and demonstrated, though there may be important research in the laboratory. In other instances, as discussed below, technologies have been demonstrated to meet the requirements in these areas, but

HURDLE		REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	RATING	COMMENTS
VEHICLE:				
	VEHICLE PLATFORM	Capable of applying non-propulsion system improvement made on conventional gasoline vehicles		See Vehicles & Engines chapter for details
	CABIN & CARGO SPACE	No functional impact to customer relative to conventional vehicles		No functional impact to customers due to packaging improvement in current generation vehicles
	ON-BOARD STORAGE SYSTEM	Vehicle range between fueling is acceptable (>=300 miles)		Some FCEVs have demonstrated range of 300 miles or greater; however, not across all vehicle classes
	SAFETY	Comparable with conventional vehicles		FCEVs have been designed to the same safety standard as conventional vehicles
FUEL CELL:				
	DURABILITY & DEGRADATION	Last life of vehicle (150,000 miles) and degradation does not materially impact customer		>150,000 mile life has been demonstrated in the lab and must be proven in field trials
	EXTREME WEATHER PERFORMANCE	Comparable with conventional vehicles		Rapid startup in cold weather and sustained high power performance in hot weather do not yet match conventional vehicles
	PRECIOUS METAL REQUIREMENTS	Vehicle life is comparable to conventional vehicles and fuel cell system costs are not prohibitive		Platinum requirements have dropped significantly and are not expected to be a technical or economic limitation
ELECTRIC MOTOR:				
	POWER & TORQUE	Comparable with conventional vehicles		Electric drive results in no comprises in power and torque
FCEV ECONOMICS:				
	UPFRONT PRICE PREMIUM	Vehicle price results in acceptable economics for consumers		Current costs for fuel cell and storage system are high; lower costs can be achieved with scale production and lower platinum requirements
	FUEL COST PER MILE	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

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"

Figure 15-2. *FCEV Summary Readiness Ratings*

HURDLES		REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	RATING	COMMENTS
CENTRALIZED PRODUCTION & DISTRIBUTION:				
	EMISSIONS COMPLIANCE	Fully compliant with regulations	Blue	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	Yellow	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	Yellow	Investments needed to expand existing capacity
	DISTRIBUTION ECHNOLOGY	Payload capacity can meet demand requirements without materially impacting existing fueling station business operations	Yellow	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	Blue	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	Red	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	Blue	~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	Red	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	Yellow	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	Red	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	Yellow	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	Red *	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	Blue	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)	Red	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	Red	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	Red *	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

Blue: MINIMAL/NO BARRIERS

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

Red: 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.

Figure 15-3. *Hydrogen Fuel Production Summary Readiness Ratings* there is some uncertainty to whether these technology advancements can achieve the material scale needed for wide-scale commercialization.

In Figure 15-4, the supply chain and detailed hurdle ratings show the key technology components for FCEVs and hydrogen fueling infrastructure for each component.

The following is a listing of key assumptions made in determining the ratings in Figure 15-4:

- Non-fossil energy feedstocks for hydrogen production include biogas, biomass, renewable electricity, and nuclear power
- Fossil energy feedstocks for hydrogen production include natural gas, coal, and oil products
- All vehicles store compressed gaseous hydrogen on-board at pressures up to 10,000 pounds per square inch (psi).

FUEL CELL ELECTRIC VEHICLE CONSIDERATIONS

Over the past two decades, major automotive companies have invested billions of dollars worldwide in FCEV research, development, and deployment programs.[15] This investment has been augmented by supply base investment, government cost share through demonstration programs, and technical contributions from national laboratories and universities. Progress over this timeframe has taken FCEVs from benchtop propulsion system experimentation to on-the-road demonstration fleets with keys in customers' hands. In 2009, leading auto manufacturers (Daimler, Ford, General Motors/Opel, Honda, Renault/Nissan, Hyundai/Kia, and Toyota) signed a joint "Letter of Understanding" signaling they will be prepared to start the commercialization of FCEVs around 2015. They called for hydrogen fueling infrastructure in four initial target markets: Germany, the United States, Japan, and South Korea.

From a customer perspective, FCEVs offer excellent acceleration, high efficiency (low fuel consumption), quiet operation, low levels of vibration, acceptable driving range, and rapid refueling with a cleaner fueling interface (fully sealed—no vapors, no drips, no smell). From a societal perspective, FCEVs offer zero tailpipe emissions, an alternative to petroleum, and a pathway to renewable and sustainable transportation. As noted in the hydrogen fuel discussion, the per-mile GHG footprint of the FCEV is approximately 50% lower than that of a today's conventional non-hybrid gasoline vehicle when using natural gas as the feedstock. Multiple pathways such as biomass reforming or electrolysis using wind or solar can reduce this footprint significantly, though likely at higher fuel cost.

One way to assess the current status of FCEV technology is to examine data from real world experience. This means looking at the FCEVs that have been deployed on the road to date, assessing their driving performance, measuring their durability, and estimating their costs through bottom-up analytical methods. Over the past decade, a growing number of FCEVs have been deployed on the road as part of demonstration programs or automaker pilot programs (see Figure 15-5).

Driver feedback and publicly available information support the following conclusions compared to conventional gasoline vehicles:[16]

- Driving performance is already competitive or better
- Range is acceptable for some but not all customers
- The vehicle fueling experience was not satisfactory at some early demonstration stations.

Another way to assess the current status of FCEV technology is to look at the R&D progress that could feed into the next generation of vehicles. While much of this work is proprietary, technical papers and press releases provide an indication of where the industry may be going. Key trends that can be seen in R&D include:

- Fuel cell system cost reductions of approximately 80% since 2002 by reduction in use of precious

15 Daily Tech (website), "GM to Launch Fifth Generation Fuel Cells, Commercial Hydrogen Vehicles in 2015," September 25, 2009, http://www.dailytech.com/GM+to+Launch+Fifth+Generation+Fuel+Cells+Commercial+Hydrogen+Vehicles+in+2015/article16346.htm.

16 Edmunds (website), "All Dressed Up and Nowhere to Refuel," January, 29, 2010, http://www.edmunds.com/chevrolet/equinox/2008/road-test.html; Edmunds Auto Observer (website), "3 Days with Honda's Clarity Helps Bring Hydrogen Debate Into Focus," September 5, 2009, http://www.autoobserver.com/2009/09/3-days-with-hondas-clarity-helps-bring-hydrogen-debate-into-focus.html; and The Daily Green (website), "Road Testing Toyota's Fuel Cell Car Prototype for Six Months," October 15, 2010, http://www.thedailygreen.com/living-green/blogs/cars-transportation/fuel-cell-cars-connecticut-test-461010.

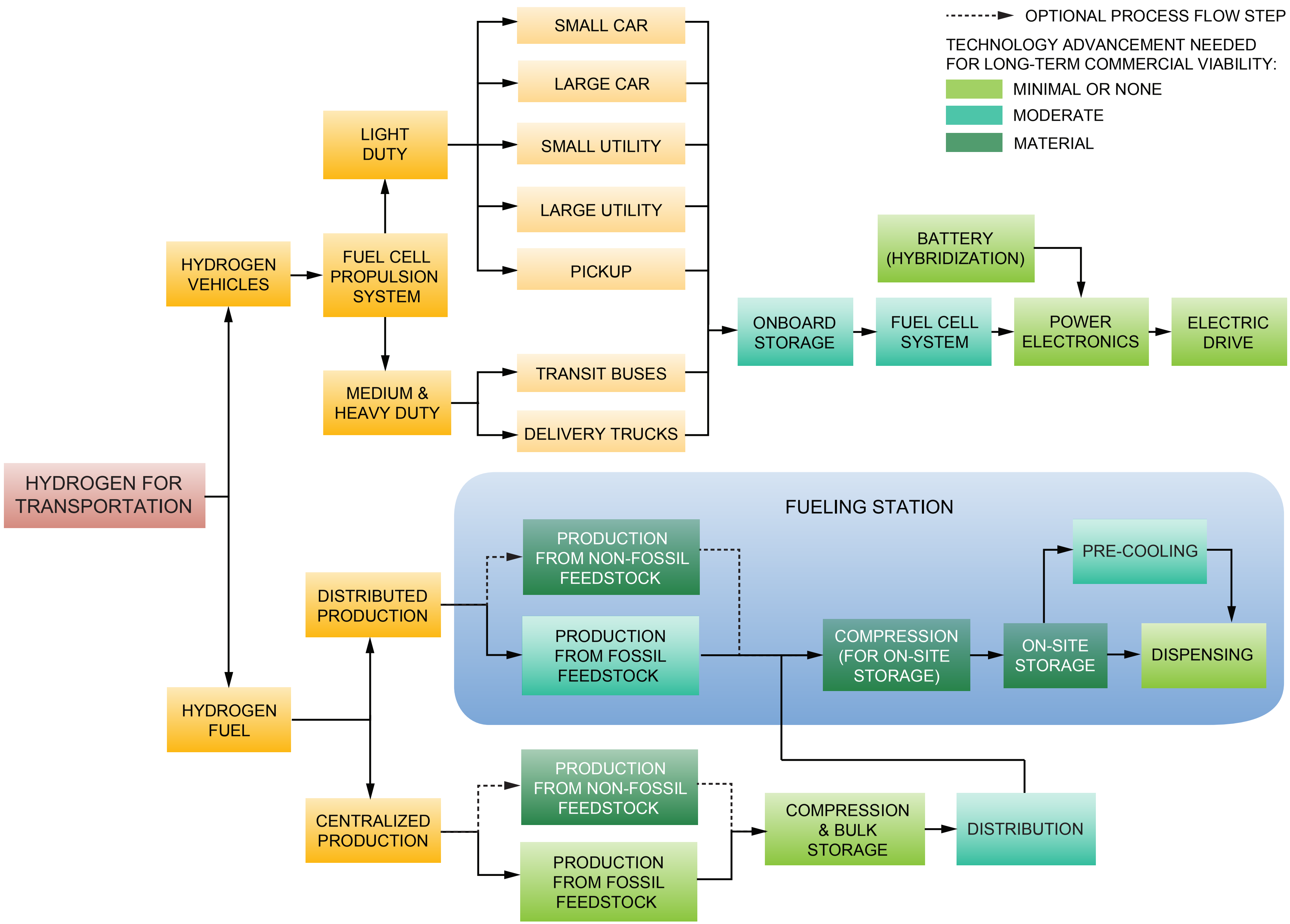
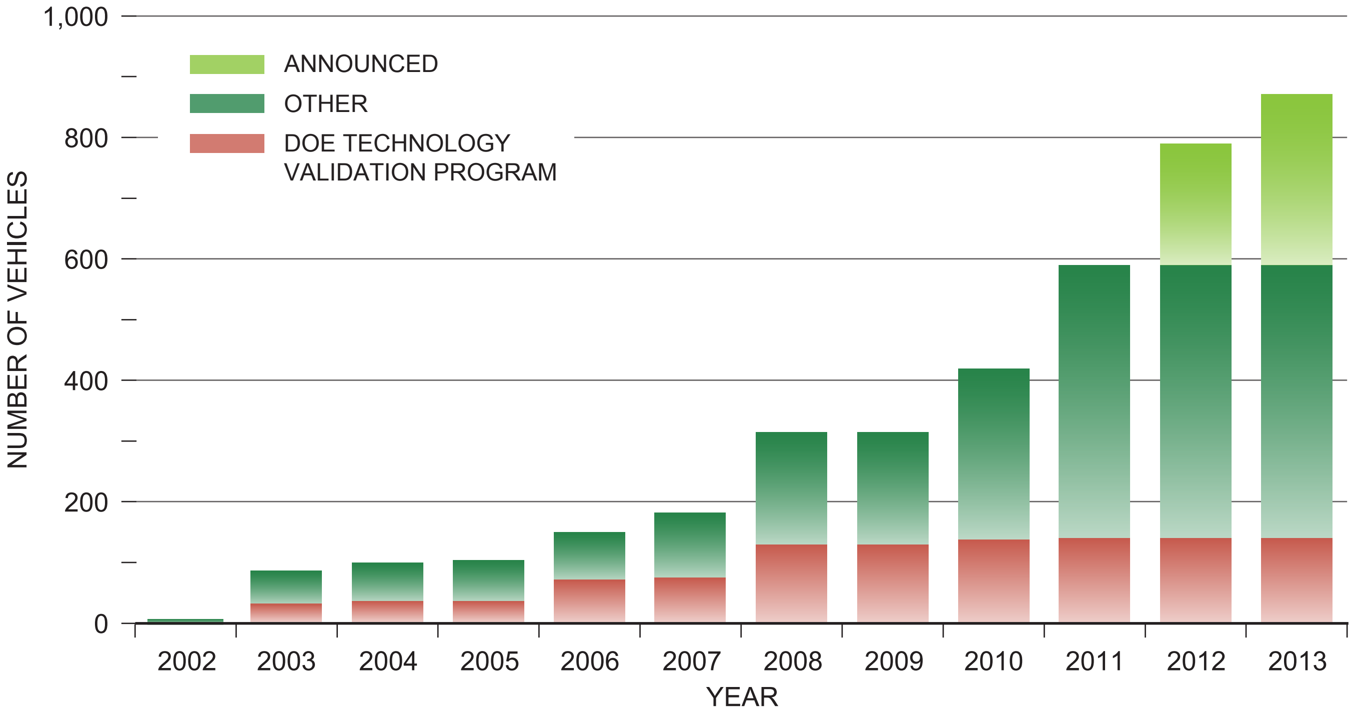


Figure 15-4. *Supply Chain and Detailed Hurdle Ratings*



Notes: Distribution of announced vehicles over the years 2011–2013 is estimated.
Retired vehicles have not been subtracted from totals.

Figure 15-5. *Historical and Planned Deployments of FCEVs in the United States*

metal catalysts in the fuel cell stack and other improvements[17]

- Fuel cell system power density improving 60% over the past five years[18]
- Vehicle efficiency and packaging improvements leading to increased range of 300 or more miles[19]
- Stack durability matching vehicle lifetime targets demonstrated in accelerated laboratory testing.[20]

Much of this progress may be demonstrated in the newest FCEVs over the next several years, and confirmation of these advances could form the basis for each automaker's individual market entry decision.

Table 15-4 is a summary of the status of key characteristics that must be addressed for FCEV commercial readiness. The status and advancement opportunities for each of these characteristics are discussed in greater detail below.

Vehicle Efficiency

Current fuel cell system technologies offer net conversion efficiencies (air and hydrogen in, direct current electric power out) as high as 59%.[21] DOE data show efficiencies of 42–53% at full power and 53–59% at typical operating levels.[22] These high efficiencies are key to managing per-mile fuel costs and providing adequate vehicle range from available on-board hydrogen storage. They

17 U.S. Department of Energy, Hydrogen and Fuel Cells Program: Program Records, DOE Hydrogen Program Record 10004, "Fuel Cell System Cost – 2010," September 16, 2010, http://hydrogen.energy.gov/program_records.html.

18 U.S. Department of Energy presentation, "FreedomCAR and Fuel Partnership Report," 2010.

19 Savannah River National Laboratory and National Renewable Energy Laboratory (SRNL/NREL), *Evaluation of Range Estimates for Toyota FCHV-adv Under Open Road Driving Conditions,* August 10, 2009, http://www.nrel.gov/hydrogen/pdfs/toyota_fchv-adv_range_verification.pdf.

20 J. Kurtz, K. Wipke, and S. Sprik, "Analysis Results of Lab and Field Fuel Cell Durability," NREL presentation at 2010 Fuel Cell Seminar, October 10, 2010.

21 McKinsey & Company, *A portfolio of power-trains for Europe: a fact-based analysis,* 2010.

22 National Renewable Energy Laboratory (website), Hydrogen & Fuel Cells Research, "Hydrogen Fuel Cell Electric Vehicle Learning Demonstration," http://www.nrel.gov/hydrogen/proj_learning_demo.html.

Technology Benefits	Recent Achievements	Near-Term Focus Areas
☑ Vehicle Efficiency	☑ Acceleration (Stack Power)	■ Durability & Degradation
☑ Zero Tailpipe Emissions	☑ Refueling Time	■ Cost
☑ Low Noise	☑ Interior Space	
☑ Low Vibration	☑ Sustained High Power	
	☑ Freeze start	
	☑ Driving Range	
□ Better than conventional	□ Parity with conventional	■ Not yet at parity with conventional

Table 15-4. *Summary of FCEV Status*

also mean that FCEVs can stretch limited energy resources into higher mileage. The fuel economies of several FCEVs have been compared to their same model year conventional gasoline (non-hybrid) counterparts in Table 15-5.

A same model year comparison basis was chosen to neutralize the effects of changes in aerodynamics, rolling resistance, and mass in the underlying vehicle glider (chassis plus body). These changes results from year-to-year differences in physical dimensions, standard equipment, styling, and structural design or material selection. A second reason for same model year comparison is to capture a common point in time, as technical improvements continue in all technology pathways, and market-driven or regulation-driven tradeoffs between vehicle price and fuel efficiency may also differ from year to year.

The conventional gasoline vehicle, rather than a hybrid counterpart or other alternative fuel variant, is used as the comparison basis here and throughout this chapter because the conventional gasoline vehicle dominates today's new vehicle sales. Comparing favorably to vehicle types with limited market share (e.g., hybrid) is not sufficient when considering wide-scale commercialization; the conventional vehicle is today's dominant technology and the one to beat. All fuel/vehicle pathway options are compared in the integrated analysis of this report.

These data provide an early indication of the potential of FCEVs to achieve more than double the efficiency compared to conventional gasoline vehicles. This advantage is expected to be maintained if FCEVs incorporate further efficiency improvement opportunities including:

1. General vehicle efficiency measures (which are applicable to all vehicles) such as chassis/body mass reduction, reduced drag, and low rolling resistance tires. Higher fuel economy standards

	FCEV (miles/kg)	Conventional (miles/gal)	Ratio (FCEV/Conventional)
2007 Chevrolet Equinox*	45	20	2.3
2010 Toyota Highlander†	68	22	3.1
2011 Honda Clarity*	60	27/29‡	2.2/2.1
2011 Mercedes F-Cell*	53	No U.S. equivalent	–

Note: Most efficient equivalent conventional vehicle selected for comparison.

* U.S. Department of Energy website, http://www.fueleconomy.gov.

† SRNL/NREL, *Evaluation of Range Estimates for Toyota FCHV-adv Under Open Road Driving Conditions,* August 2009, http://www.nrel.gov/hydrogen/pdfs/toyota_fchv-adv_range_verification.pdf.

‡ Honda Accord/Civic assumed for comparison because no direct comparable vehicle is available.

Table 15-5. *Comparison of FCEV and Conventional Gasoline Vehicle Fuel Economy* may cause these measures to be adopted in increasing numbers on high-volume vehicle platforms, and the benefits may carry over to FCEVs as well from a high-volume, low-cost supply base.

2. Improvements in batteries, power electronics, and electric traction motors. Investment in plug-in electric vehicles and their growing volumes could drive improvement in these subsystems that are shared by FCEVs.
3. Fuel cell stack, balance of plant, and operating strategy improvements, including reduced stack internal resistance, lower ancillary power draw for higher efficiency at low load levels, and operation of the fuel cell system at higher efficiency points for more of the drive cycle.
4. Hydrogen storage system mass reduction. Better use of carbon fiber (higher strength translation efficiency) and simplification of high-pressure valves and closure hardware.

Zero Tailpipe Emissions

FCEVs combine hydrogen fuel with oxygen from the air to produce water vapor as their only exhaust product. There is no carbon in hydrogen fuel, and there is no emission of GHG out the tailpipe. With a compressed gaseous storage system, there are also no evaporative fuel emissions. FCEVs produce no criteria pollutants such as nitrogen oxides, volatile organic compounds, or particulate matter from the tailpipe, which can be particularly important in urban areas seeking to comply with air quality requirements related to ground level ozone pollution.

Noise and Vibration

The heart of the fuel cell system is the fuel cell stack, which functions as the "engine" in converting on-board stored hydrogen energy to electric power for propelling the vehicle. The stack, which is essentially a battery with a fuel supply, does not produce the noise and vibration that an internal combustion engine produces. Downstream of the stack in the electric drive system, three-phase electric power from the inverter delivers steady and continuous torque, in contrast to the power strokes of internal combustion, which are rapid and regular but not continuous, making vibration difficult to mitigate.

The most noticeable noise from the FCEV is from the compressors or fans that move air through the stack or past the coolant system heat exchangers. Opportunities exist to reduce these air flow needs and to reduce noise by improving air movement devices.

Acceleration

The limiter on acceleration performance in early FCEVs was fuel cell stack power density (the fuel cell could not produce sufficient power to achieve desired acceleration). In recent years, significant progress has been made in this area. Figure 15-6 shows progress through 2009 on the fuel cell system (stack plus fuel/air handling and balance of plant) power density and specific power. Both metrics are already within 20% of DOE 2015 targets and are expected to exceed these targets as next generation stack designs are implemented.

Auto manufacturers are transitioning to thin-plate separator technology in their stack designs, and packaging of adequate power on board the vehicle is no longer viewed as a challenge. Acceleration times for today's FCEVs are comparable to their conventional counterparts, and in many cases the FCEVs feel faster because of the excellent off-the-line acceleration that is characteristic of all vehicles powered by electric motors. Acceleration is now an area where FCEVs can likely deliver value to the customer by outperforming their conventional counterparts, especially from a standing start.

The key opportunity for further improvement in acceleration lies in mass reduction. Original equipment manufacturers (OEMs) are applying resources to optimize the vehicle and propulsion system at the design, materials and systems integration level to meet vehicle weight and specific power targets. Today's FCEVs have been built in low volumes (up to 120 units per model). As OEMs prepare for commercialization, enablers for volume production of FCEVs will also serve as enablers for further optimization of the fuel cell propulsion system.

Refueling Time

FCEVs offer fully electric drive with refueling times comparable to gasoline vehicles. FCEVs can now receive hydrogen for 300 or more miles of driving in as little as three minutes using the recently

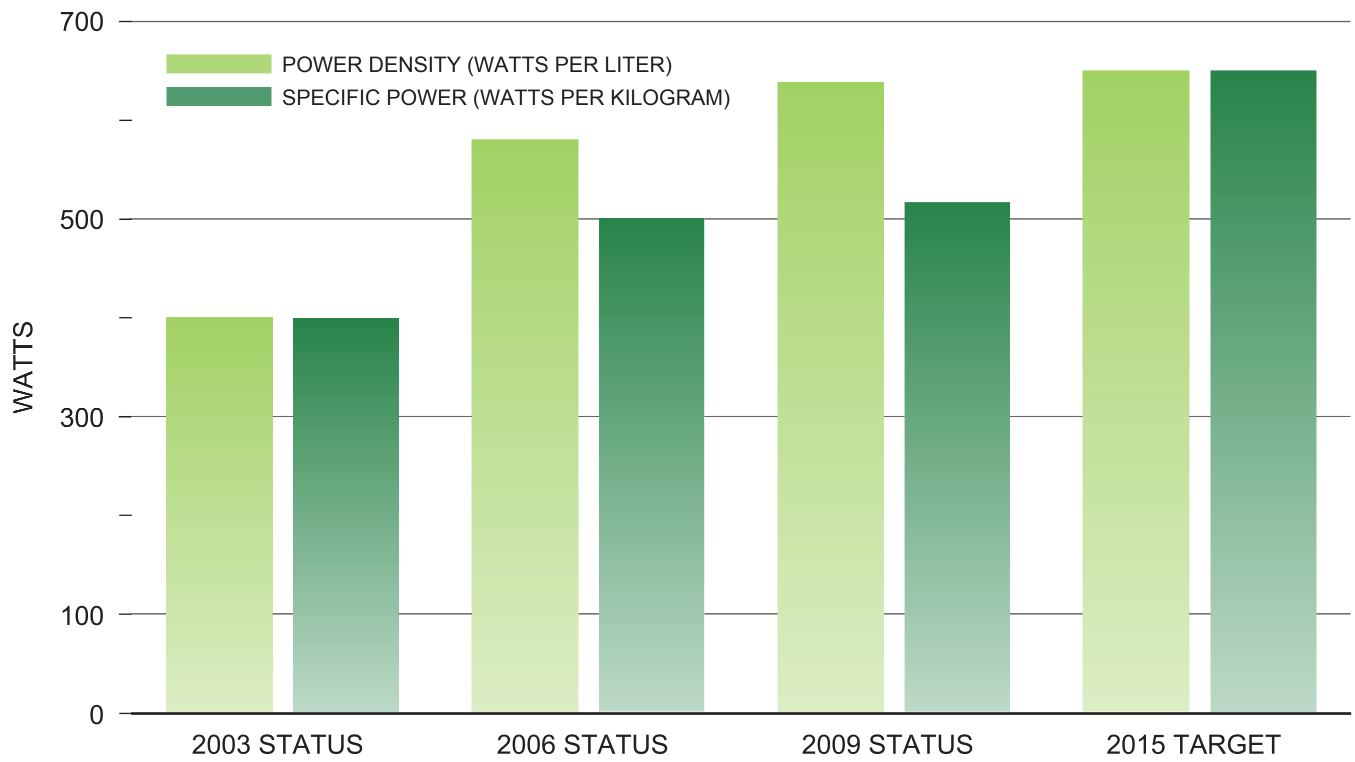


Figure 15-6. *Fuel Cell System Power Density and Specific Power*

developed industry standard fueling protocol.[23] Table 15-6 provides a directional comparison of fueling rates for gasoline and hydrogen, using representative parameter values.

Realization of fast hydrogen refueling depends on adoption and execution of the standard protocol on fueling infrastructure. Stations in Germany and the United States have demonstrated three-minute fueling of current FCEVs and most new stations receiving public funding are now required to provide this level of capability.

23 SAE International, *Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles,* SAE Technical Information Report J2601, March 16, 2010.

Interior Package/Cargo Space

Interior space has, in the past, been traded off against hydrogen storage volume and vehicle driving range. Hydrogen storage containers built for high pressure must be cylindrical in shape, so they cannot be easily conformed to underbody packaging as with a gasoline fuel tank in a conventional vehicle.

One common solution is elimination of the spare tire, using run-flat tires and including an inflation kit in the vehicle as a substitute to free up underbody space for the storage cylinders. A further solution is to build the vehicle around the hydrogen storage system. This approach is shown

Fuel	Transfer Device	Transfer Process			Vehicle Efficiency		Range Transfer Rate
		Rate	Units	Eff	Miles	Unit	miles / min
Gasoline	Retail Pump	7	gal / min	100%	30	miles / gallon	210.00
Hydrogen	A70 Dispenser (29 MPa/min)	7	kg / 3 min	100%	60	miles / kg	140.00

Table 15-6. *Gasoline/Hydrogen Fueling Rates*

in Figure 15-7. Some vehicles use as many as four separate cylindrical tanks to create a flat overall package for under floor fitting. Using this array of approaches, the reduction in interior passenger/cargo space in today's FCEVs is minimal.

Sustained High Power Operation

The fuel cell stack operates at much lower temperature than a conventional engine, and this makes the transfer of waste heat to the environment a challenge. An FCEV will perform well under typical vehicle duty cycles; however, it will struggle to pull a heavy load up a long grade at speed on a hot day. This challenge may be addressed in the future with new stack materials that operate at higher temperature or with novel thermal management concepts.

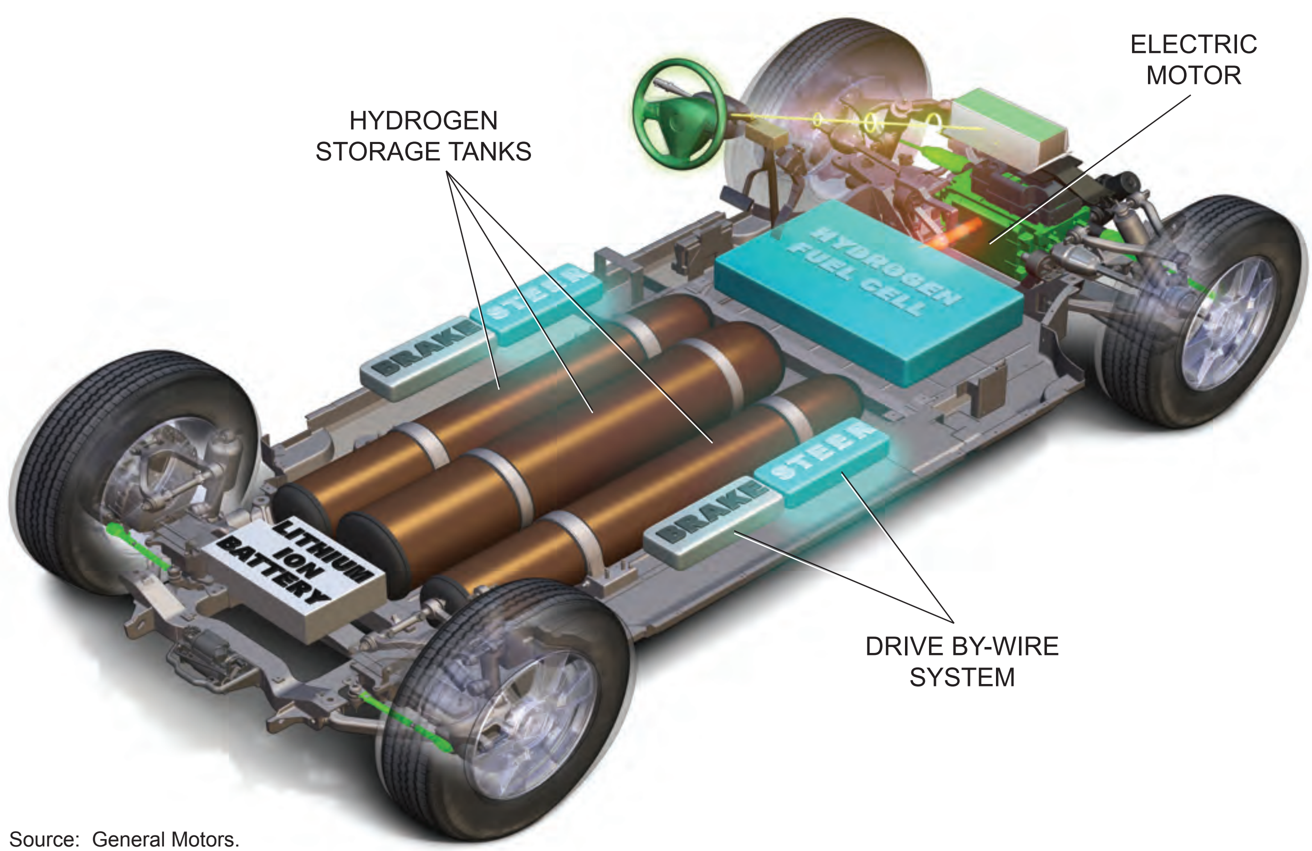
Freeze Start

Water is the product of the chemical reaction in the fuel cell stack, and water product that remains in the stack will freeze during cold parking. This created two issues for early FCEVs:

- The stack could not be started from its frozen state.
- Damage from freezing could destroy or degrade the stack.

Considerable progress has been made in addressing these issues, and FCEVs can now be started even after soaking down to -35°C or lower. FCEVs have been deployed to cold weather regions to validate this progress, and they have performed through several winters of demonstration and validation testing. These vehicles have shown both the ability to start from cold and the ability to withstand freeze/thaw cycles with minimal degradation of stack life.

An opportunity for further improvement is start times. Consumers are accustomed to an almost instant start with gasoline vehicles, and they expect to have full power immediately, even on a



Source: General Motors.

***Figure 15-7.** Longitudinal Packaging of Hydrogen Storage in Skateboard Chassis* cold morning. FCEVs do not yet match this performance as they require up to 60 seconds for full fuel cell power operation from an extreme cold condition.[24] Features such as remote start and cabin preconditioning are in place to mitigate the impact to the vehicle user, but stack start time from cold is an area needing continued improvement.

Driving Range

Conventional vehicles provide a 300–500 mile range on a single tank of gasoline. Vehicle range is specified in response to consumer preferences and targets for station-fueled vehicles are not expected to change significantly as vehicles evolve. Compressed gaseous hydrogen storage cannot match the energy density of gasoline, but vehicles using compressed hydrogen have now demonstrated driving ranges of 300 miles or more.[25] Packaging of the hydrogen storage cylinders is a design challenge, but there are concurrent design advantages from electric propulsion system architecture. With fewer mechanical linkages in the power delivery system, the FCEV designer has degrees of freedom that the conventional vehicle designer does not. Automotive designers now have a better understanding of how to incorporate the added volume requirements for hydrogen storage and provide adequate vehicle driving range using compressed gaseous hydrogen storage.

While a hydrogen storage breakthrough is not needed to move forward with commercial market entry, there are opportunities for improved driving range (or reduced mass and volume of the hydrogen storage system) in the following areas:

- Vehicle efficiency improvement – more miles from a given quantity of onboard hydrogen
- Increased usable hydrogen – lowering of the hydrogen storage system pressure floor to allow the vehicle to access a higher percentage of the hydrogen in the tank
- Novel storage materials – hydrogen stored and extracted from materials that bind it in a compact and lightweight form.

24 Shinji Aso, Mikio Kizaki, and Yasuhiro Nonobe, "Development of Fuel Cell Hybrid Vehicles in TOYOTA," paper presented at IEEE Conference, April 2007.

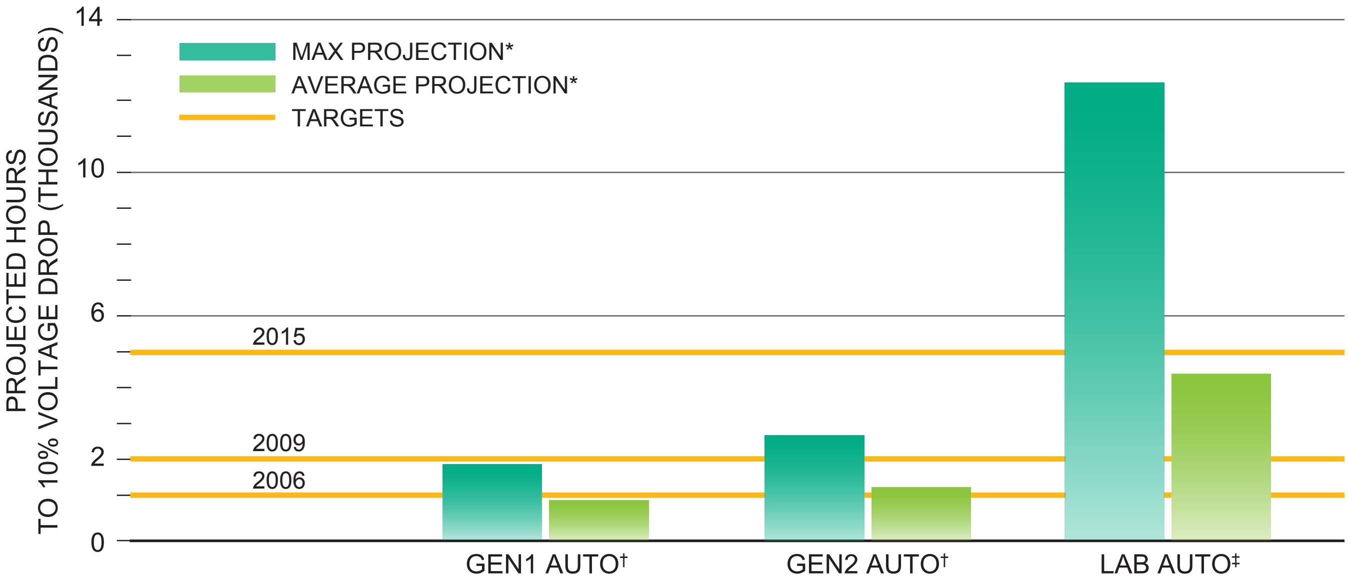
25 Savannah River National Laboratory and National Renewable Energy Laboratory (SRNL/NREL), *Evaluation of Range Estimates for Toyota FCHV-adv Under Open Road Driving Conditions,* August 10, 2009, http://www.nrel.gov/hydrogen/pdfs/toyota_fchv-adv_range_verification.pdf.

Durability & Degradation

Durability is a measure of whether the vehicle performs adequately over its expected lifetime of operation. Reliability, another measure that is related to durability, means that the vehicle does not fail suddenly and without warning. Today's conventional LD vehicles typically run for 5,000 hours and cover 150,000 miles. This same 5,000 hours of vehicle run time is the target for FCEVs for commercial introduction. Hydrogen storage systems are expected to be as durable as compressed natural gas (CNG) systems, which have been proven capable of lasting over the lifetime of their vehicles. Achievement of durability targets for FCEVs therefore rests on a durable fuel cell stack.

The fuel cell stack can fail in several ways. The electrolyte membrane can physically fail due to stress, chemical attack, or high-current hot spots. A rupture in the membrane, regardless of cause, means the end of stack operation. Membrane physical failure plagued early FCEVs, but improvements (e.g., manufacturing, assembly, and controls strategies) over the past few years are moving the industry beyond this failure mode. Durability work now focuses on minimizing stack degradation. When the stack degrades, it loses peak power capacity and it suffers efficiency losses at intermediate power levels. The fuel cell stack, like batteries and all other electrochemical systems, is subject to degradation over usage cycles and calendar life. The goal is not to eliminate this degradation, but rather to slow its rate such that power loss over 5,000 hours (150,000 miles of operation) does not impact the ability of the vehicle to meet its performance targets. This is consistent with the approach currently used to manage conventional vehicle performance degradation.

Although not necessarily a criteria for defining the usable life of a vehicle, a common measurement point used by DOE to evaluate stack degradation is the number of hours of operation until loss of 10% of original power output. Using this definition, DOE measured stack operating life as shown in Figure 15-8 over the duration of its Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project. The maximum projections of stack durability based on on-road data have improved from 950 hours in 2006 to over 2,500 hours in 2009. Although the average durability



Notes: * The DOE 10% voltage degradation metric is used for assessing voltage degradation; it may not be the same as end-of-life criteria and does not address catastrophic failure modes.
† Gen1 and Gen2 Data from DOE's Learning Demonstration (2005–2010).
‡ Laboratory data providers may not be the same as participants in DOE's Learning Demonstration; 49% of data are full active area short stacks.

Source: National Renewable Energy Laboratory.

Figure 15-8. *Comparison of Fuel Cell Vehicle Field and Laboratory Durability Projections*

projection for all fleets in the DOE demonstration is less than 1,100 hours, the maximum projection of 2,500 hours for the best performing second generation fleet well exceeded DOE's 2009 durability goal of 2,000 hours.

In the laboratory, vehicle fuel cell systems have logged over 7,500 hours of operation, and the maximum projected durability for these laboratory systems exceeds 12,000 hours,[26] further underscoring the potential of the next generation FCEVs to meet a 5,000 hour durability target. The next step towards achieving fuel cell durability targets is to deploy next generation FCEVs in real world settings and confirm that on-road performance compares with laboratory projections.

FCEV Cost

Fuel cell propulsion system costs have not declined as quickly as originally anticipated when industry began work in the mid 1990s toward commercialization. The 2010 costs of an FCEV were too high for market entry, but future costs are expected to be reduced through the following:

- Scale economies afforded through automated high volume production
- Less use of platinum in the fuel cell stack
- Simpler designs using fewer and less costly components
- Reduced use of carbon fiber in the hydrogen tanks.

Upon commercial introduction (~2015), FCEVs are expected to have a price premium of ~1.4X more than comparable gasoline ICE vehicles.[27] Assuming a gasoline ICE vehicle costs $25,000 to $35,000, a comparable FCEV is expected to cost $35,000 to $50,000 at this time. These prices are expected to come down over time to be cost competitive with

26 J. Kurtz, K. Wipke, and S. Sprik, "Analysis Results of Lab and Field Fuel Cell Durability," NREL presentation at 2010 Fuel Cell Seminar, October 10, 2010.

27 Autonomie, *Potential of Technologies for Displacing Gasoline Consumption by Light-Duty Vehicles through 2045,* September 2011, http://www.autonomie.net/publications/fuel_economy_report.html.

other LD vehicle options and ongoing effort will be needed to lower the cost of subsequent generations of vehicles.

Most of the FCEV key subsystems are also found on vehicles using different propulsion systems. The base characteristics of chassis and body (together termed "glider") are common across all vehicle types. The same kinds of electric traction (electric drive motors) used in hybrid and plug-in electric vehicles will be used in FCEVs, and the batteries used in hybrids are very similar to the batteries that will be used in FCEVs. The two major subsystems that differentiate FCEVs from other vehicle types and other electric vehicles (plug-in hybrid or pure battery electric vehicles) are the hydrogen storage system and fuel cell system. These two systems are key cost drivers and continue to receive development resources from the automotive industry and other sources.

Hydrogen Storage System Cost

The FCEV hydrogen storage system (HSS) differentiates FCEVs from other electric vehicles, but it shares many characteristics with CNG storage systems. CNG vehicles have a long history, and there are over 14 million CNG vehicles in operation globally today. The hydrogen community has referenced existing work on CNG storage systems and made changes as appropriate to account for the higher pressure and different characteristics of hydrogen. The result is a hydrogen storage system that can safely contain pressure over the full life of the vehicle, meet crash safety requirements, and safely vent its contents when exposed to fire.

While CNG storage systems can be either steel or fiber-wrapped, the higher pressures used in hydrogen storage make fiber-wrapped vessels the only viable option for achieving desired range with a reasonable storage system mass. All automakers with FCEVs deployed in the United States today use carbon fiber storage vessels, and the carbon fiber itself is the dominant cost driver for the overall storage system.

Opportunities for taking significant cost out of the hydrogen storage system include the following:

- Reduced carbon fiber usage through improved winding patterns that make more efficient use of the fiber strength (increased translation efficiency).
- Improved manufacturing methods that reduce the cost of high-strength carbon fibers. This would benefit a broad array of applications, including conventional vehicles for structural use in lightweighting.
- Simplified hydrogen storage system balance of plant that reduces the number of valves, the number of manifolds, and the length of piping.
- Scale economies afforded through volume production.
- Reduce carbon fiber usage through a shift from prescriptive burst pressure ratios to performance-based storage system safety requirement.
- Improved tank manufacturing processes.

A 2010 study by TIAX[28] estimates the current cost of hydrogen storage in 2015, based on high-volume manufacturing, to be $13.50/kWh ($450/kg) to $27.20/kWh ($910/kg) for 70 megapascals (MPa) (or 700 bar or 10,000 psi) service pressure and 5.6 kg usable hydrogen capacity. TIAX costs are in year 2005 dollars.

Using details from the TIAX analysis, upper and lower bounds were established for 2015 HSS costs with the following assumptions:

- Production volume of 500,000 vehicles per year
- Single Type IV tank (carbon fiber wrap around polymer liner) at 70 MPa
- Carbon fiber cost range of $25–$40/kg (pre-impregnated fiber)
- Initial burst pressure ratio of 2.25x (157.5 MPa minimum burst pressure)
- Carbon fiber safety factor of 10% applied by tank manufacturer
- Fiber translation efficiency of 80% (translation efficiency indicates how effectively the strength of the fiber is used when wound into the tank)
- Usable system storage assumes 95% fill level after station fueling
- Ratio of lower to upper bound costs consistent with TIAX Monte Carlo simulation.

The resulting cost and mass parameters are shown in Tables 15-7 and 15-8.

28 TIAX LLC and Argonne National Laboratory, *Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Applications,* September 2010.

	Fixed Cost	Variable Cost ($/kg)
Upper Bound Cost	$1,063	$826
Lower Bound Cost	$528	$410

Table 15-7. *2015 Factory Cost Parameters*

	Fixed Mass (lbs)	Variable Mass (lbs/kg hydrogen)
Upper Bound Mass	42.6	36.1
Lower Bound Mass	42.6	36.1

Table 15-8. *2015 Hydrogen Storage System Mass Parameters*

A 30% markup was assumed from OEM factory cost to Retail Price Equivalent (RPE).

To project costs over time, an improvement rate of 3% per year was assumed for 2015 to 2020, an improvement rate of 2% per year was assumed for 2020 to 2025, and an improvement rate of 1% per year was assumed from 2025 to 2050. Vehicle volumes were assumed to be less than 500,000 per year early on, and costs were increased by 60% for 2015, 28% for 2020, and 17% for 2025 based on assumed yearly volumes of 30,000, 80,000, and 130,000 respectively. Volumes were assumed to reach 500,000 or more from 2030 and thus bring costs into alignment with the TIAX high-volume cost basis.

Mass was held constant over time in the upper bound cost case. It was assumed that cost reduction in this case is driven largely by reduction in carbon fiber costs from the $40/kg starting point in 2015. Mass was decreased by 1% per year in the lower bound cost case. It was assumed in this case that fiber costs would not come down significantly over time from their starting point of $25/kg in 2015, but quantity of carbon fiber could be reduced. This reduction would occur due to lower fiber safety factors as fiber quality improves, lower initial burst pressure ratios as tank manufacturing quality improves, and higher translation efficiency through improved fiber winding patterns.

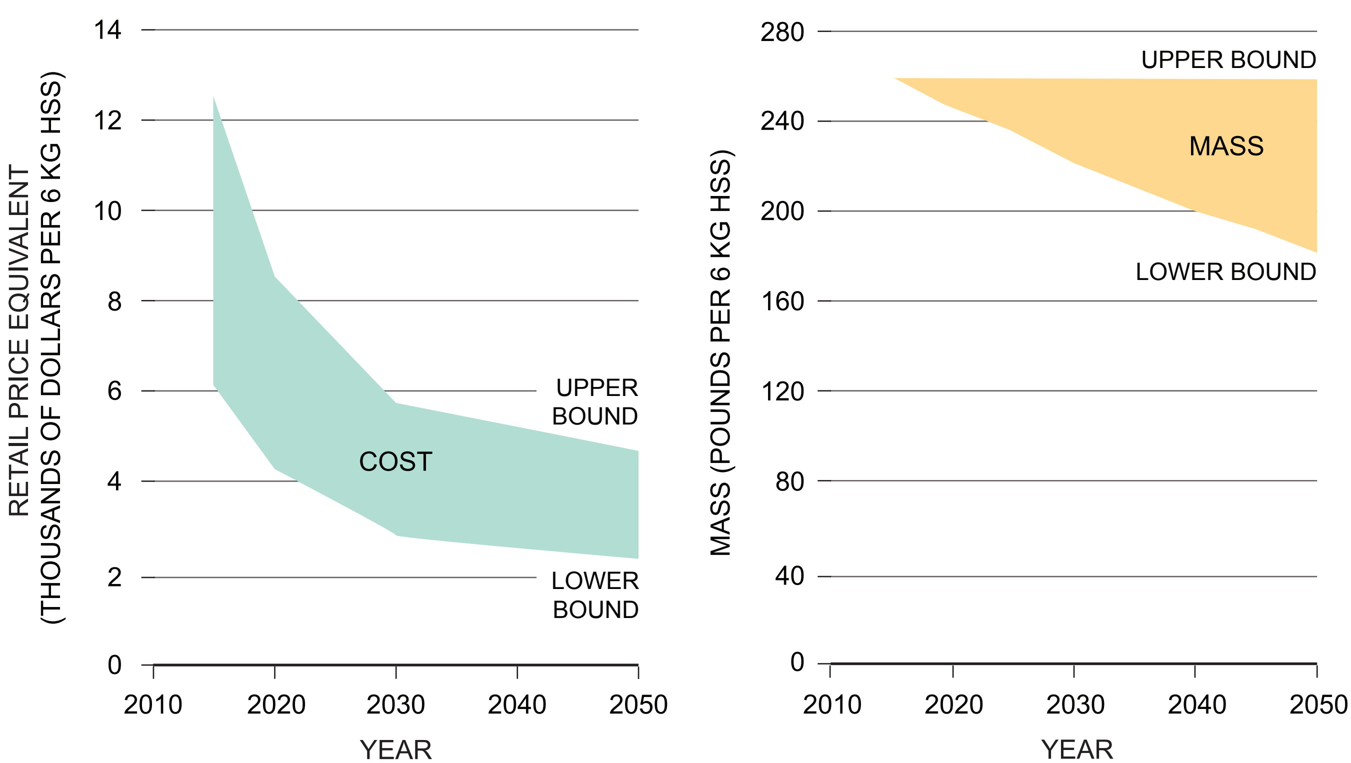


Figure 15-9. *Hydrogen Storage System (HSS) Retail Price Equivalent and Mass over Time*

Figure 15-9 shows the resulting HSS RPE and mass upper and lower bounds for a 6 kg HSS, a size that could provide 300 miles of range for a larger vehicle. These data assume production minimum volumes of 30,000 units annually; at very low volumes, the HSS RPE is expected to be higher than shown in Figure 15-9.

Fuel Cell System Cost

The fuel cell system is in many ways similar to a battery pack. Like a battery pack, it includes at its core a series of cells that convert chemical energy to direct current electric power. Within the fuel cell system, there are traditional components such as compressors and valves that will yield cost reduction when produced at volume. There are also unique materials such as the membranes, catalyst layers, gas diffusion layers, and bipolar plates.

The projected cost of the fuel cell system for an FCEV has fallen over 80% in less than a decade based on modeled costs for high-volume manufacturing (500,000 units/year) of an 80-kW fuel cell system.[29] The 2010 projected cost of fuel cell systems at various volumes is shown in Figure 15-10.[30] In 2002, an 80-kW fuel cell system for an FCEV, including both the fuel cell stack and the balance of plant, was estimated to cost $275/kW under high-volume manufacturing.

Based on projected fuel cell technology advancements from 2010 to 2015, Directed Technologies Incorporated (DTI) estimated that the high-volume manufacturing cost of an 80-kW fuel cell system to fall to $39/kW in 2015[31] (see Figure 15-11.)

Opportunities to reduce the cost of fuel cell systems include the following:

- Membrane materials that can be volume manufactured at lower cost

29 U.S. Department of Energy, Hydrogen and Fuel Cells Program, DOE Hydrogen Program Record 10004, "Fuel System Cost – 2010," September 16, 2010.

30 Directed Technologies Inc., *Mass Production Cost Estimation for Direct H2 PEM Fuel Cell Systems for Automotive Applications: 2010 Update,* September 30, 2010.

31 Ibid.

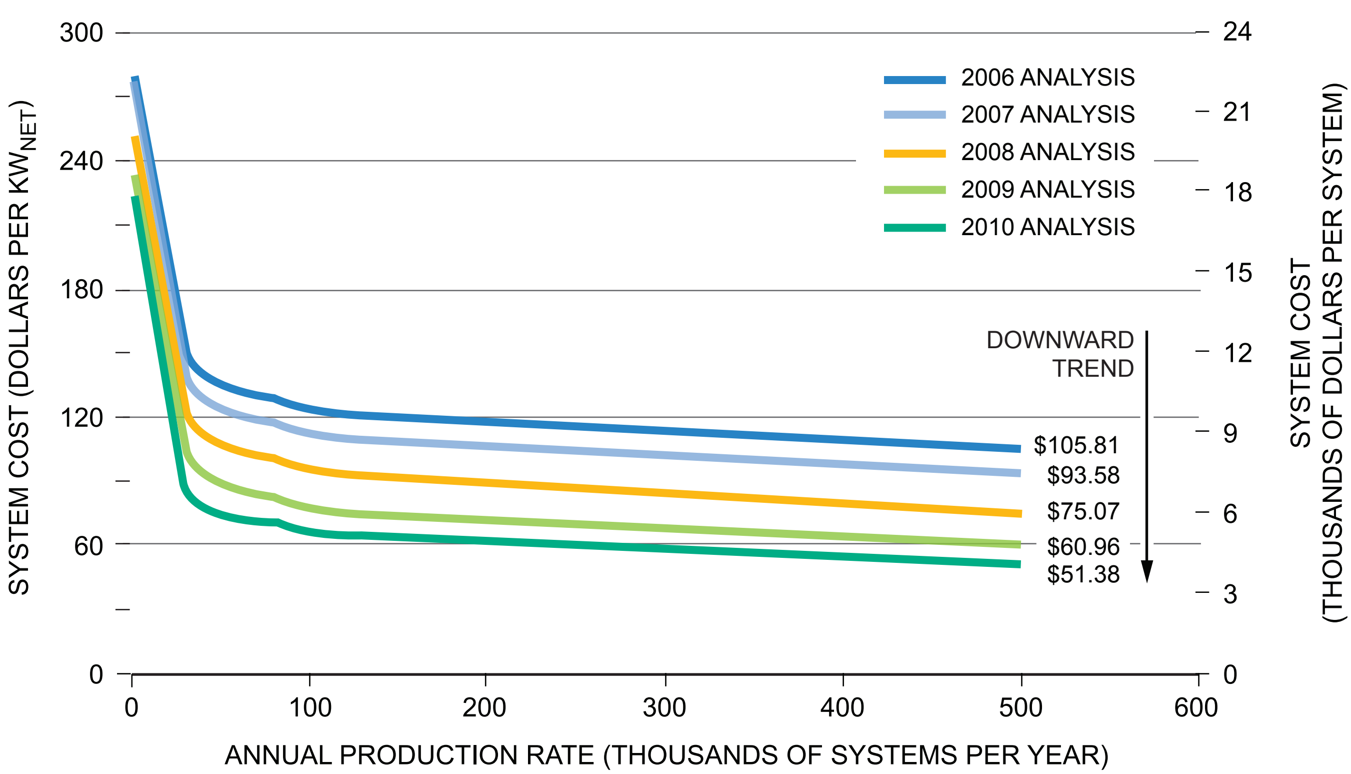


Figure 15-10. *Cost of Fuel Cell System Based on Projected 2010 Technology*

- Tougher membranes that can be made thinner and still meet durability requirements
- Catalyst structures that increase the effective surface area of precious metals
- New catalysts that do not use precious metals
- Membranes that can operate at higher temperature for increased activity with less catalyst
- Rapid manufacturing techniques for each of the layered materials
- Integration of layered materials into unit pieces for quick assembly
- Plate materials that are conductive, chemically stable, and low in cost.

Using the DTI estimate of approximately $40/kW as a 2015 high-volume baseline cost, fuel cell system cost upper and lower bounds over time were established by applying a ±20% uncertainty margin to the 2015 value and an improvement rate of 3% per year for 2015 to 2020, 2% per year for 2020 to 2025, and 1% per year from 2025 to 2050. Vehicle volumes were assumed to be less than 500,000 per year early on, and costs were increased by 60% for 2015, 28% for 2020, and 17% for 2025 based on assumed yearly volumes of 30,000, 80,000, and 130,000, respectively. These cost vs. volume multipliers were based on the same DTI fuel cell system analysis and were also applied to the HSS costs as described above.

A 30% markup was assumed from OEM factory cost to RPE. Mass of the fuel cell system was based on the 2009 status shown in Figure 15-6. However, this 2009 mass status did not reflect the thin plate stacks that OEMs have adopted for future stack design.[32] The mass per kW was scaled by 75% to account for this change and was then held constant over time. Figure 15-12 shows the resulting fuel cell system RPE and mass.

FCEV Cost Projections

From an overall cost of ownership perspective, a recent analysis performed by McKinsey & Company projected that after 2025 the total cost of ownership for all vehicle powertrain types (gasoline ICE, diesel

32 McKinsey & Company, *A portfolio of power-trains for Europe: a fact-based analysis,* 2010.

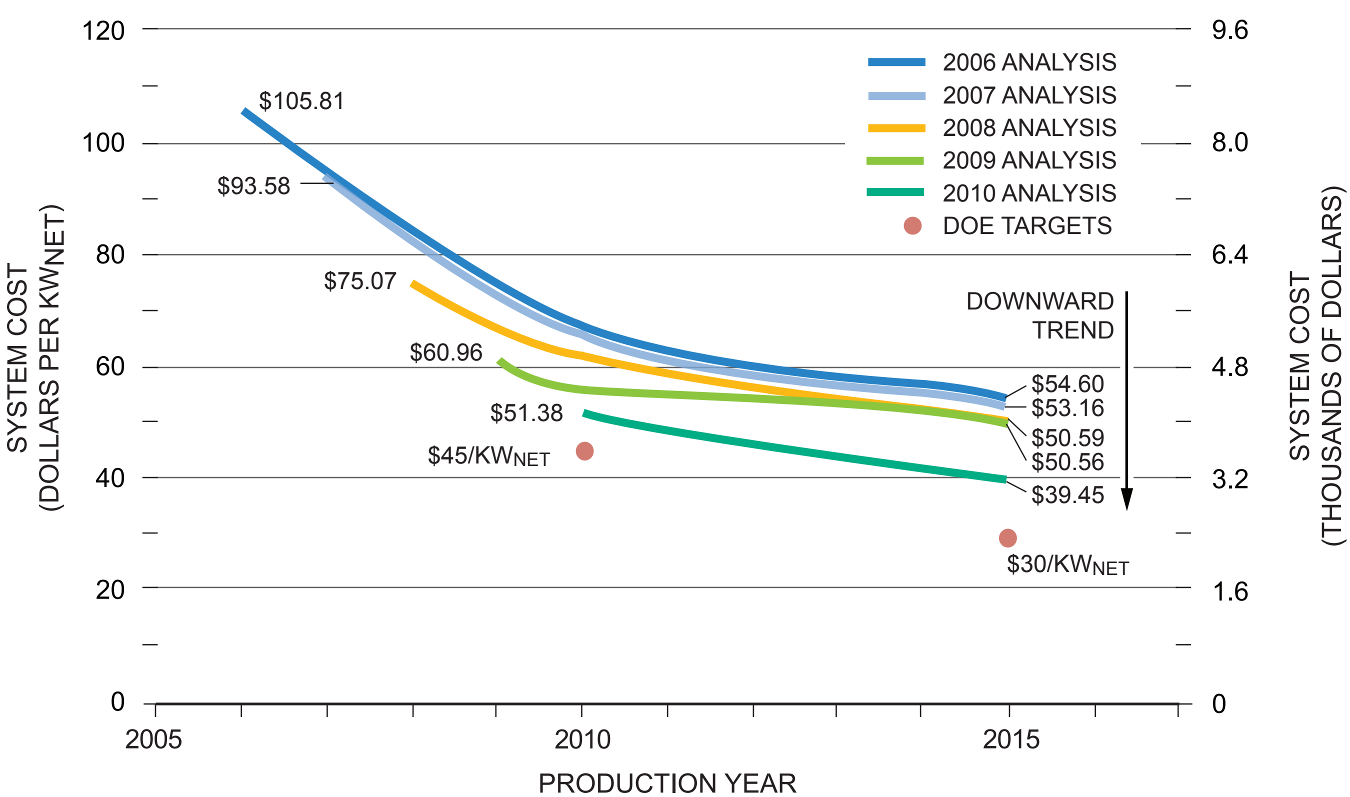


Figure 15-11. *Cost of Fuel Cell System Based on Projected 2015 Technology*

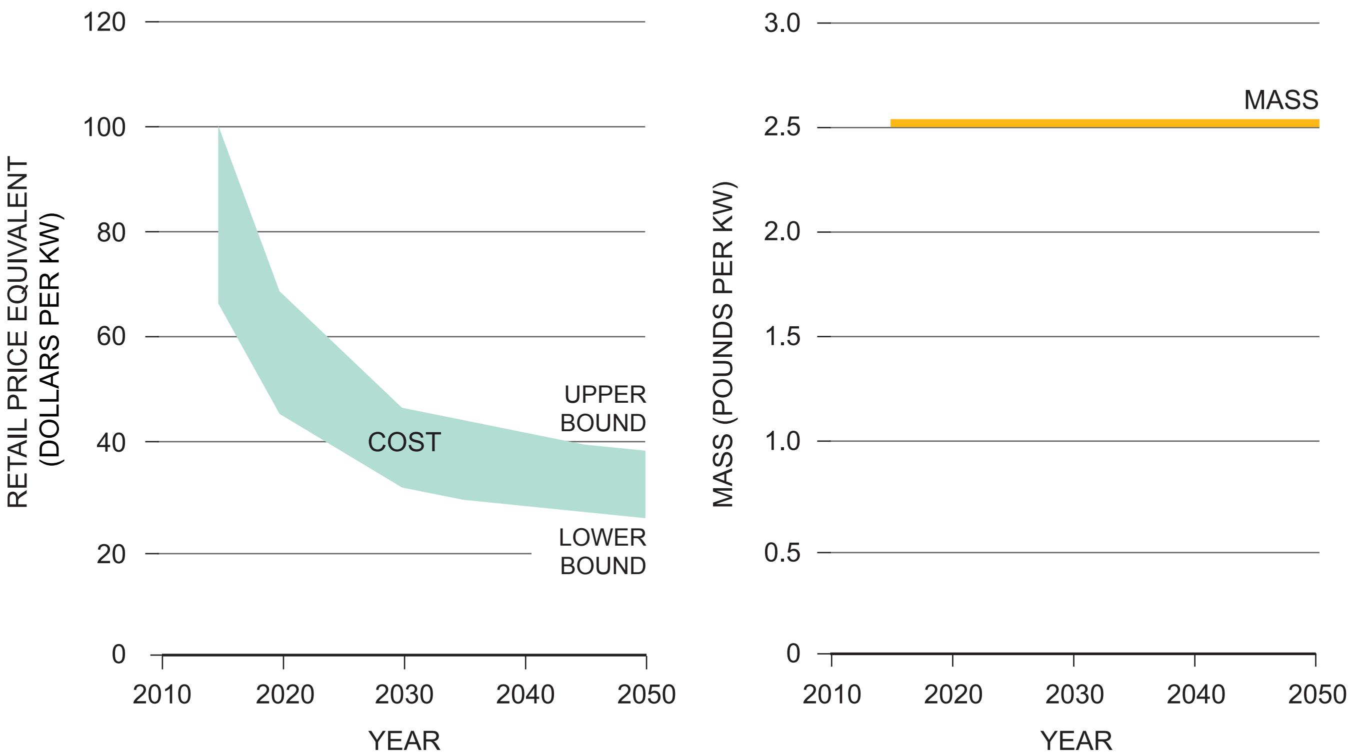


Figure 15-12. *Fuel Cell System Retail Price Equivalent and Mass over Time*

ICE, battery electric vehicles, plug-in hybrid electric vehicles, and FCEVs) converge, and that by 2050 the total cost of ownership varies by less than 5% across all vehicle platforms.[33] For FCEVs, this results from both high fuel economy (thereby reducing the fuel costs of ownership) and reductions in the FCEV purchase price.

This is supported by a 2007 study that estimated an incremental cost range of $3,600 to $5,100 for an FCEV in 2030 over a conventional gasoline ICE vehicle.[34]

HYDROGEN FUEL AND INFRASTRUCTURE CONSIDERATIONS

Hydrogen has been produced by and/or supplied to a wide variety of industries for over 50 years. In 2010, 52.5 billion kg of hydrogen was produced worldwide, and even in the absence of FCEVs, the annual demand for hydrogen is expected to increase 30% to 69 billion kg/year by 2014.[35] The vast majority of hydrogen today is produced for use by oil refineries, the chemical industry (methanol, ammonia, hydrochloric acid), the food industry (oil/fat hydrogenation), steel and glass making (an oxygen scavenger), pharmaceutical reactions, and electric generator cooling (heat transfer media).

Table 15-9 is a summary of the status of key characteristics for hydrogen fueling infrastructure readiness. The status and advancement opportunities for each of these characteristics are discussed in greater detail below.

Two approaches can be used to provide hydrogen for transportation fuel applications. The centralized approach is where hydrogen is produced at a large centralized facility and distributed to fueling stations where it is further compressed, stored, and dispensed into vehicles. The distributed approach is where hydrogen is produced at

33 Ibid.

34 Matthew A. Kromer and John B. Heywood, *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet,* Laboratory for Energy and the Environment, Massachusetts Institute of Technology, May 2007.

35 SRI Consulting, *Chemical Economics Handbook – Hydrogen,* IHS Chemical, July 2010.

Technology Benefits	Recent Achievements	Near-Term Focus Areas
☑ Domestic Feedstock	☑ Distribution	■ Fuel Cost
☑ Large Scale Production	☑ Dispensing	■ Fueling Network
☑ Low GHG Emissions		■ On-site Compression
		■ On-site Storage

☐ Better than conventional ☐ Parity with conventional ■ Not yet at parity with conventional

Table 15-9. *Hydrogen Fueling Infrastructure Readiness Summary*

distributed sites (e.g., onsite at a fueling station) and compressed, stored, and dispensed thereafter. The feedstock and station equipment (other than distributed hydrogen production equipment) for both approaches can be similar (see Figure 15-13).

This section addresses feedstock that can be utilized to produce hydrogen; approaches commonly used to produce and distribute hydrogen; equipment needed to compress, store, and dispense hydrogen into vehicles; fueling network needs; emissions; and cost.

Feedstock

Hydrogen can be produced from a variety of feedstocks, both renewable and fossil. Additionally, industrial process waste streams can be a feedstock. Today, 96% of all hydrogen worldwide is produced from fossil feedstock at large centralized facilities, with natural gas being the most common hydrocarbon feedstock[36] (see Figure 15-14).

36 Ibid.

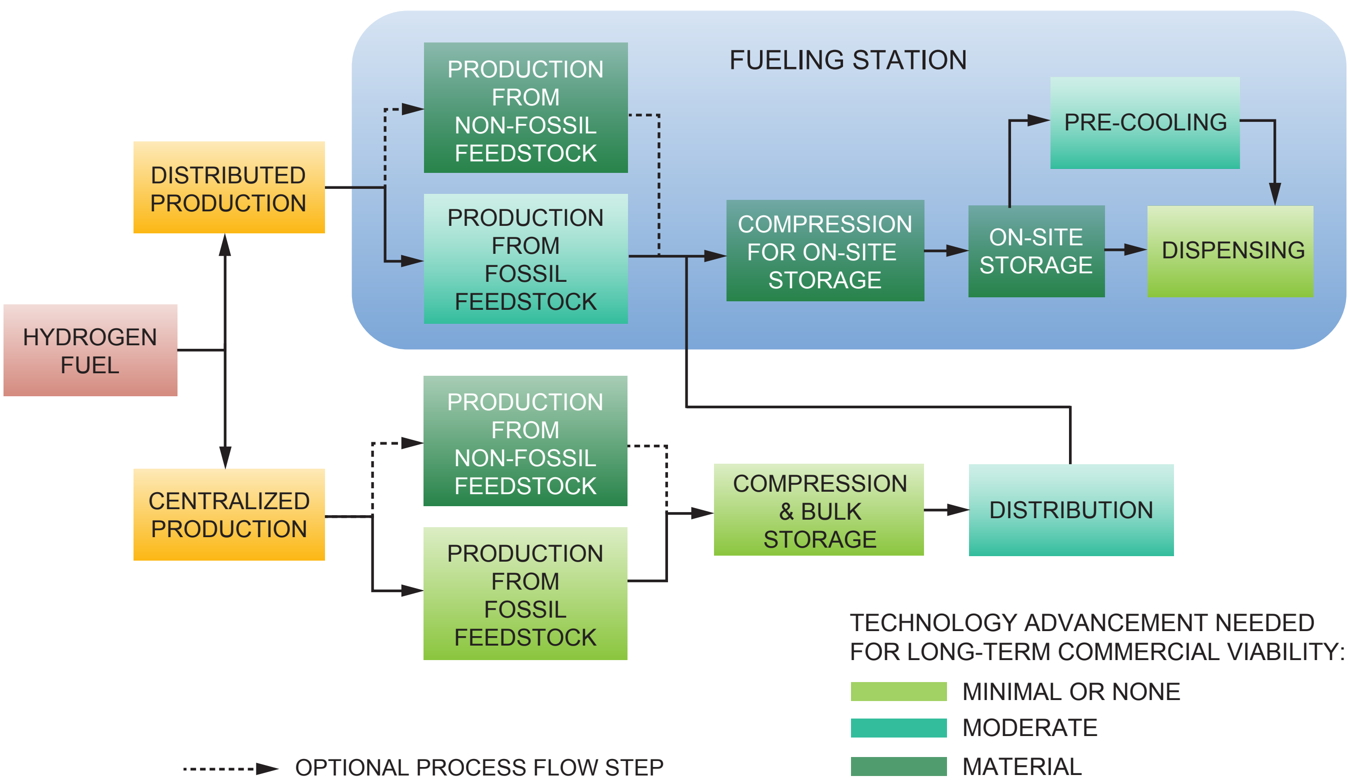


Figure 15-13. *Centralized & Distributed Hydrogen Fuel Approaches*

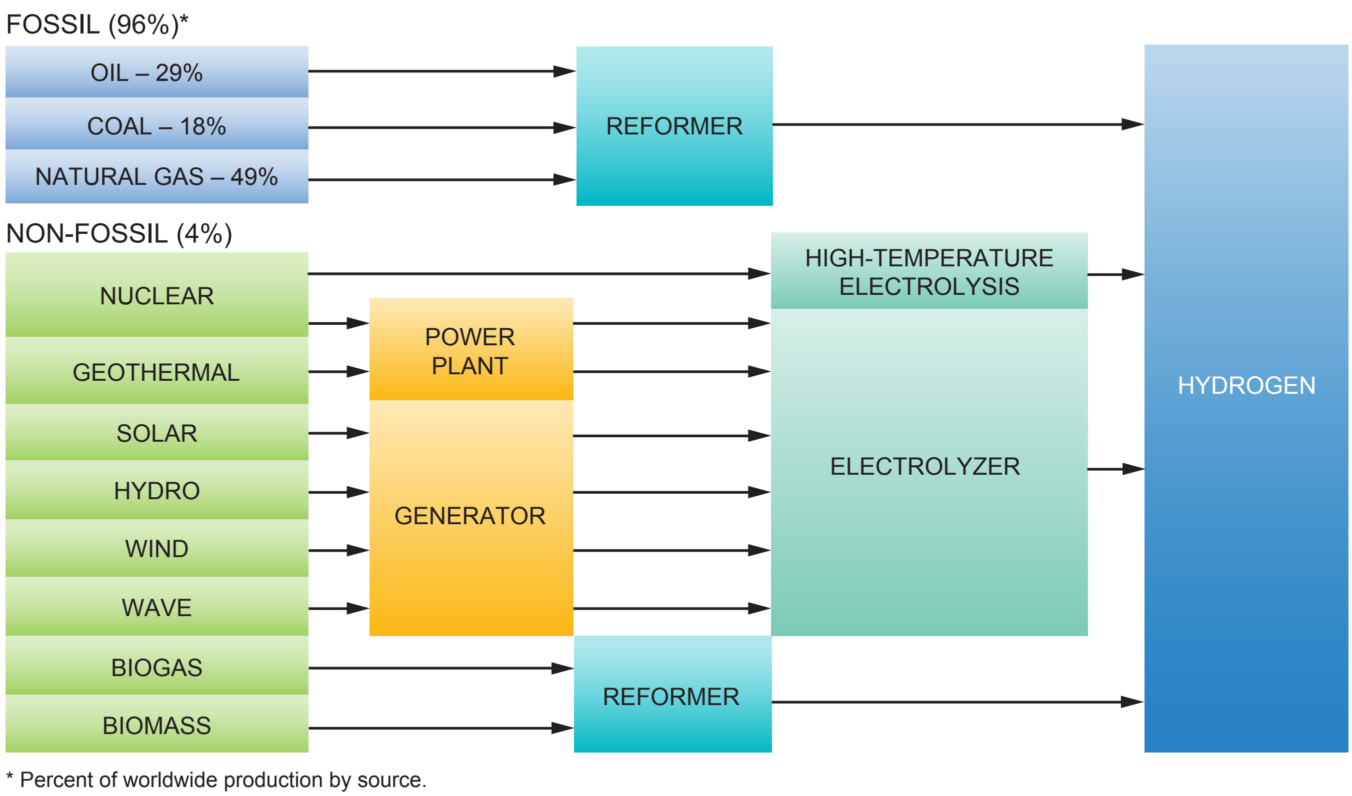


Figure 15-14. *Feedstock Options for Hydrogen Production Pathways*

Conventional Feedstock

Innovations for economical extraction of an abundance of shale-based natural gas in the United States provide an opportunity to explore a greater role for natural gas in meeting U.S. energy needs. According to the EIA, "Of the natural gas consumed in the United States in 2009, 87% was produced domestically."[37] The future availability of large quantities of shale gas will further allow the United States to consume a predominantly domestic supply of natural gas.[38]

According to the EIA, the United States possesses 2,552 trillion cubic feet (tcf) of potential natural gas resources. Natural gas from shale resources, considered uneconomical just a few years ago, account for 827 tcf of this resource estimate. At the 2009 rate of U.S. consumption (about 22.8 tcf per year), 2,552 tcf of natural gas would be enough for ~110 years.[39]

To put the natural gas needs of a hydrogen-based transportation system in context, it has been estimated that the deployment of 10 million FCEVs would increase U.S. natural gas consumption by 2%.[40] According to AEO2010, the current U.S. national vehicle fleet is approximately 220 million vehicles. If 50% of these vehicles (110 million vehicles) were FCEVs using hydrogen produced from natural gas, total U.S. natural gas consumption would increase by approximately 20%. The use of natural gas as a feedstock for the early deployment of FCEVs should not have a significant impact on natural gas consumption; however, if the majority of the national vehicle fleet were FCEVs, this would likely have a material impact on natural gas consumption.

37 Energy Information Administration, "Energy in Brief," 2010.

38 National Petroleum Council, *Prudent Development: Realizing the Potential of North America's Abundant Natural Gas and Oil Resources,* September 2011.

39 U.S. Energy Information Administration (website), Energy in Brief, "What is shale gas and why is it important," July 9, 2012, http://www.eia.doe.gov/energy_in_brief/about_shale_gas.cfm.

40 Britta K. Gross, Ian J. Sutherland, and Henk Mooiweer, *Hydrogen Fueling Infrastructure Assessment,* GM Research & Development Center, December 2007.

Renewable Sources

Non-fossil resources that could be leveraged to produce hydrogen include biogas, biomass, nuclear, solar, wind, digester gas, and other waste streams. A 2007 study by the National Renewable Energy Laboratory (NREL) concluded that if all available and applicable feedstock is deployed only for this purpose, "approximately 1 trillion kg of hydrogen could be produced annually from wind, solar and biomass resources in the United States."[41] This amount of renewable hydrogen production is enough to fuel the entire U.S. vehicle fleet ten times over for the foreseeable future. The renewable resources available for hydrogen production are widely distributed across the United States. As seen in Figure 15-15, the vast majority of counties in the United States are capable of producing renewable hydrogen. These resources need to be assessed further for technical and economic viability as hydrogen feedstock, especially in relation to their use in other sectors like electric power generation and as a feedstock for other transportation fuels.

Waste Stream Sources

Finally, hydrogen is a by-product of various manufacturing processes. Gaseous waste streams, including those from chlor-alkali plants, styrene, ethylene, and acetylene production, could be utilized to produce hydrogen for FCEVs, although a clean-up step would be needed.[42]

Hydrogen Production and Distribution

The three most commonly deployed processes to produce hydrogen in the United States today are steam methane reforming, conversion of chlor-alkali effluent, and water electrolysis. Additionally, efforts are under way to develop economical technologies that utilize renewable feedstock for the production of hydrogen, resulting in lower carbon dioxide (CO_2) emissions ("renewable hydrogen"). Brief overviews of selected hydrogen production processes are provided below.

Steam Methane Reforming of Natural Gas. This process uses natural gas as a feedstock to produce hydrogen and is currently the most prevalent. Hydrogen production via steam methane reforming (SMR) is a process where natural gas is broken down in a reaction with high temperature steam (steam reforming reaction) in the presence of a catalyst to produce a hydrogen-rich gas. The hydrogen content is further enriched with an additional catalytic step (water gas shift reaction) where the carbon monoxide and steam in the gas mixture further react to produce hydrogen and carbon dioxide.[43] The final products are hydrogen and CO_2. The CO_2 is typically released into the atmosphere but could be sequestered by deploying carbon capture and sequestration (CCS). Biogas can also be an alternative feedstock for the SMR process to significantly reduce the net CO_2 emissions from this pathway. A discussion on renewable natural gas can be found in Chapter Fourteen of this report, "Natural Gas." The efficiency of SMR ranges from 70 to 80% on a lower heating value (LHV) basis at peak loading and can be as high as 90% when optimized with the coproduction and use of heat and power at large production facilities.[44] Efficiency falls rapidly at partial loading; therefore, full utilization of production capacity is desired.

Water Electrolysis. Electrolysis involves splitting water molecules with electric power into oxygen and hydrogen. The oxygen is typically released into the atmosphere and the product hydrogen is captured, compressed, stored, and distributed. Electrolysis typically has a lower efficiency than SMR (55 to 70% on an LHV basis when measured from electricity input to fuel output);[45] however, unlike SMR, efficiency is best at low output levels and declines as output increases. At long-term average historical electricity and natural gas prices, water electrolysis is the more expensive alternative. However, electrolysis offers some noteworthy benefits. Electrolysis plants are compact, operate at low temperatures, and produce no CO_2 locally.

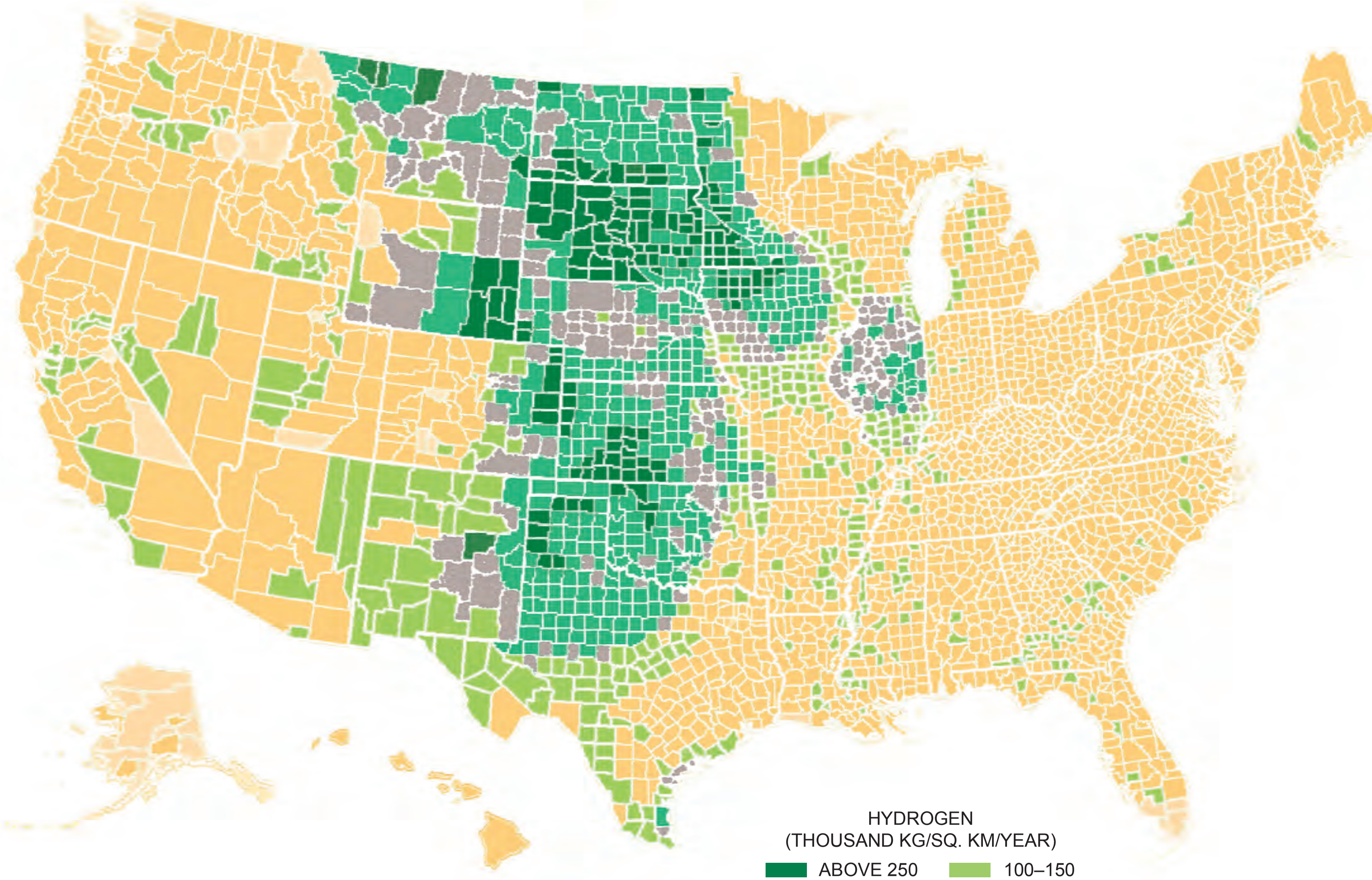
41 A. Milbrandt and M. Mann, *Potential for Hydrogen Production from Key Renewable Resources in the United States,* National Renewable Energy Laboratory, NREL/TP-640-41134, February 2007.

42 National Hydrogen Association, *Hydrogen and Fuel Cells: The U.S. Market Report,* March 2010.

43 Britta K. Gross, Ian J. Sutherland, and Henk Mooiweer, *Hydrogen Fueling Infrastructure Assessment,* GM Research & Development Center, December 2007.

44 Pamela L. Spath and Margaret K. Mann, *Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming,* National Renewable Energy Laboratory, NREL/TP-570-27637, Revised February 2001.

45 National Renewable Energy Laboratory, *Current (2009) Stateof-theArt Hydrogen Production Cost Estimate Using Water Electrolysis,* Independent Review, published for the U.S. Department of Energy Hydrogen Program, NREL/BK6A146676, September 2009.



Note: This analysis shows hydrogen potential from combined renewable resources – wind, solar, and biomass. Select environmental and land use exclusions were applied.

Source: National Renewable Energy Laboratory.

Figure 15-15. *Hydrogen Potential from Renewable Sources (Total Kilograms of Hydrogen per County, Normalized by County Area)*

Use of hydroelectric power, wind power, or nuclear power can reduce or eliminate the total CO_2 emissions from this pathway. Electrolysis is well understood; however, this technology is not typically selected over SMR due to higher costs. In cases where electricity is produced using hydrocarbon feedstocks, it is usually more economical to extract hydrogen from the hydrocarbon source directly than from water through the electrolysis process.

Renewable Hydrogen Production. Gasification of biomass, electrolysis with renewable electricity, and SMR with renewable natural gas are well known processes for producing renewable hydrogen and are expected to become competitive before other renewable hydrogen production options. DOE is exploring longer-term, advanced production technology approaches including the following:[46]

- *Advanced fermentation of hydrocarbons* – conversion of lignocellulosic biomass into sugar-rich feedstocks including hemicelluloses and cellulose that can be fermented directly to produce hydrogen, ethanol, and high-value chemicals.
- *Biological water splitting* – production of hydrogen by water splitting photosynthetic microbes during their metabolic activities using light energy (e.g., algal production of hydrogen).
- *Photoelectrochemical water splitting* – production of hydrogen by directly splitting water into hydrogen and oxygen using multi-junction cell technology developed by the photovoltaic industry.
- *Conversion of biomass and wastes* – production of hydrogen via pyrolysis of biomass resources such as agricultural residues like peanut shells; consumer wastes including plastics and waste grease; or biomass specifically grown for energy uses. Biomass pyrolysis produces a liquid product (bio-oil) that can be used for the production of hydrogen.
- *Solar thermal splitting* – production of hydrogen using highly concentrated sunlight to generate the high temperatures needed to split methane into hydrogen and carbon or water into hydrogen and oxygen. Concentrated solar energy generates temperatures of several hundred to over 1,500°C for these reactions.[47]

Each of the renewable options mentioned above is economically challenging and scalability can be limited due to lack of readily available renewable feedstock. The most advanced renewable hydrogen production technologies are still in the research phase. Investments are needed to evaluate alternatives and advance promising options through research, towards pilot scale and commercialization at scale such that hydrogen can be produced reliably and economically in the long term. These opportunities are not considered critical path for the near term because hydrogen production from natural gas is already commercial and has a relatively low well-to-wheels carbon footprint (discussed in detail in the "Emissions" section later in this chapter).

Due to renewable resource supply limitations and geographic variations in resource costs and availability, multiple renewable hydrogen production technologies may be appropriate and should be pursued. Multiple renewable technology options could offer feedstock optionality and the potential to better optimize to varying local conditions such as biomass availability, electricity prices, water constraints, and sunlight.

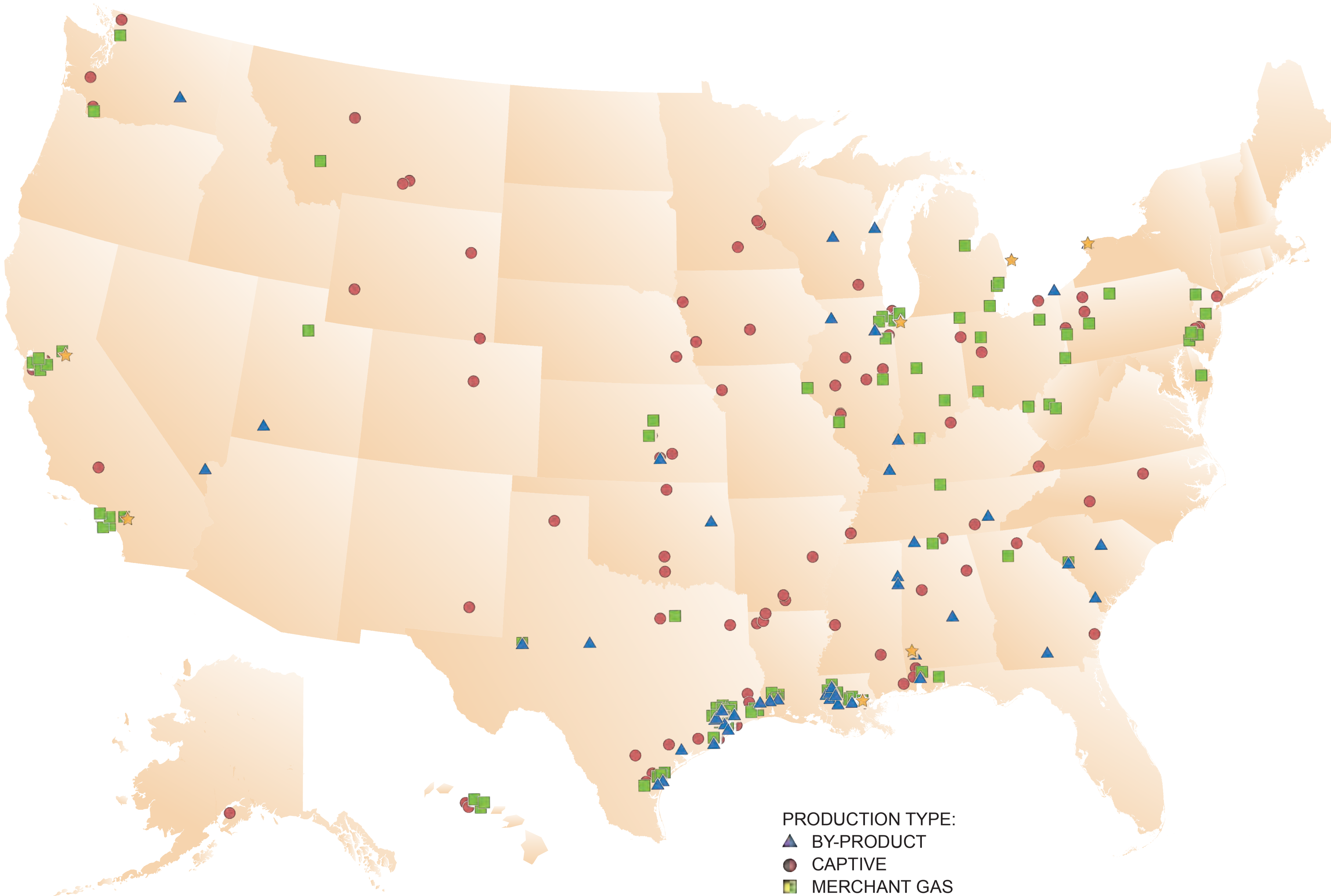
Centralized Production

Large hydrogen production facilities (>18,000 kg/day) exist in nearly every state, supplying approximately 1,000 locations with bulk hydrogen (see Figure 15-16). Some of these facilities could expand production capacity if needed. Leveraging existing assets to provide merchant hydrogen capacity is a strategy practiced in the industrial gas industry. Excess merchant hydrogen production capacity exists today; however, this supply is limited and the location of excess hydrogen capacity may not align with demand and quality requirements and should be further explored.

Excess bulk hydrogen production capacity at existing refineries is limited to small quantities if at all. Existing refinery hydrogen production capacity is, and will continue to be, required to produce gasoline and diesel fuel. Refinery hydrogen demand

46 National Renewable Energy Laboratory (website), Hydrogen & Fuel Cells Research, "Hydrogen Production and Delivery," www.nrel.gov/hydrogen/proj_production_delivery.html.

47 FreedomCAR and Fuel Partnership, *Hydrogen Production Roadmap: Technology Pathways to the Future,* January 2009.



Source: National Renewable Energy Laboratory.

Figure 15-16. Existing Centralized Hydrogen Production Facilities is expected to grow significantly in the next 10–20 years as refineries process heavier crude oil and as diesel demand grows, both of which require more hydrogen.

Central hydrogen production also offers the opportunity for adding CCS, once the technology matures and costs are reduced, thus further reducing CO_2 emissions. CCS technologies are being demonstrated today.

Distribution

After production at a large centralized facility, hydrogen can be (1) compressed and distributed in gaseous state through pipelines, where available; (2) compressed and distributed in gaseous state by truck; or (3) liquefied by cooling to -253°C and delivered by truck. Pipelines are technically possible and often the lowest cost option with sufficient demand, as demonstrated by existing hydrogen pipeline networks in the Gulf Coast (Texas to Louisiana) and Southern and Northern California. DOE Hydrogen Program analysis suggests pipeline distribution could be a low cost option for hydrogen delivery at very large-scale in some geographies.[48] In the time frame of this analysis (through 2050), pipeline distribution is not expected to represent a significant share of hydrogen deliveries given the challenges associated with permitting, right of way, and growth to large-scale demand. Since the inclusion of pipeline distribution on a limited basis will not materially impact the average cost of dispensed hydrogen, distribution by truck is the primary focus area for this analysis.

On-road hydrogen deliveries are traditionally made by tankers that carry up to 4,000 kg of liquid hydrogen to stationary liquid hydrogen storage tanks or by tube trailers that carry up to 250 kg of gaseous hydrogen at 2,500 psi in steel cylinders. Two new on-road hydrogen distribution technologies (composite gaseous tube trailers and dual-phase tankers) were introduced in 2010. These new technologies use composite gaseous storage tubes and have the capability to increase gaseous hydrogen distribution capacity for each delivery by increasing payload capacity and integrating technologies on board delivery trucks. Descriptions of these new on-road technologies are provided in Table 15-10.[49]

The benefit of an increased capacity for each delivery is a reduction in delivery costs due to simpler logistics and economies of scale. Additionally, if deliveries can be made at pressures at or above the pressure needed at the site, the need for on-site compression can be reduced and potentially eliminated.

Frequent delivery to a retail fueling location adds logistics complexity for station operators. Opportunities exist to further increase the carrying capacity of hydrogen delivery trucks through increasing service pressure by (1) the development and use of advanced materials; (2) advancement of codes and permitting that currently limit the use of advanced materials; and (3) integration of delivery and ground systems advancements.

Additional opportunities exist in the development of technologies that leverage existing distribution infrastructure, such as the existing natural gas pipeline network, to locally produce hydrogen to serve a region. For example, The Gas Company in Hawaii distributes blended hydrogen (~15%) and natural gas (~85%) in its pipelines. The hydrogen could be separated from the natural gas at delivery point if economical.

Distributed Production

In this approach, a small-scale hydrogen production unit would be deployed at a refueling facility, thus avoiding the need for a hydrogen distribution system; however, the distribution of the energy feedstock must still be considered. SMR and water electrolysis processes are commonly used options for distributed hydrogen production. Today, these technologies are more commonly used to produce hydrogen for smaller industrial processes. However, both processes have been successfully demonstrated in real world settings for fueling applications. Distributed SMR and water electrolysis systems capable of producing approximately 100 kg/day and 60 kg/day, respectively (supporting up to 100 and

48 U.S. Department of Energy, Fuel Cell Technologies Program, "DOE Hydrogen Production and Delivery Research & Development Progress," presented at IPHE Meeting, Shanghai, China, September 21, 2010, http://iphe.net/docs/Events/China_9-10/1-3_2010-9-21_IPHE_PDRD.pdf.

49 Air Products Presentation to NPC Study Hydrogen Team on March 23, 2011.

Composite Gaseous Tube Trailers	Dual-Phase Tankers
• Constructed using composite storage cylinders (approved in 2010) vs. steel cylinders • Delivery capacity up to 1,000 kg at 500 bar – Each truck can carry up to 4 modules with 250 kg/module capacity • Can eliminate on-site compression for fuel dispensing at 350 bar; factors to evaluate include fueling time and delivery frequency • Reduces compression requirement for fuel dispensing at 700 bar • Several trailers in commercial use today	• Carry liquid hydrogen with vaporizer and compressor on board • Delivery capacity up to 4,000 kg at 700 bar • Liquid and gaseous delivery capability • Effective for higher volume deliveries and routes with smaller deliveries to multiple sites • Can eliminate on-site compression for fuel dispensing at 350 or 700 bar; factors to evaluate include fueling time and delivery frequency • Several on the road worldwide

Table 15-10. *Comparison of New Technology for Hydrogen Distribution*

60 FCEVs, respectively), have been demonstrated for fueling applications today.[50,51] Larger systems are available, but the scale of future distributed production systems will depend on footprint requirements, land availability, economics, and demand.

Although not considered critical path for commercialization, incremental technology advancements are needed to: (1) reduce production equipment costs; (2) increase the density (production capacity/area) of water electrolysis systems; and (3) improve technologies that can produce renewable hydrogen.

A comparison of centralized vs. distributed production of hydrogen is provided in Table 15-11.

50 Rob Regan, et al., "DTE Energy Hydrogen Technology Park," DOE Hydrogen Program FY 2005 Progress Report.

51 Puneet Verma and Dan Casey, "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," DOE Hydrogen Program 2008 Annual Merit Review Proceedings, June 2008.

Compression, Storage, and Dispensing

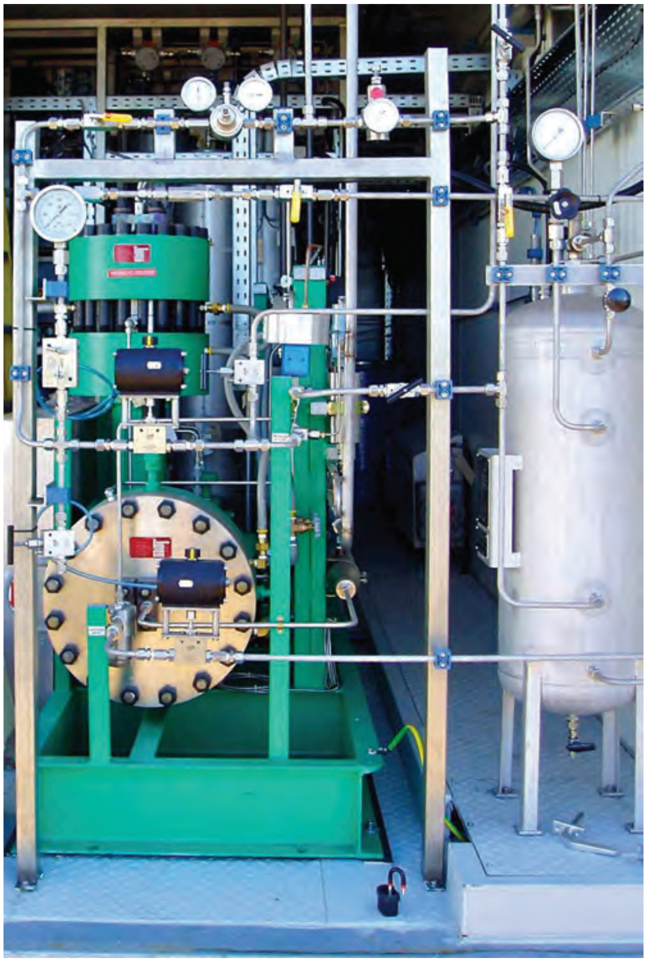
If delivered to a fueling station as a liquid, hydrogen is stored in a liquid tank and subsequently converted to a gas through the use of a vaporizer. After being converted, or if delivered as a gas, hydrogen is compressed to high pressures (if delivery pressure is lower than desired), stored in on-site cylinders, and dispensed as needed (see Figure 15-17). In the case of liquid hydrogen, a more efficient alternative to vapor compression is to pump the liquid directly to the desired pressure.

An example of a station configuration that incorporates hydrogen fueling is shown in Figure 15-18.[52]

Compression

Current FCEVs require 350 or 700 bar (5,000 or 10,000 psi) hydrogen. The land, maintenance, and

52 U.S. Department of Energy, H2A Delivery Scenario Analysis Model Version 2.2.



Source: These photos courtesy of the National Renewable Energy Laboratory.

Figure 15-17. *Typical On-Site Compression, Storage, and Dispensing Equipment*

capital required to compress hydrogen to 350 and 700 bar can be significant and operationally challenging. A typical hydrogen compression system for fueling requires ~100 sq. ft. of land at a fueling station and should be located where equipment noise is either not a concern or can be buffered. The cost

Centralized Production & Distribution	Distributed Production
• Lower cost way to produce hydrogen – Natural gas feedstock is lowest cost • Existing industrial production capacity can be leveraged for vehicle fueling • Hydrogen distribution systems and logistics are required • Commonly distributed by truck at high pressure or as cryogenic liquid • New distribution technologies have lowered historical costs • Allows for broader allocation of fixed costs due to economies of scale	• Does not require hydrogen distribution system and logistics • Greater land requirements • In use in industrial settings and successfully demonstrated for vehicle fueling • Provides flexibility in feedstock choice on a site-by-site basis • Limited operating flexibility for SMR due to partial load (<50%) efficiency degradation and inability of frequent start/stop operation • Peak efficiency is lower than that of centralized systems, which leverage steam and power co-production capabilities • Distribution savings do not offset fixed costs at small scale

Table 15-11. *Centralized vs. Distributed Production of Hydrogen*

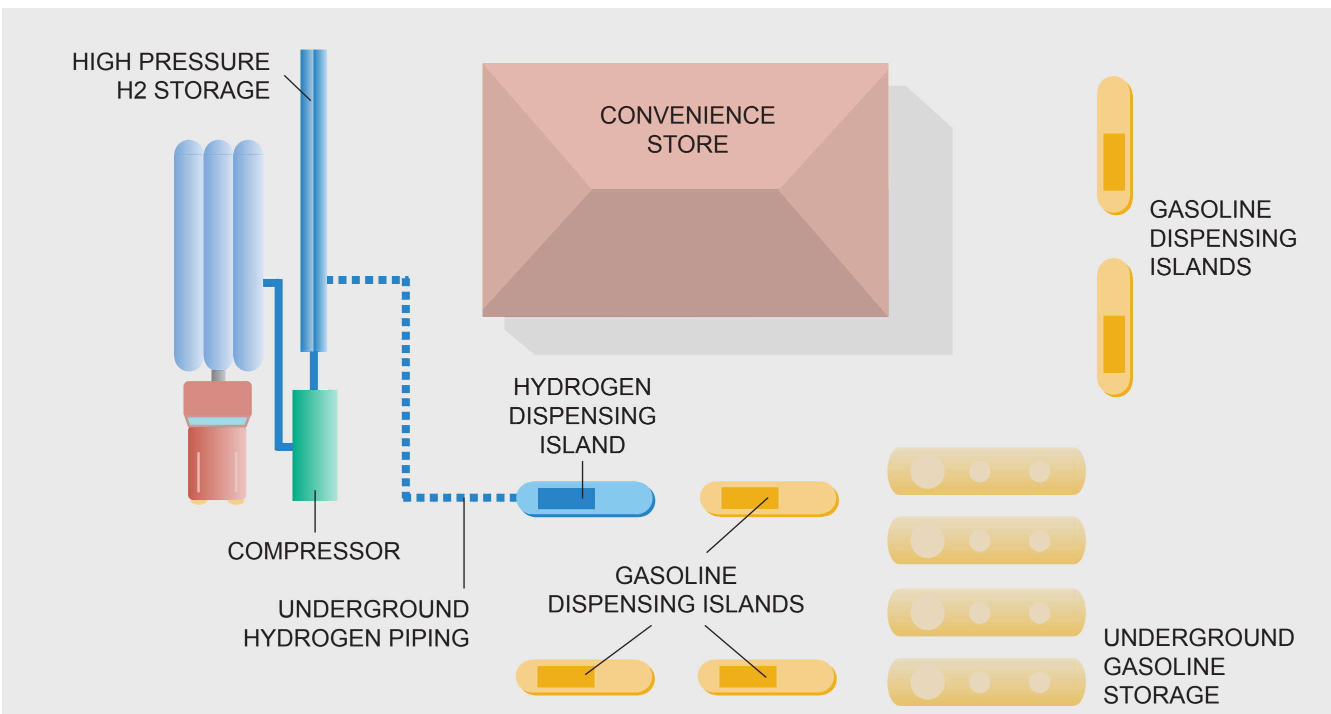


Figure 15-18. *Example Station Configuration*

of a compression system can range from 20 to 50% of the total cost of hydrogen fueling infrastructure at a fueling location. Additionally, based on operating data from demonstration fueling stations, the reliability of high-pressure hydrogen compressors at fueling locations has to date been inadequate for commercial applications.[53] Investigating the maintenance events for hydrogen refueling

53 National Renewable Energy Laboratory (website), Hydrogen & Fuel Cells Research, "Hydrogen Fuel Cell Electric Vehicle Learning Demonstration," http://www.nrel.gov/hydrogen/proj_learning_demo.html.

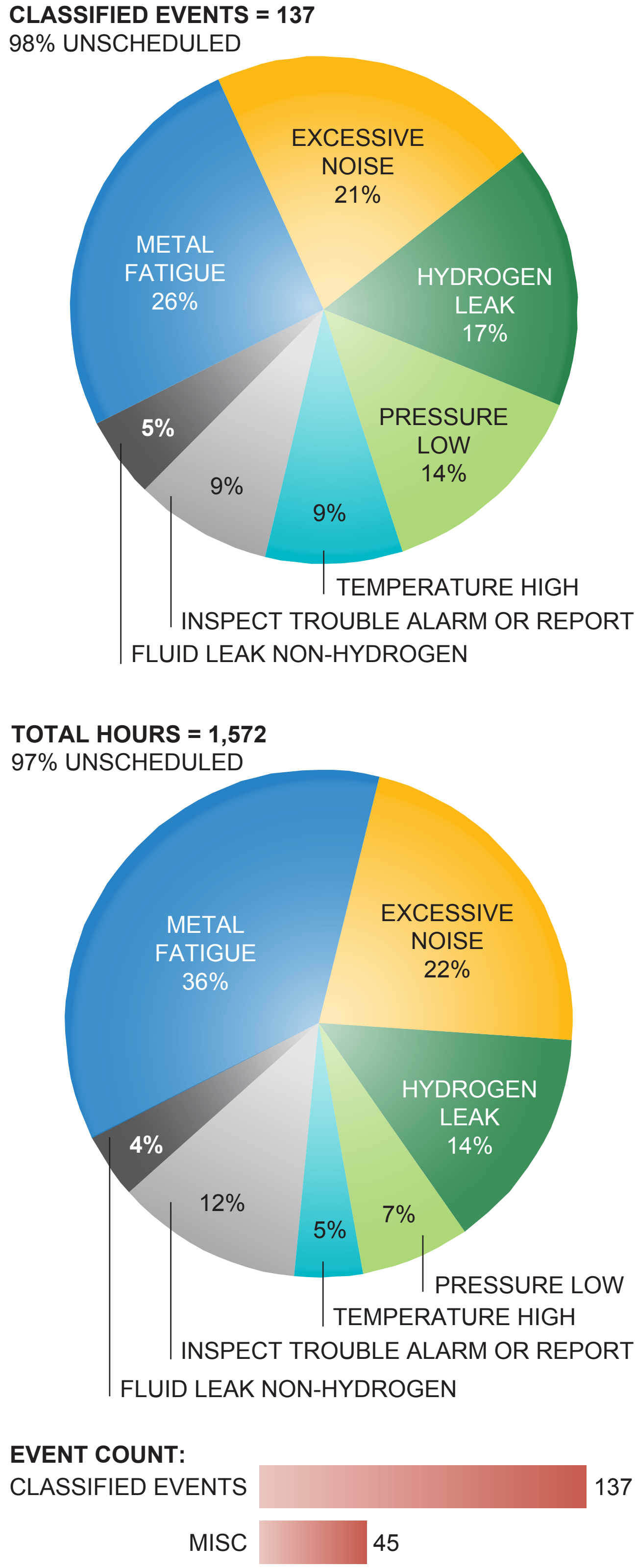
infrastructure occurring over a two-year period at ten fuel cell material handling equipment demonstrations funded by DOE and the U.S. Department of Defense, the NREL characterized the common modes of hydrogen compressor failures (shown in Figure 15-19).[54]

One industrial gas provider, for example, has made advancements towards the commercial introduction of a high-pressure, high-throughput compressor that uses an ionic fluid and is expected to be more reliable and require less land than comparable traditional compressors. Although this advancement is promising, compression will still require significant land at the station.

Reducing or eliminating the need for on-site compression through high-pressure delivery (>1,000 bar) and high-pressure storage, which is possible using the technology advancement discussed previously in the "Distribution" discussion, can address the land, cost, and operating challenges associated with hydrogen compression at a fueling station.

As another alternative to compression of gaseous hydrogen at a large-scale dispensing station, hydrogen may be liquefied at the central production plant and delivered in liquid form to the station. Under this scenario, liquid hydrogen can be pumped directly into a medium- or high-pressure station buffer for dispensing at 350 or 700 bar into an FCEV. This configuration is shown in Figure 15-20. The benefits of this approach are low energy use at the station (~10% of gaseous compression energy), smaller equipment size for a reduced station footprint (when compared to on-site production), and lower energy needs to meet the pre-cooling requirements for rapid hydrogen fueling. The penalty of higher energy use at the central plant for liquefaction is partially offset by reduced distribution energy costs for liquefied hydrogen compared to truck distribution of gaseous hydrogen and by reduced station energy use in pre-cooling and dispensing.

Storage systems onboard FCEVs may advance in the future such that high-pressure dispensing is no longer required. DOE is pursuing the development of advanced materials for onboard hydrogen storage. No material has yet been identified which has



Note: MISC includes the following failure modes: cavitation, debris infiltration, failed closed, flow high, manufacturing defect, moisture infiltration, operator protocol, preventative maintenance, maintenance error, upgrade, replace failed parts, other.

Source: National Renewable Energy Laboratory.

Figure 15-19. Hydrogen Compressor Failure Modes

54 National Renewable Energy Laboratory (website), Hydrogen & Fuel Cells Research, "Early Fuel Cell Market Demonstrations," http://www.nrel.gov/hydrogen/proj_fc_market_demo.html.

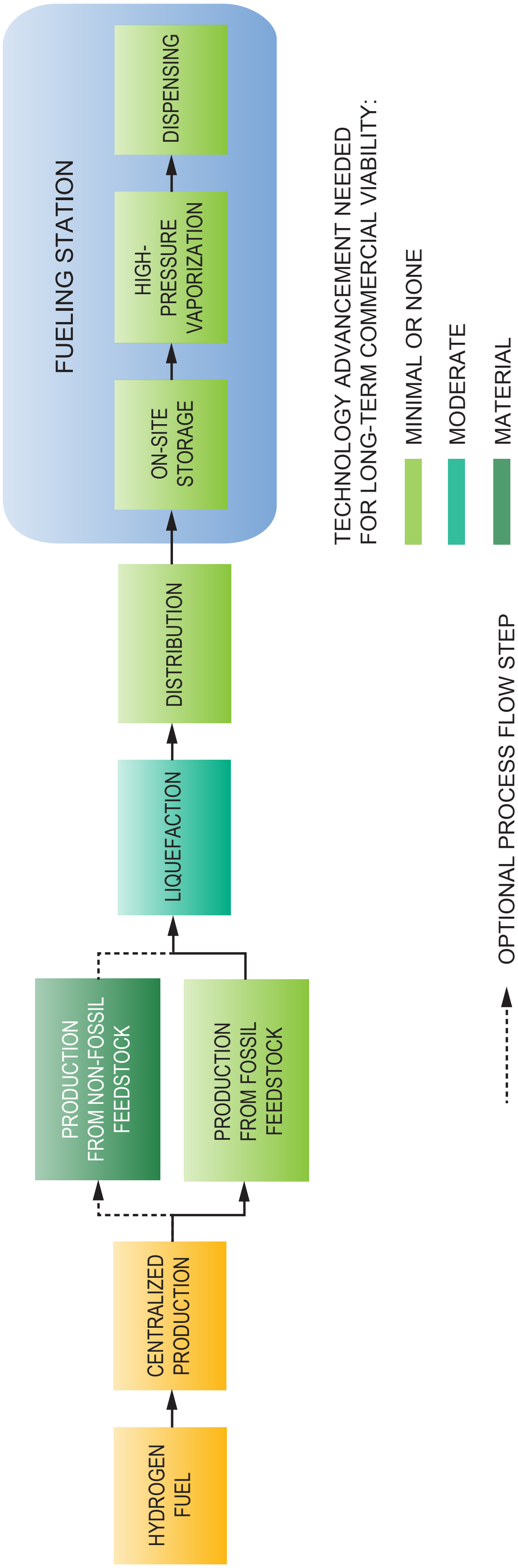


Figure 15-20. *Liquid Delivery Configuration to Eliminate Compression*

a high probability of achieving the necessary performance criteria. If this or other efforts to reduce or eliminate the need for high-pressure dispensing are successful, they would offer greater flexibility in on-site storage systems development, because compression requirements could be based on the need for hydrogen storage capacity on-site rather than dispensing pressure.

Storage

At fueling locations, hydrogen is typically stored in liquid tanks and/or a cascade of steel tubes capable of holding high-pressure hydrogen (commonly >700 bar) on concrete slabs at (or close to) ground level. Hydrogen is not typically stored underground due to safety practices which require visual inspection of hydrogen storage vessels. Installing steel tube storage systems on elevated platforms has been demonstrated; however, the cost of constructing a platform strong enough to support the weight of a storage system has been found to be prohibitive. The use of lightweight composite tube storage systems has not been demonstrated and the potential use of this technology on elevated platforms requires further investigation.

Based on demonstration hydrogen stations built to date, a traditional steel tube storage system with 300 kg storage capacity occupies ~450 square feet of land, not including setback requirements, which vary based on site specifics (less than 5 to 30 feet for gaseous and 50 feet for liquid hydrogen).[55] This is a significant footprint requirement at existing retail fueling locations where commercial land is leveraged for revenue generation through convenience stores, auto repair garages, car washes, and other offerings. Going forward, the use of composite versus steel storage tubes[56] may reduce land requirements for a comparable system by ~75% from historical levels, not including setback requirements, due to thinner cylinder wall thickness and the ability to store hydrogen at higher pressures (up to 1,050 bar). Given limited availability of land at existing fueling locations and the land requirements for contemporary hydrogen fueling equipment, technology advancements are

55 National Fire Protection Association, *NFPA 55: Compressed Gases and Cryogenic Fluids Code, 2010 Edition,* Table 11.3.2.2 and Table 11.3.2.2.1(a), 2010.

56 American Society of Mechanical Engineers, *ASME Boiler and Pressure Vessel Code, Section VIII, Division 3, Article KD-10,* 2010.

needed for large volume hydrogen dispensing capabilities. However, the integration of low volumes of hydrogen into some existing conventional fueling locations for commercial introduction of FCEVs is feasible and being demonstrated today.

Of the total installed storage capacity of a compressed gas system, ~70–80% is useable as dispensable fuel at service pressure. FCEVs are commonly filled by balancing the pressure within the vehicle's tank with a pressure in the storage system. Therefore, in order to achieve full fills, some hydrogen must remain in the station's storage system. Because greater storage capacity than that which is usable must be installed, land and capital requirements must be increased accordingly.

The cost of a storage system represents a significant portion (>25%) of the total capital required for the hydrogen fueling system. Reducing the cost of this system could materially impact total capital requirements and hydrogen fueling economics.

Advanced storage systems that require less land and capital are needed for the mass deployment of hydrogen fueling infrastructure. One opportunity is the development of advanced compression technologies that allow for greater utilization of the total installed storage system capacity by drawing low-pressure hydrogen from storage and boosting it to fueling pressures as the FCEV is being fueled. The cost of advanced compression technologies will need to be balanced with the cost savings from lower storage requirements.

On-site storage systems cost can be reduced through the development of advanced materials for hydrogen storage that are not more costly than current steel or composite systems and have greater storage density. Significant efforts have been made to advanced storage material for vehicle storage systems; however, government investments in on-site storage system solutions have been limited. Because on-site systems have different considerations than vehicle storage system, it should not be assumed that advancements in one area will transfer to the other. Therefore, targeted efforts towards on-site storage system advancements could be beneficial.

Another opportunity is to develop underground storage systems for hydrogen. This development would need to address the concerns and requirements that exist and are reflected in the codes and standards in place as of 2012 for underground hydrogen storage systems. Successful development of underground hydrogen storage systems would minimize the need for a dedicated footprint at a fueling location, similar to conventional fuels today.

Dispensing

High-pressure hydrogen dispensers are being deployed to handle both 350 and 700 bar dispensing needs and incorporate industry standard fueling protocols to allow for rapid fueling. However, hydrogen cannot currently be sold to the consumer on a unit basis due to lack of accurate flow meters for fuel measurements at point of sale. Industry and government are working on solutions to this issue. In the meantime, interim approaches are being pursued that include selling hydrogen on a per-fill basis regardless of quantity, similar to propane cylinder exchanges.

Safety

As is the case for all fuels, appropriate precautions need to be taken in the handling of hydrogen. Hydrogen is not inherently less safe than other fuels. It does, however, have different characteristics than those of conventional liquid fuels which need to be considered. Some key characteristic differences are as follows:

- Hydrogen is over 14 times lighter than air; therefore, if released, it rises rapidly and diffuses into the air.
- Hydrogen concentration greater than 4% mixed with air is needed for combustion.
- A combustible hydrogen/air mixture requires 0.02 millijoules of the energy needed to ignite when compared to a gasoline/air mixture.
- When ignited, a hydrogen flame is very pale blue and almost invisible in daylight due to the absence of soot.
- A hydrogen flame typically extends less than 500 diameters from the release hole (for example, for a 1 mm diameter leak, the flame length will be less than 0.5 m).

Hydrogen burns with greater vigor than gasoline, but for a shorter time. Hydrogen gas rises quickly due to its high buoyancy and diffusivity. Consequently, hydrogen fire zones are relatively close to the leak, vertical plume, and highly localized. If a car hydrogen cylinder vents and the venting hydrogen stream is ignited, the fire burns away from the car and the interior typically does not get very hot.

Hydrogen is typically stored at pressures over 700 bar at fuel stations. The strain these pressures create on station components and the potential leak or burst that can result in the event of a component failure is a common consideration in developing safety standards.

National and international codes and standards are being developed and adopted by local jurisdictions. The required setback distances in these standards suggest that the location of the hydrogen storage system is the greatest concern. A listing of common setback distances is shown in Table 15-12.[57] These distances could be reduced through the installation of mitigating technologies such as isolation walls.

The National Fire Protection Association Codes 2, 50, 52, 55, and 853 provide codes and standards information related to hydrogen fueling stations.

57 U.S. Department of Energy, Energy Efficiency & Renewable Energy (website), Alternative Fuels Data Center: Fuels & Vehicles: "Hydrogen Fueling Infrastructure Development," http://www.afdc.energy.gov/afdc/fuels/hydrogen_infrastructure.html#setbacks.

Fuel Costs

This analysis evaluates the near-term total cost of hydrogen (dispensed hydrogen) based on cost data from recent government-funded hydrogen infrastructure deployments in 2008 dollars unless otherwise stated. Dispensed hydrogen cost is evaluated on a $/kg basis where,

Dispensed Hydrogen Cost =
Cost of (Production + Distribution + Compression + Storage + Dispensing)

This analysis uses 2011 costs for infrastructure capital and operating expenditures based on industry cost data together with costs for government-funded hydrogen station deployments in California to calculate the dispensed hydrogen cost for the centralized and distributed hydrogen production approaches. Where appropriate, NREL's H2A Production Analysis tool (H2A), together with default H2A assumptions, was used to convert available cost data to a $/kg basis.[58] H2A is a well-known and widely used techno-economic modeling tool within the hydrogen

58 U.S. Department of Energy, Hydrogen and Fuel Cells Program (website), "DOE H2A Production Analysis," 2012, http://www.hydrogen.energy.gov/h2a_production.html.

NFPA 52	**Table 11.3.2.2 — Minimum Distance from Liquefied Hydrogen Systems to Exposures**	
	Wall adjacent to system constructed of combustible materials*	50 feet
	Table 10.3.2.2.1 (a) — Minimum Distance from Outdoor Gaseous Hydrogen Systems to Exposures	
	Air intake openings	30 feet
	Lot lines	30 feet
	Wall openings	30 feet
	Parked vehicles	15 feet
	Building (with combustible walls)	10 feet
NFPA 55	**Table 9.3.1.4 — Separation Distances for Outdoor Gaseous Hydrogen Dispensing Systems**	
	Building, line of adjoining property that can be built on, any source of ignition†	10 feet
	Nearest public street or public sidewalk†	10 feet
	Storage containers†	3 feet

Setbacks are applicable to a 7,000 psi hydrogen system
* 1,500 liter liquid hydrogen storage tank
† Only pertains to dispensing equipment

Table 15-12. *2010 National Fire Protection Association (NFPA) Safety Setback Distances* industry and DOE. It calculates the dispensed hydrogen costs based on operating and capital inputs with transparency and consistency among multiple pathways. Steam methane reforming of natural gas was assumed for both the centralized and distributed approach because this is commonly regarded as the most economical method for hydrogen production.

Key Inputs and Assumptions

Installed Capacity

Standard H2A case studies are based on an assumed fueling station capacity of 1,500 kg/day, which is comparable to a current gas station. Recognizing that the deployment of new stations with only hydrogen fueling can be cost-prohibitive, this analysis is based on the assumption that, at least in the near term, hydrogen will be integrated into existing stations as an option similar to diesel or E85. Therefore, an installed capacity to dispense 250 kg/day during the initial roll-out period was used for this analysis. The benefits of economies of scale will improve at higher capacities.

Demand for Installed Capacity

The H2A default input for fueling station capacity utilization is 85% and was used for this analysis. The California Fuel Cell Partnership suggests that a network of stations be deployed with an assumed installed capacity utilization of 70%.[59]

Natural Gas Price

This analysis uses AEO2010 industrial natural gas price projections, including a cost sensitivity range for natural gas prices based on AEO2010 Low and High Oil Price Cases. Figure 15-21 shows AEO2010 natural gas price projections and other AEO natural gas prices for comparison purposes only.

Due to the abundance of North American shale gas and coalbed methane sources, sufficient natural gas supply is projected to be available through the study period (2050). As mentioned previously, in a case where a significant share of the future national

59 California Fuel Cell Partnership, *Hydrogen Fuel Cell Vehicle and Station Deployment Plan: A Strategy for Meeting the Challenge Ahead, Action Plan,* February 2009.

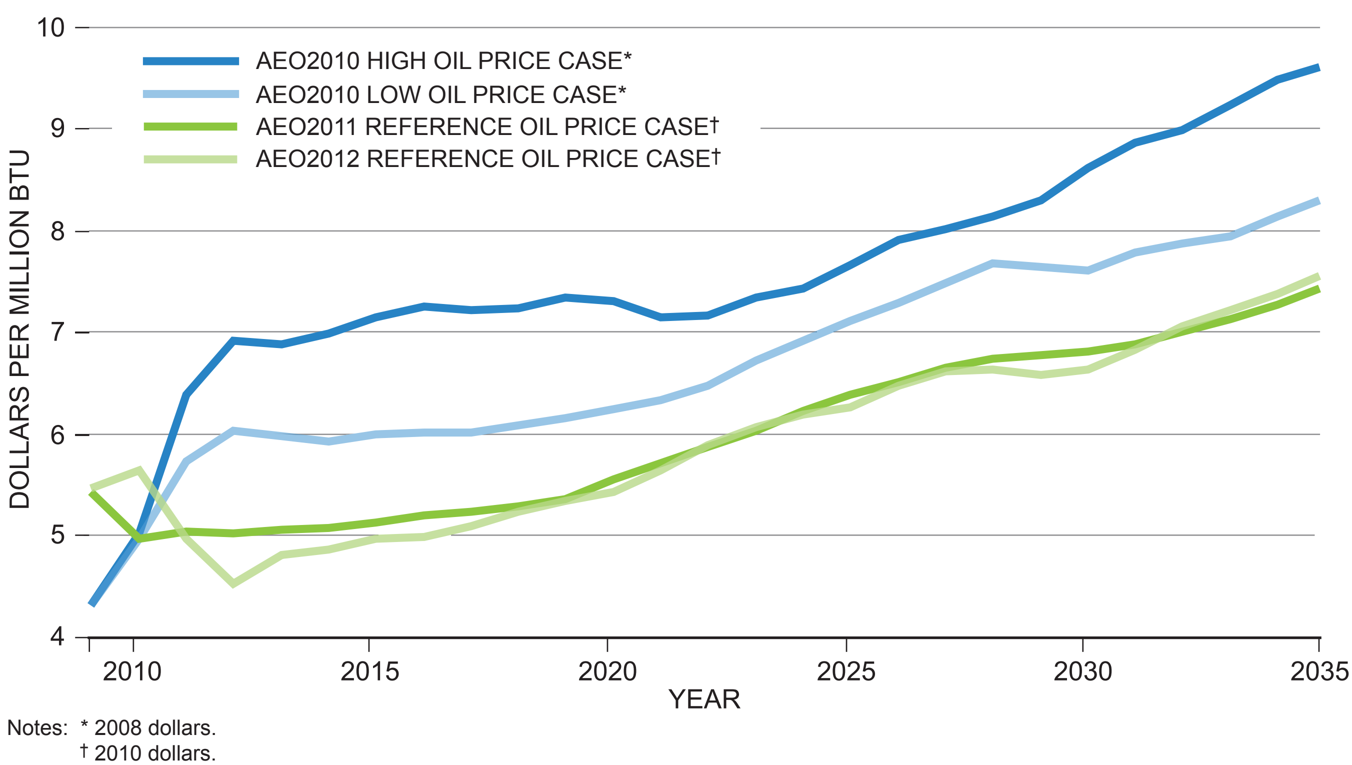


Figure 15-21. *EIA Annual Energy Outlook Natural Gas Price Projections*

vehicle fleet is FCEVs and hydrogen is produced primarily from natural gas, sufficient natural gas supply is expected; however, demand may materially increase from current levels. The impact on natural gas prices from demand increases is outside of the scope of this study and should be explored if natural gas is selected as a long-term feedstock for hydrogen production. The impact of significant changes in natural gas prices on hydrogen costs is explored in the sensitivity analysis.

Rate of Return

The H2A default input for real, after-tax internal rate of return (IRR) is 10% and is used for this analysis. IRR requirements can have a material economic impact and should be considered.

Incentives

No incentives for infrastructure were included in this analysis.

Centralized Approach Capital Investment

Centralized hydrogen production and distribution using the "Gaseous Composite Tube Trailers" technology previously discussed is the assumed centralized approach for this analysis. Centralized production capacity expansion or green field capacity development will be needed if FCEVs achieve material market share. Typical centralized hydrogen production facilities produce approximately 50,000 to 470,000 kg/day and cost approximately $75 to $225 million.[60] This results in a capital investment of approximately $500 to $1,500/kg daily installed capacity for centralized production.

Grants awarded by the California Energy Commission in November 2010 for hydrogen fuel stations provide ranges for capital investment requirements for the centralized approach for gaseous and liquid hydrogen deliveries (see Table 15-13). Costs are highly dependent on station size and gaseous vs. liquid hydrogen deliveries. This is reflected in the broad range of installed daily capacity for similar costs.

The capital requirement for fueling station upgrades (compression, storage, and dispensing equipment) and on-time fuel loading equipment upgrades for the central plant (included in the California Energy Commission awards) range from approximately $8,000 to $20,000/kg installed daily capacity. After deducting the one-time costs for fuel loading equipment upgrades and allowing for cost reductions from experience, the next group of similar fueling stations could be as low as $1 million ($4,000/kg installed daily capacity).

Therefore, the total capital requirements for the centralized approach (production + fuel loading upgrades + fueling station upgrades) range from approximately $4,500 to $21,500/kg installed daily capacity.

Station Location	Capacity (kg/day)	Capital Investment w/out Production (millions)
Irvine, CA	100–250	$1.96
Santa Monica, CA	100–250	$2.04
Beverly Hills, CA	100–250	$2.00
Los Angeles, CA	100–250	$2.00
Hermosa Beach, CA	100–250	$2.01
Irvine, CA	100–250	$2.03
Diamond Bar, CA	100–250	$1.99
Hawthorne, CA	100–250	$2.00

Source: California Energy Commission, "Alternative and Renewable Fuel and Vehicle Technology Program, Grant Solicitation PON-09-608, Hydrogen Fuel Infrastructure," Revised Notice of Proposed Award, Sacramento, CA, November 17, 2010, www.energy.ca.gov/contracts/PON-09-608_Revised_NOPA.pdf.

Table 15-13. *Capital Investment for Centralized Approach for Hydrogen Delivery (in 2011 Dollars)*

Distributed Approach Capital Investment

Recent grant awards by the California Air Resources Board for hydrogen fuel stations provide ranges for capital investment requirements for the distributed approach. For the distributed approach where hydrogen is produced at a fueling station (production + fueling location), capital requirements range from approximately $31,000 to

60 Argonne National Laboratory, Transportation Technology R&D Center, "Hydrogen Distribution Infrastructure," Jefferson Laboratory Fuel Cells Workshop, November 2002.

$40,000 per kg installed daily capacity (see Table 15-14).

Station Location	Capacity (kg/day)	Capital Investment (millions)
Newport Beach, CA	100	$4.00
Los Angeles, CA	140	$4.30

Source: California Energy Commission, "Alternative and Renewable Fuel and Vehicle Technology Program, Grant Solicitation PON-09-608, Hydrogen Fuel Infrastructure," Revised Notice of Proposed Award, Sacramento, CA, November 17, 2010, www.energy.ca.gov/contracts/PON-09-608_Revised_NOPA.pdf.

Table 15-14. *Capital Investment for Distributed Approach for Hydrogen Delivery (in 2011 Dollars)*

Because the production capacity of the hydrogen stations receiving state of California grant awards was less than the assumed installed capacity for this analysis (250 kg/day), the capital investment for the distributed approach was calculated by applying a scaling factor to the cost of capital equipment for the larger 250 kg/day station and adding to the equipment cost other fixed site costs. The assumed scaling factor for this analysis is 0.6, which is commonly accepted in the fuel infrastructure industry and is applied as follows:

new scaled equipment cost = known cost*(new capacity/known capacity)^scaling factor

Use of this scaling factor on the recent state of California grant awards results in range of $14,000 to $28,000/kg installed daily capacity (~$3.5 to $7 million) for a 250 kg/day distributed approach station. If larger capacity stations are deployed, the $/kg daily capacity will decrease further as the total capital requirement increases.

Operating Expenses

Operating expense assumptions for both the centralized and distributed approach included, but were not limited to, station operating labor, maintenance, utilities, insurance, and land rental, where applicable. The centralized case also includes the cost of hydrogen at the plant gate and the cost of hydrogen deliveries to the station. The operating costs for the distributed approach include natural gas feedstock.

For the centralized approach, total dispensed hydrogen costs for a 250 kg/day capacity station are ~$9 to $12/kg in 2008 dollars and consist of the following:

- $1.44/kg ($1.33/kg in 2005 dollars)[61] for production at the plant gate
- $1.28 to $2.31/kg for delivery ($1.25 to $2.25/kg in 2007 dollars)[62]
- $169,700/year for remaining operating expenses ($175,000/year in 2011 dollars).

Future delivery costs are expected to be lower than today's projected values. Based on its recent technology advancements, one large industrial gas supplier has stated hydrogen delivery costs could be equal to or lower than $1.25/kg, which represents the bottom end of the range mentioned above.[63] Remaining operating cost estimates range from $250,000[64] to <$125,000[65] (in 2011 dollars) and were assumed to be $175,000 for this analysis.

For the distributed approach, total fixed annual operating expenses for a 250 kg/day capacity station are assumed to be approximately $375,000/year (not including variable natural gas feedstock costs).

Taxes

AEO2010 assumes fuel taxes for gasoline to be $0.42/gallon. Due to the greater efficiency of FCEVs, fewer kg of hydrogen would be sold than gasoline for comparable vehicles for equivalent miles traveled. For this analysis, taxes for hydrogen are assumed to be ~$1/kg so that revenue neutrality for the government is maintained.

Near-Term Hydrogen Economics

Monte Carlo Simulation

Monte Carlo simulations were performed to evaluate potential hydrogen fuel costs resulting from

61 Mark Ruth, Melissa Laffen, and Thomas A. Timbario, *Hydrogen Pathways: Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Seven Hydrogen Production, Delivery, and Distribution Scenarios,* National Renewable Energy Laboratory, NREL/TP-6A1-46612, September 2009.

62 FreedomCAR and Fuel Partnership, Hydrogen Delivery Technical Team Update, May 2011

63 Air Products written comment to California Energy Commission, Docket 10-ALT-1, March 2011.

64 University of California Davis, Hydrogen Station Analysis 2011.

65 Air Products discussion with NPC Hydrogen Subgroup, 2011.

varying a range of values for key cost parameters for both the centralized and distributed hydrogen production cases. A Monte Carlo simulation is a problem solving technique used to approximate the expected range of outcomes by running multiple trials during which the value of model inputs are randomly selected based on their probability of occurring. Table 15-15 shows the decision variables used in the Monte Carlo analysis along with their ranges. The results of these simulations indicate that the near-term dispensed hydrogen costs (including taxes) range from $9 to $12/kg for the centralized production case and from $15 to $25/kg for the distributed approach. These cost ranges represent the lower quartile to upper quartile probable dispensed hydrogen costs based on the Monte Carlo cost analysis. Figure 15-22 and Figure 15-23 show the complete probability forecast for total dispensed hydrogen cost from hydrogen produced using the centralized and distributed approach, respectively, based on the Monte Carlo analysis.

Input Parameters	Centralized Approach	Distributed Approach
Natural Gas Cost ($/million BTU)	$5.82–$7.44	$5.82–$7.44
Fixed Annual Operating Cost	$125K–$250K	$200K–$525K
Delivery Cost ($/kg)	$1.25–$2.25	NA
Equipment Life	10–20 Years	10–20 Years
Total Station Capital Cost	$1M–$2M	$3.5M–$7M
Station Demand Factor	50%–95%	50%–95%
After-tax IRR	0%–20%	0%–20%
Station Capacity (kg/day)	100–400	100–400

Table 15-15. *Near-Term Hydrogen Cost Ranges for Monte Carlo Analysis*

Sensitivity Analysis

The results of a sensitivity analysis on both the centralized and distributed approach are shown in Figure 15-24 and Figure 15-25, respectively. For the centralized case, the fueling station's installed capacity, followed by demand for the installed capacity, has the greatest impact on hydrogen fueling economics. If stations larger than 250 kg/day capacity are deployed and the demand for hydrogen fuel exists (FCEVs are deployed in sufficient numbers), dispensed hydrogen costs would decrease.

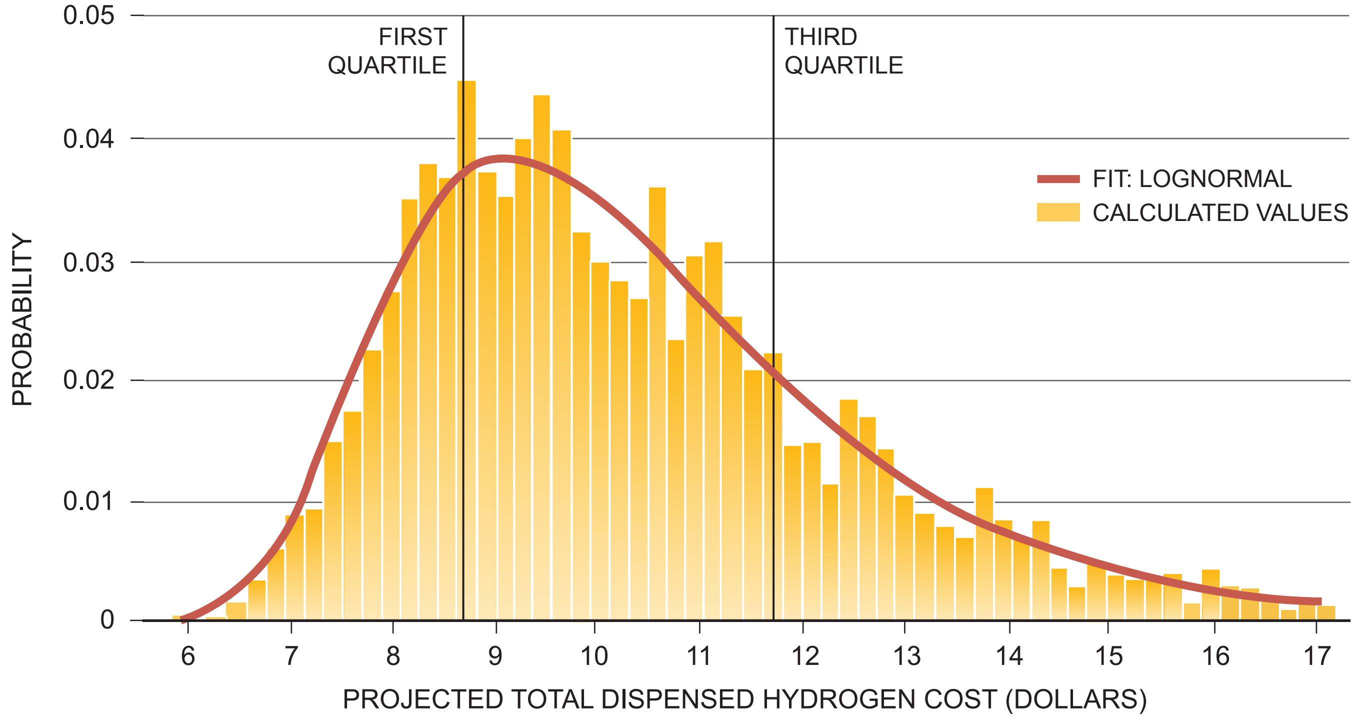
The potential near-term dispensed hydrogen costs and infrastructure capital requirements are shown in Table 15-16.

Approximately 10% and 5% of the dispensed hydrogen cost is for feedstock (natural gas) for the centralized and distributed approach, respectively, compared to gasoline where approximately 70% of the total fuel cost is for feedstock (crude oil) in 2010.[66] This suggests that hydrogen has the potential to reduce fuel price volatility when compared to convention fuels because a smaller portion of dispensed fuel costs are for feedstock, assuming natural gas and crude oil have comparable price volatility.

66 American Petroleum Institute (website), "What's Up With Gasoline Prices?", May 2011, http://www.api.org/oil-and-natural-gas-overview/fuels-and-refining/gasoline/whats-up-with-gasoline-prices.aspx.

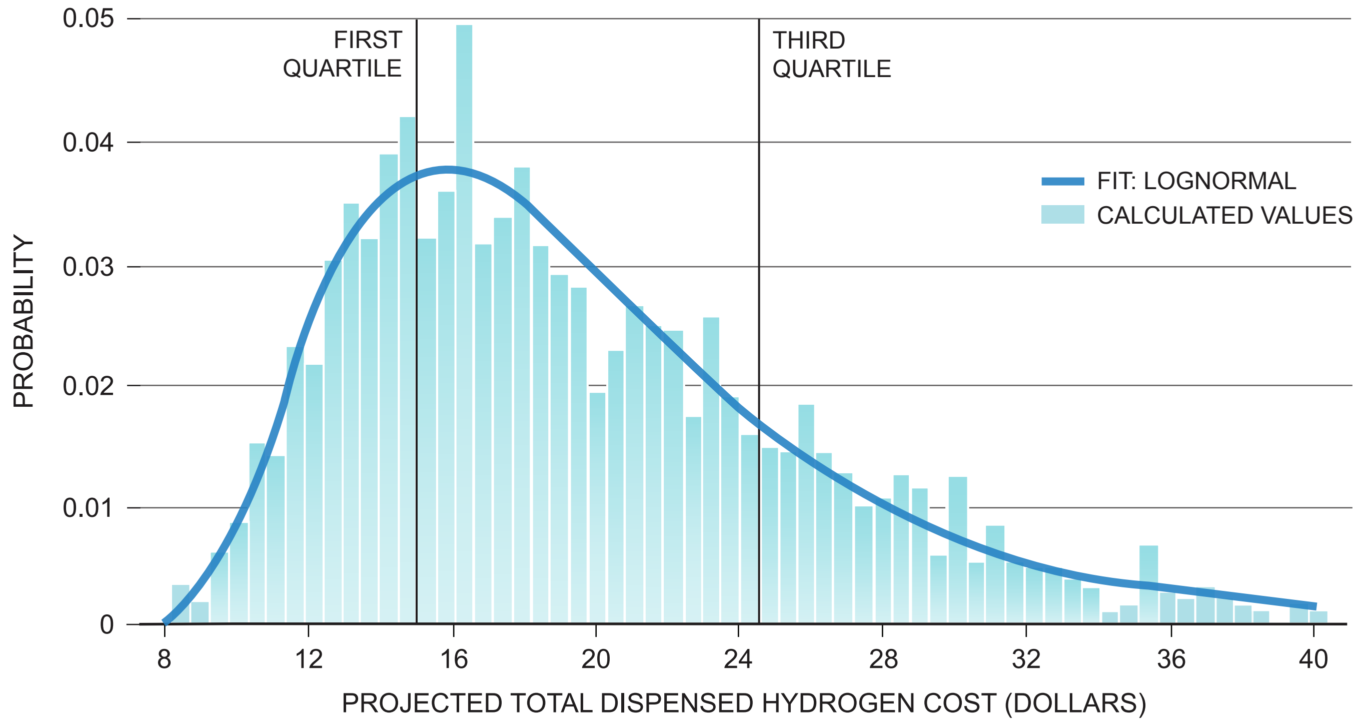
	Near-Term Dispensed Hydrogen Cost	Capital Requirement	
	($/kg)	($ per station)	($/kg per day installed capacity)
Centralized Approach	$9–$12	$1–$2 million	$4,500–$21,500
Distributed Approach	$15–$25	$3.5–$7 million	$14,000–$28,000
Note: Dispensed hydrogen cost ranges represent the lower quartile to upper quartile probable costs based on a Monte Carlo cost simulation.			

Table 15-16. *Economics for Early-Phase Hydrogen Fueling Stations*



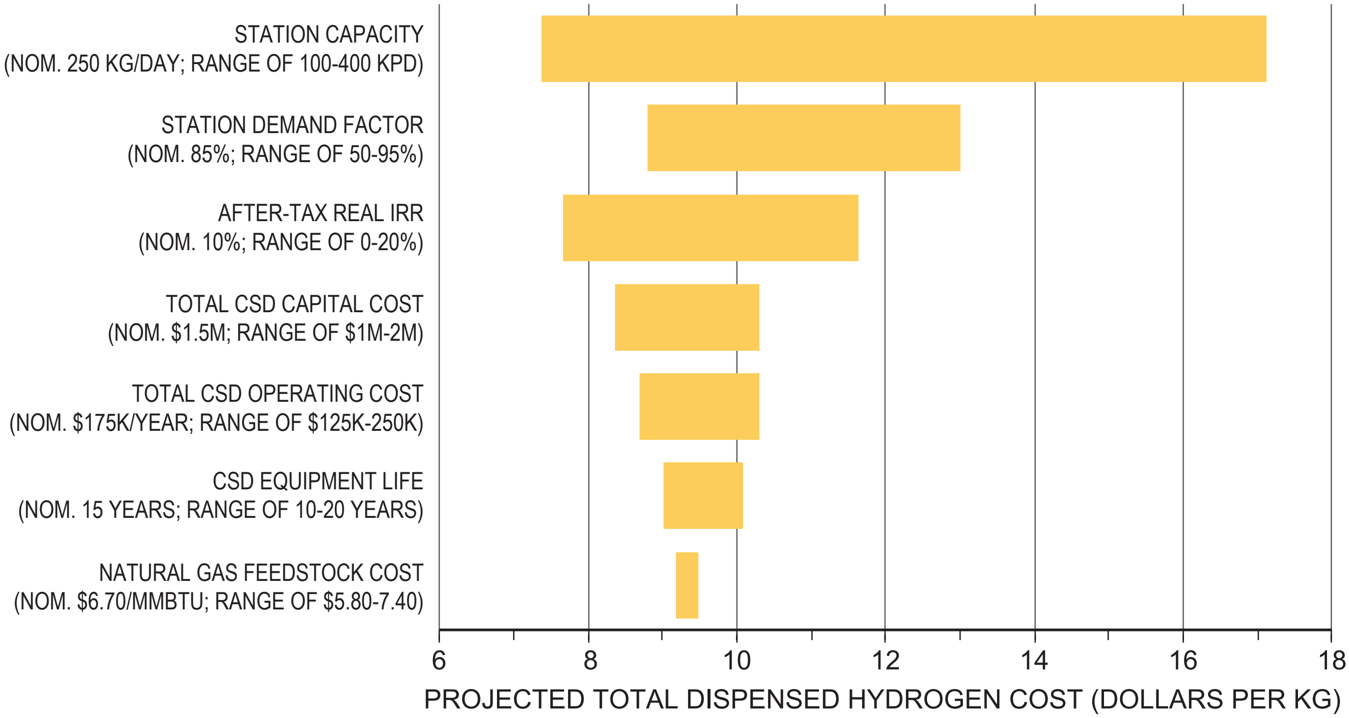
Note: Based on NPC Hydrogen Subgroup Analysis.

Figure 15-22. *Projected Near-Term Hydrogen Cost for the Centralized Approach*



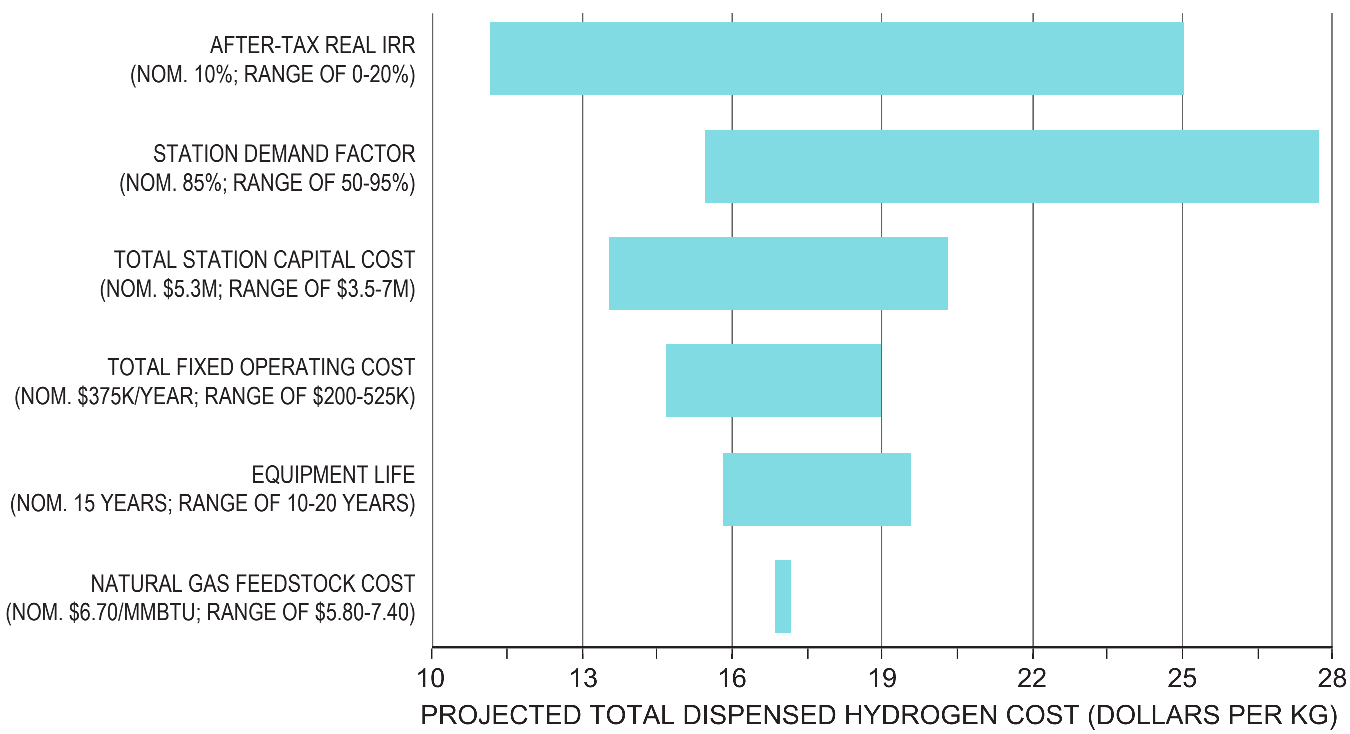
Note: Based on NPC Hydrogen Subgroup Analysis.

Figure 15-23. *Projected Near-Term Hydrogen Cost for the Distributed Approach*



Note: Based on NPC Hydrogen Subgroup Analysis.

Figure 15-24. *Centralized Approach Sensitivity Analysis for Hydrogen Station Compression, Storage, and Dispensing (CSD) Costs*



Note: Based on NPC Hydrogen Subgroup Analysis.

Figure 15-25. *Distributed Approach Sensitivity Analysis for Hydrogen Production and Dispensing*

Analysis conducted in 2010 by California Fuel Cell Partnership suggests that each FCEV requires ~1 kg of installed daily fueling capacity;[67] therefore, "$/kg per day installed capacity" is equal to the infrastructure capital requirement for each FCEV in the national vehicle fleet assuming 250 kg/day stations. This assumes that investments in supply (station deployment) and demand (FCEV deployment) are coordinated and match.

If renewable hydrogen is required, the dispensed hydrogen cost is expected to be higher. If renewable hydrogen is produced via steam reformation of renewable natural gas and renewable natural gas prices are about two times the cost of conventional natural gas, then the cost of renewable hydrogen would increase by ~$1/kg. However, if renewable hydrogen is produced via centralized water electrolysis using renewable wind electricity, the projected production cost (not including distribution and fueling location costs) of renewable hydrogen is expected to be over $3/kg higher than the projected cost for producing hydrogen from natural gas at central plants.[68]

Future Hydrogen Economics

The cost of hydrogen would decrease if (1) technology advancements are made in the areas previously discussed (particularly compression and storage at the station), (2) larger capacity stations can be deployed, and (3) there is sufficient demand.

A Monte Carlo analysis was performed to evaluate future hydrogen costs by scaling and updating key near-term inputs. The future cost ranges assumed are listed in Table 15-17, and a table showing the rational and scaling calculations for each variable is shown in Appendix 15C at the end of the chapter.

These inputs result in a future dispensed hydrogen cost of $6 to $7/kg (see Figure 15-26) and $7 to $9/kg (see Figure 15-27) for the centralized and distributed approach, respectively.

An exponential decay function was fit to the near-term and future dispensed hydrogen centralized production costs presented previously and resulted in the hydrogen cost curves shown in Figure 15-28.

Barring any policy or regulatory drivers, the economics of the centralized approach is what other options will have to meet or beat in order to be adopted. As demand increases and technology improves, the economics for the distributed approach may be able to compete with the centralized approach and should be evaluated as both pathways evolve and advance.

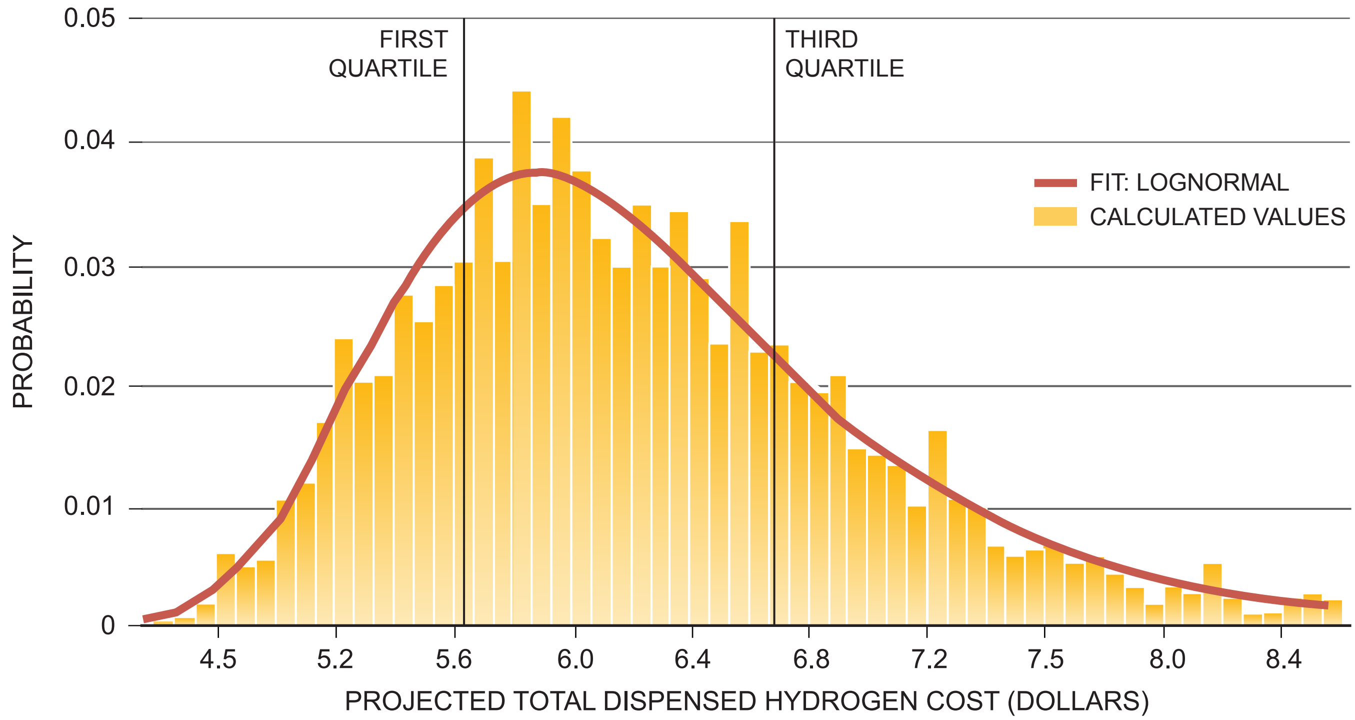
Due to the significantly greater efficiency (two to three times) of an FCEV over that of a conventional gasoline vehicle (non-hybrid), the cost of hydrogen fuel can be greater than that of gasoline on an energy equivalent basis. The cost of fuel for consumers should be compared on a cost-per-mile basis and is presented in Table 15-18. Under most

67 California Fuel Cell Partnership, *Hydrogen Fuel Cell Vehicle and Station Deployment Plan: A Strategy for Meeting the Challenge Ahead,* Action Plan, February 2009.

68 Genevieve Saur and Todd Ramsden, *Wind Electrolysis: Hydrogen Cost Optimization,* National Renewable Energy Laboratory, NREL/TP-5600-50408, May 2011.

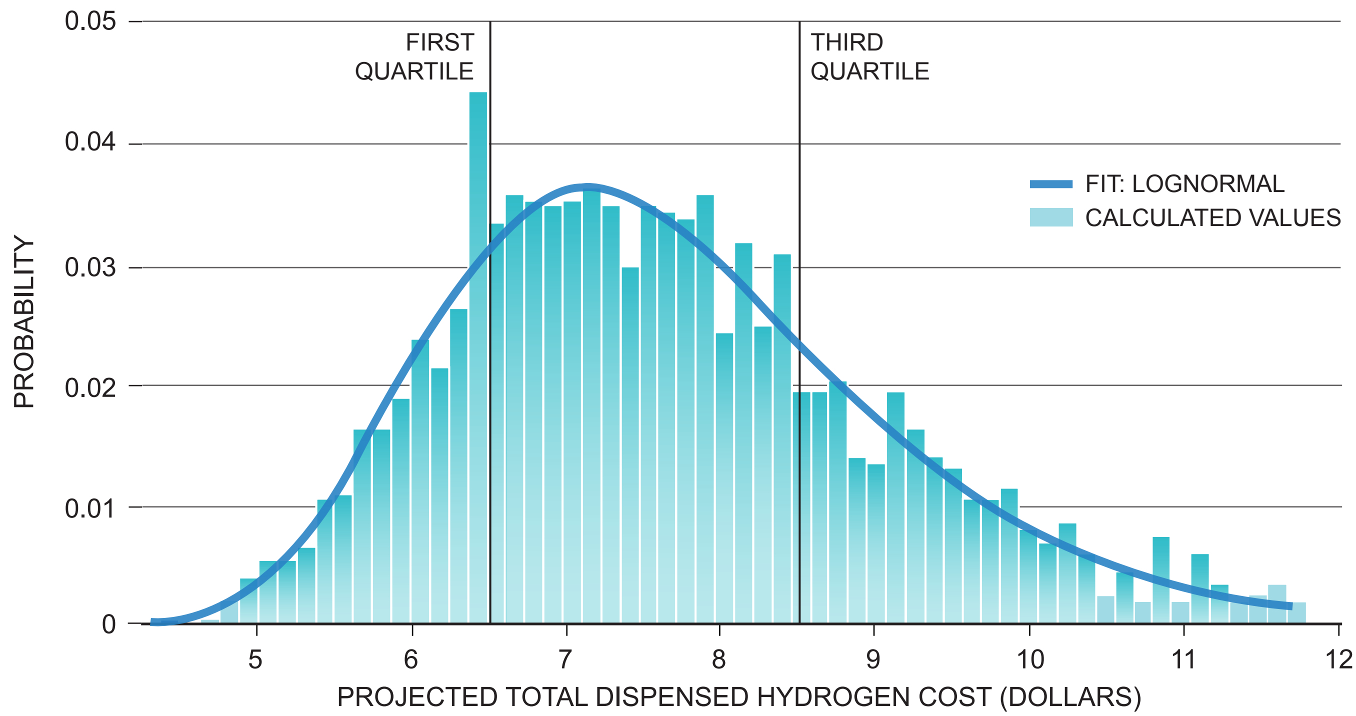
Input Parameters	Centralized Approach	Distributed Approach
Natural Gas Cost ($/million BTU)	$6.92–$13.15	$6.92–$13.15
Fixed Annual Operating Cost	$75,000–$225,000	$150,000–$475,000
Delivery Cost ($/kg)	$1.00–$1.50	NA
Equipment Life	10–20 Years	10–20 Years
Total Station Capital Cost	$1.5 million–$4.5 million	$5 million–$11.5 million
Station Demand Factor	50–95%	50–95%
After-Tax Internal Rate of Return	5–15%	5–15%
Station Capacity (kg/day)	500–1,500	750–1,500

Table 15-17. *Future Hydrogen Cost Ranges for Monte Carlo Analysis*



Note: Based on NPC Hydrogen Subgroup Analysis.

Figure 15-26. *Projected Future Hydrogen Cost for the Centralized Approach*



Note: Based on NPC Hydrogen Subgroup Analysis.

Figure 15-27. *Projected Future Hydrogen Cost for the Distributed Approach*

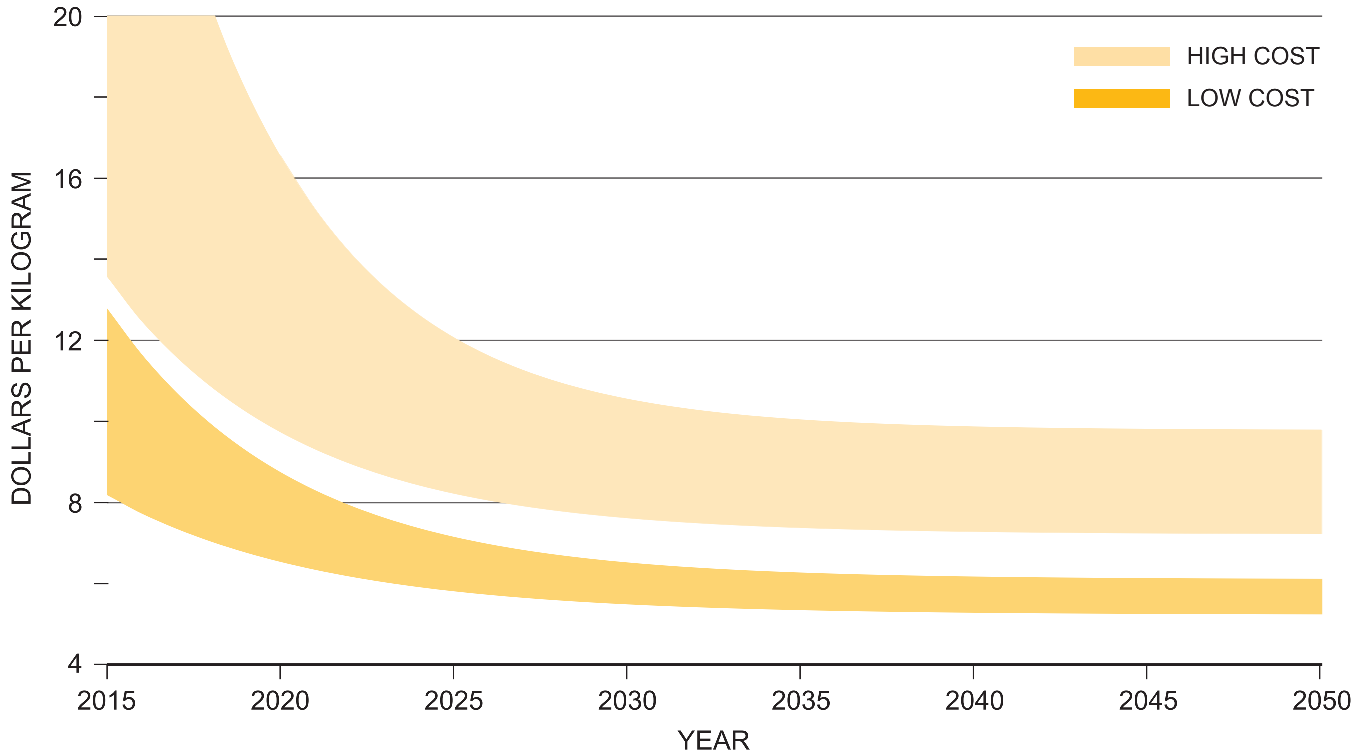


Figure 15-28. *Dispensed Hydrogen Cost Over Time*

Gasoline Price	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 efficiency based on centralized pathway discussion in this chapter.
FCEV efficiency assumed to range from 2X to 3X of gasoline vehicle.

Table 15-18. *Fuel Cost Ratio Comparison (Hydrogen $/Mile vs. Gasoline $/Mile)* cases considered, hydrogen compares favorably with gasoline on a per-mile basis, and hydrogen is favorable in all cases from 2030 where oil is at High or Reference Case prices.

Station Deployment

The cost of dispensed hydrogen is significantly impacted by station fueling capacity (due to economies of scale) and utilization. Both fueling capacity and utilization are inversely proportional to the dispensed cost of hydrogen fuel. Because demand at a station is finite, the largest capacity would be at a station that offers only hydrogen.

However, large-scale deployment of hydrogen-only fueling stations may be prohibitive. There may be insufficient demand for a sustained period before FCEV deployments can support wide-scale fuel availability through large hydrogen-only stations. Larger stations require greater capital and would have lower utilization than smaller stations. The benefits of greater utilization at stations where hydrogen is commingled with other fuels may offset the lost opportunity for economies of scale at larger hydrogen-only stations. Therefore, for hydrogen to achieve wide-scale availability, it will likely need to be commingled at existing stations alongside gasoline (similar to diesel or E85).

Theoretical modeling calculations have been developed/used by academia and government to determine the minimum number of fueling locations needed. However, actual competitive conditions and real world conditions are expected to influence deployments.

The Consumer Choice Module of the National Energy Modeling System, which is used by the EIA for developing energy-economic projections, suggests that a fuel needs to be available at approximately 30% of the locations within a geography for a consumer to view it at par with current conventional fuels. This topic is discussed in greater detail in Chapter One, "Demand," and Chapter Five, "Infrastructure."

Alternatively, a 2011 analysis by the University of California, Irvine, found that less than 15% of existing fueling stations in a Southern California region can provide sufficient coverage to make fuel available (within a 5-minute drive) to the local populations.[69] Fueling capacity requirements for each location were not considered in this analysis. The University of California, Irvine, analysis is being expanded to evaluate other cities and suggests that if fueling locations are thoughtfully selected, hydrogen could be accessible to a population within a geographic region with availability at less than 15% of existing stations.

The fueling requirements of early adopters may be met by clustering stations in select early markets. Using this approach, less than 1% of existing stations would need to offer hydrogen in the early years.[70]

There are ~162,000 fueling stations in the United States today.[71] In order to eliminate infrastructure availability concerns for FCEV drivers, 24,000 to 48,000 (15 to 30%) of these stations would need to offer hydrogen nationwide. Using a targeted geography approach where densely populated regions are prioritized, the expected initial capital investment requirement would be lower. For example, if California was the target market, 1,125 to 2,250 stations out of ~7,500 retail sites[72] would be needed for full coverage.

Initial Stages of Infrastructure Deployment

In the initial stages, deployment supply (fueling stations) and demand (FCEVs) will need to match and be coordinated. Demonstration fleet experiences suggest early adopter consumers typically do not require the same level of convenience as mass market consumers and are willing to accommodate the inconveniences that may occur in the initial stages such as being unable to drive to destination locations.

Due to existing hydrogen fueling infrastructure economics and limited FCEV deployments, there is insufficient fuel demand to support fixed station costs, and there is little justification for the

69 Shane Stephens-Romero, Tim Brown, and Scott Samuelsen, "Using STREET to Optimize Hydrogen Infrastructure Investments in Targeted Communities," presentation at the Fuel Cell and Hydrogen Energy Conference in Washington, DC, February 2011.

70 Michael Nicholas and Joan Ogden, *An Analysis of Near-Term Hydrogen Vehicle Rollout Scenarios for Southern California,* Institute of Transportation Studies, University of California, Davis, January 2010.

71 American Fuel & Petrochemical Manufacturers, "Fuel Facts," Washington D.C., 2012.

72 United States Census Bureau, "2010 County Business Patterns (NAICS)," U.S. Department of Commerce, 2010, http://censtats.census.gov/cgi-bin/cbpnaic/cbpdetl.pl.

deployment of a network of hydrogen fueling stations without incentives. If targeted technology advancements are realized and greater numbers of FCEVs are deployed, hydrogen fueling infrastructure economics are expected to improve. The deployment of early FCEVs and fueling stations will have to be actively coordinated to ensure alignment among fuel providers, auto manufacturers, and government on plans, incentives, and policies, as is currently being done in early adopter regions.

Hydrogen fueling infrastructure availability is a key factor to support the entry of FCEVs into the marketplace. Because of this, the focus for early sales of FCEVs is expected to be in a few key urban areas. This will allow adequate hydrogen infrastructure to be deployed to meet the fueling needs of those new FCEVs. By the same token, by concentrating FCEV sales in particular markets, operators of hydrogen fueling stations will have access to a larger local customer base. Therefore, it is likely that hydrogen infrastructure will be deployed in only a few urban markets initially and then will be phased to a wider set of strategic urban areas. As these geographies overlap a fueling network will evolve.

This clustering of hydrogen infrastructure is being pursued in Southern California, where a clustered group of hydrogen fueling stations will be used to serve the initial deployment of FCEVs. A 2006 study convened by DOE identified Los Angeles and New York City as the best early markets for hydrogen FCEVs.[73] After initial rollouts in these very large metropolitan areas, FCEVs may then be deployed into other progressively smaller metropolitan areas. If FCEVs are deployed into an array of cities that comprise the 20 key urban areas in the United States, hydrogen infrastructure could then expand out of these key urban areas along interstates, eventually enabling deployment of FCEVs throughout the United States. A summary of the key requirements for a successful fueling infrastructure deployment is shown in Figure 15-29.

Southern California Examples

Optimized geographic placement of hydrogen infrastructure can achieve consumer convenience similar to that of current gasoline retail stations at significantly lower station density, resulting in the required level of coverage with least capital expense. To develop regional infrastructure plans, the STREET[74] methodology was developed at the University of California, Irvine, with a foundation of mathematical optimization combined with real-world considerations and constraints such as selected market regions, land use, travel density,[75] and the ability to project urban air quality, impact on water resources, and GHG emissions in future years (e.g., 2050).[76]

Application of STREET to Southern California shows that the average travel time to a gasoline station from anywhere in the region is roughly 4 minutes. Equivalent travel time can be matched with

73 M. Melendez and A. Milbrandt, *Geographically Based Hydrogen Consumer Demand and Infrastructure Analysis: Final Report,* National Renewable Energy Laboratory, NREL/TP-540-40373, October 2006.

74 STREET = Spatially and Temporally Resolved Energy and Environmental Tool.

75 S. D. Stephens-Romero, T. M. Brown, J. E. Kang, W. W. Recker, and G. S. Samuelsen, "Systematic Planning to Optimize Investments in Hydrogen Infrastructure Deployment," *International Journal of Hydrogen Energy* 35, no. 10 (2010), pages 4652-4667.

76 S. D. Stephens-Romero, M. Carreras-Sospedra, J. Brouwer, D. Dabdub, and G. S. Samuelsen, "Determining Air Quality and Greenhouse Gas Impacts of Hydrogen Infrastructure and Fuel Cell Vehicles," *Environmental Science & Technology* 43, no. 23 (2009), pages 9022-9029.

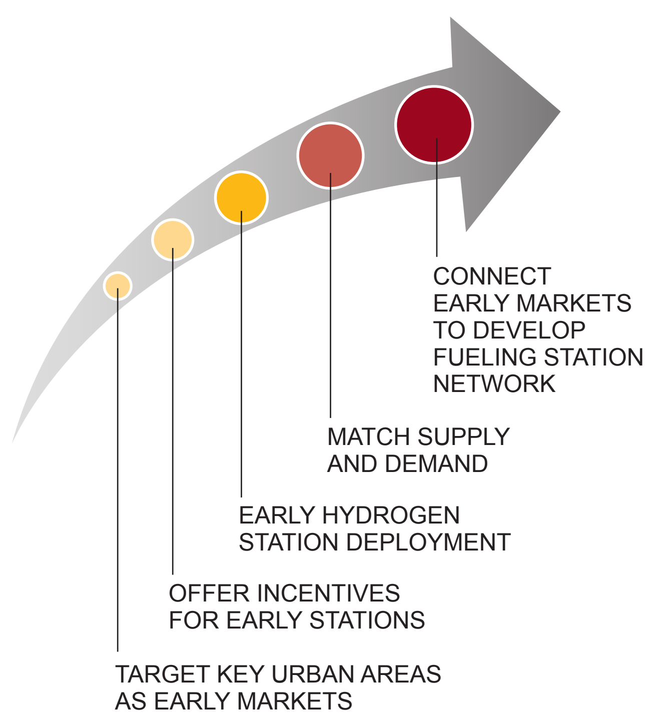


Figure 15-29. *Key Requirements for Hydrogen Fueling Infrastructure Deployment*

Source: California Fuel Cell Partnership.

Figure 15-30. *Southern California Station Location Concept*

just 12% as many hydrogen stations as current gasoline stations when optimally placed considering (1) real constraints (such as land use), (2) demographics of the resident population, and (3) competitive forces provided by telematics as opposed to replication of stations at an intersection. Such an analysis also shows that an early market can be established with even fewer stations. In particular, STREET results show that travel times to a station in the range of 6 to 7 minutes, the minimum acceptable, can be achieved with just 6% as many hydrogen stations as existing gasoline stations.[77] For southern California, ~40 stations represent the minimum number to support a regional market (see Figure 15-30), assure customer satisfaction in access to fueling, and catalyze the tipping point for private investment. This result could be readily translated to other major metropolitan areas.

77 Shane Stephens-Romero, Tim Brown, and Scott Samuelsen, "Using STREET to Optimize Hydrogen Infrastructure Investments in Targeted Communities," presentation at the Fuel Cell and Hydrogen Energy Conference in Washington, DC, February 2011.

Where applicable, hydrogen infrastructure for fueling dedicated buses and delivery truck fleets may be leveraged and used to fuel early FCEV deployments, as has been done with LNG and CNG. As the number of FCEV deployments increase and the demand for hydrogen fuel grows, hydrogen can be added to existing retail fueling stations.

Because stations would need to be installed in advance of vehicle deployments and would not have significant revenue in the early years, government incentives are expected to be instrumental for early infrastructure deployment. Industry, government and society need to determine if these investments are appropriate.

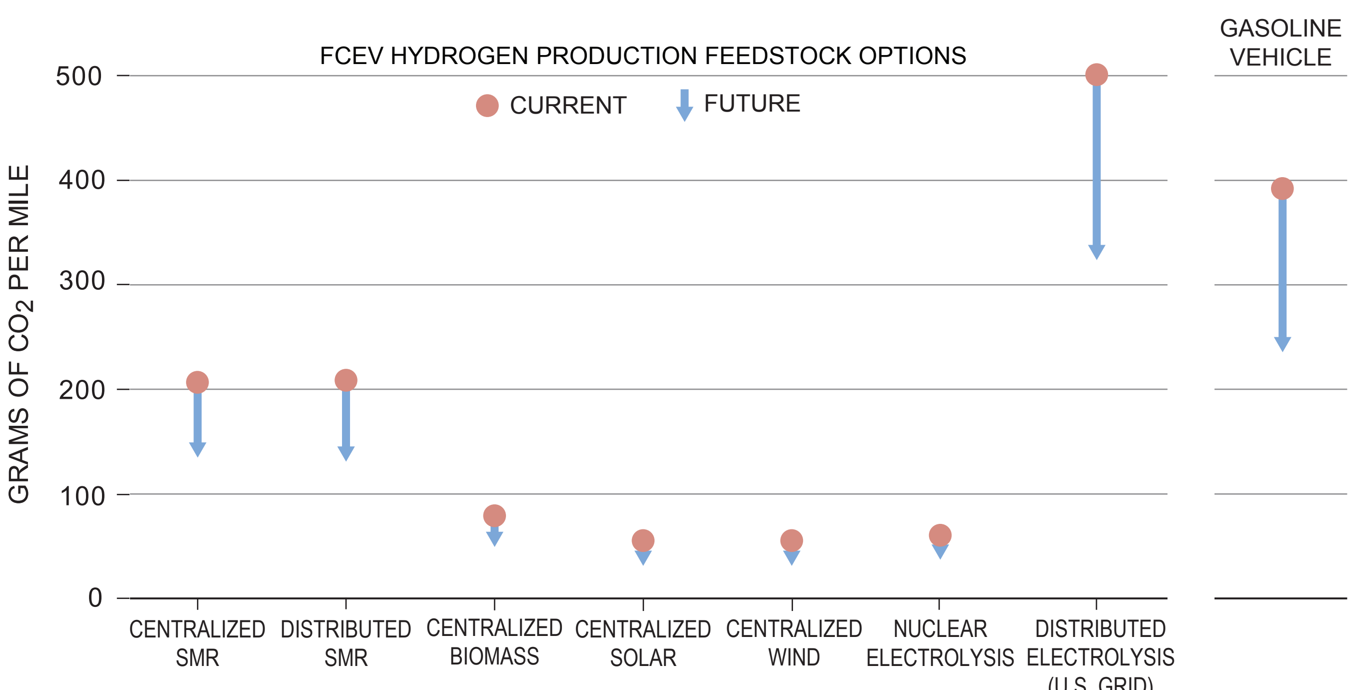
EMISSIONS AND CRUDE OIL USAGE

CO_2 Emissions

The default technology pathway for hydrogen distribution and dispensing (not production) in GREET 1.8d.1[78] is inconsistent with the distribution and dispensing approach considered in this document. Therefore, the carbon coefficients for hydrogen have been recalculated using GREET 1.8d.1 to include the following considerations:

- Increased hydrogen compression from 6,250 psi to 12,500 psi
- Added impact of cooling hydrogen to -40°C at point of fueling (~ 2 kWh/kg of hydrogen needed for this)
- Increased truck payload capacity and pressure to ~1,000 kg and 500 bar
- Eliminated all pipeline distribution
- Assumed truck distribution distance of 30 miles one-way (what is currently considered a bulk terminal in GREET would be a production facility) for the following reasons:
  - Most major metro areas fit within a 30 mile diameter
  - Most major metro areas would have sufficient demand for at least one central SMR plant
  - Average major-metro-area delivery distance would be 15 miles

78 GREET = **G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation model developed by Argonne National Laboratory. GREET 1.8d.1 is updated version released August 2010.



Notes: Assumed FCEV on-road fuel economy of 65 mpg in the near term and 100 mpg in the future.
Assumed gasoline vehicle on-road fuel economy of 30 mpg in the near term and 50 mpg in the future.
Full fuel cycle carbon coefficients from GREET 1.8d adjusted to align with technical approach discussed in chapter.

Figure 15-31. *Well-to-Wheels Carbon Dioxide Emissions Per Mile*

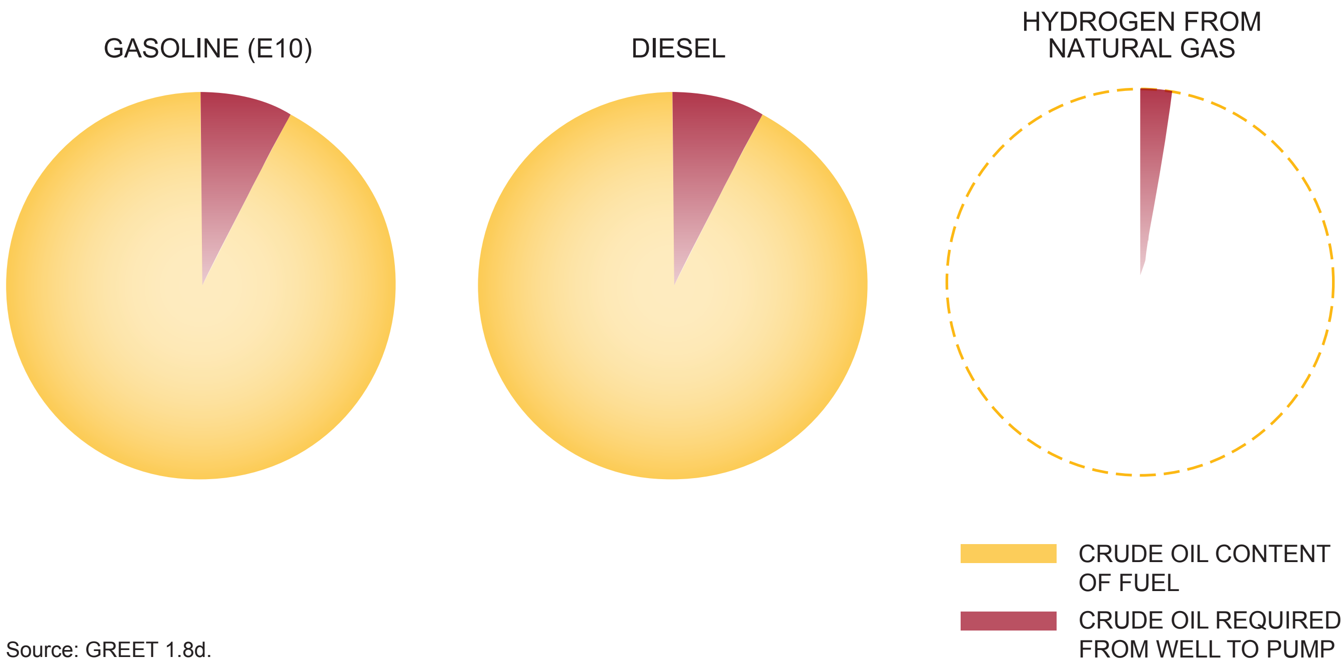


Figure 15-32. *Relative Crude Oil Requirements*

- Non-metro-area deliveries could be much longer, but for a smaller percentage of fuel
- Weighted average is assumed to be 30 miles—double the major-metro-area figure.

For the centralized SMR approach, these changes resulted in an increase in the 2020 carbon coefficient by 12%—from 25.741 to 28.852 million metric tons of carbon equivalent (MMTCe)/quadrillion BTU on a higher heating value basis. A detailed description of the changes made in GREET 1.8d.1 and results are provided in Appendix 15D at the end of this chapter.

Natural gas is a practical and feasible near-term feedstock. However, biomass and solar, wind, and nuclear electricity are potential future feedstocks for renewable hydrogen production. Using hydrogen produced with today's mature production methods, hydrogen fuel cell electric vehicles could provide significant reductions in CO_2 emissions on a well-to-wheels basis. Hydrogen from conventional natural gas in a FCEV generates ~50% lower CO_2 emissions than a gasoline car on a well-to-wheels basis. With hydrogen from renewable sources, CO_2 emissions could be reduced further (see Figure 15-31).

Impact on Crude Oil Usage

The use of hydrogen as a transportation fuel can lower crude oil consumption. Crude oil requirements for gasoline, diesel, and hydrogen from natural gas are shown in Figure 15-32. Because hydrogen can be produced from a variety of feedstocks, hydrogen has the potential of offer greater diversity than fuels derived from a single feedstock.

OTHER CONSIDERATIONS FOR SUCCESS

Policies

Recent federal policies and initiatives reflect a shift in direction from past policies and initiatives. This shift has disrupted research, development, and technology advances.

While the United States has historically held a global leadership position in the development and use of hydrogen for transportation and FCEVs, other countries are now making significant advances. Predictable and consistent policies are beneficial to effectively evaluate new fuel and vehicle technologies and progress them towards wide-scale adoption.

Rare Earth Metals

Production of large and commercial amounts of rare earth metals is concentrated in a small number of countries. Currently, these rare earths are important to electric drive vehicles, which also include FCEVs. Alternate sources and development of new magnetic materials may reduce the need for these metals; however, large-scale deployment of FCEVs would require substantial amounts of these materials. Investments would need to be made to develop an expanded supply chain for rare earth metals.

Platinum Requirements

Approximately 240 metric tons of platinum was sold in 2006 and the majority of the world production (80%) was from deposits in South Africa, followed by smaller shares from Russia and Canada. Of this total, 130 metric tons were used for vehicle emissions control devices (catalytic converters), 49 metric tons for jewelry, 13.3 metric tons in electronics, and 11.2 metric tons in the chemical industry as a catalyst. The remaining 35.5 metric tons went to various other minor applications, such as electrodes, anticancer drugs, oxygen sensors, spark plugs, and turbine engines.[79] Catalytic converters are currently the most significant demand from platinum.

Total loadings of platinum on fuel cell membranes as a catalyst are expected to drop when FCEVs enter a commercial phase. In 2005, fuel cell platinum loadings were about 1.1 grams/kW gross output. Since that time, platinum load requirements have dropped approximately 80% and current loading requirements are estimated to range from 0.2 to 0.35 grams/kW.[80] This equates to 16–28 grams of platinum per FCEV. For commercial introduction, FCEVs are expected to require approximately two times the amount of platinum than conventional gasoline and diesel vehicles and comparable amounts over the long term, 90% of which can be recycled (compared to 50% from a gasoline catalytic converter).[81]

In 2008, an independent panel concluded that given current platinum production and recycling capabilities, shortfalls of platinum availability would not hinder commercialization of fuel cell technologies for transportation.[82] Additionally, research is underway to develop fuel cells that do not require platinum. Additional information on non-precious metal catalysts is provided in Topic Paper #23 on the NPC website, "Development of Non-Precious Metal Catalysts for Oxygen Reduction in PEM Fuel Cells."

Carbon Fiber Supply

A 2008 DOE analysis suggests that hydrogen storage tanks in 2025 could require approximately 50% of total projected worldwide carbon fiber production. However, there is no resource constraint on carbon fiber production that would prevent the supply base from ramping up production in response to automotive demand.[83]

Codes and Standards

Introduction of a new fuel and vehicle system requires consideration of consumer safety as well as modification/addition to various codes and standards to guide regulators in their review and approval. The United States has a national set of codes and standards that address hydrogen technologies but adoption, to date, by local regulatory agencies has not been uniform, leading to lengthy permitting for some of the early station deployments. As additional information is gathered on hydrogen use for FCEVs, codes and standards are being updated to address various aspects including hydrogen dispensing materials, dispensing standards, component standards, fuel quality standards, fuel vehicle interface, on-board storage, etc. A number of entities are involved in updating and publishing the various codes and standards including NFPA, ASME, SAE, CSA, and UL to name a few. A coordinated effort to communicate the latest codes and standards information to the local regulators should reduce the permitting time and cost, while sharing of information between local

79 Michael W. George, *2006 Minerals Yearbook: Platinum-Group Metals*, United States Geological Survey, 2007.

80 U.S. Department of Energy, "Platinum Group Metal Loading," DOE Hydrogen and Fuel Cells Program Record # 9018, March 2010, www.hydrogen.energy.gov/pdfs/9018_platinum_group.pdf.

81 Matthew A. Kromer, Fred Joseck, Todd Rhodes, Matthew Guernsey, and Jason Marcinkoski, "Evaluation of a Platinum Leasing Program for Fuel Cell Vehicles," *International Journal of Hydrogen Energy* 34, no. 19 (October 2009), http://www.sciencedirect.com/science/article/pii/S0360319909009501.

82 National Renewable Energy Laboratory, *Fuel Cell System Cost for Transportation – 2008 Cost Estimate*, Independent Review, published for the U.S. Department of Energy Hydrogen Program, NREL/BK-6A1-45457, May 2009.

83 FreedomCAR and Fuel Partnership, *2008 Highlights of Technical Accomplishments*.

jurisdictions may lead to improved understanding of the installation and operation of hydrogen fueling facilities.

HYDROGEN AND FCEV DEVELOPMENT INVESTMENTS

Investments in research, development, and demonstration (RD&D) activities can be made by government or individual companies. Government investments are typically for pre-competitive technology development, whereas industry investments are typically targeted towards proprietary technology development.

RD&D funding can be applied to address a wide variety of FCEV and fueling infrastructure opportunities. These opportunities are discussed in detail in the vehicles and infrastructure discussions. High priority areas for pre-competitive RD&D are listed below:

FCEVs

- Durability (stack membrane materials and catalysts)
- Cost (catalysts, membrane materials, high-quality carbon fiber).

Hydrogen Fueling Infrastructure

- Compression (cost, reliability, size)
- On-site storage (cost, size)
- Fueling network (demonstrations and precompetitive infrastructure).

In addition to pre-competitive investments by government in the areas listed above, individual companies would need to continue to invest in proprietary RD&D to progress FCEVs and hydrogen fueling infrastructure towards commercial readiness.

FINDINGS

Hydrogen fueled FCEVs are a promising technology option for the U.S. LD vehicle fleet for the following reasons:

- FCEV driving performance is comparable to conventional vehicles.
- Hydrogen is currently produced primarily from domestic natural gas.
- Hydrogen is an energy carrier and can be produced from a diverse set of energy resources.
- FCEVs have significantly lower well-to-wheels GHG footprint than conventional vehicles.
- Total cost of driving on a per-mile basis can be comparable to that of conventional vehicles.

The key findings of this analysis are as follows:

Pathway Benefits

- Compared to today's conventional LD vehicles, GHG emissions can be reduced ~50% on a well-to-wheels basis by the deployment of FCEVs operating on hydrogen produced from natural gas.
  - Further reduction is possible using lower carbon feedstocks or carbon capture and sequestration.
  - Current FCEVs have two to three times the efficiency of comparable conventional vehicles on a tank-to-wheels basis.
- FCEV technology is applicable across all LD vehicle segments.
  - Operating performance (acceleration, range, etc.) of FCEVs is comparable to that of conventional vehicles.
- Hydrogen production via steam methane reforming of domestic natural gas is currently the most competitive process for hydrogen production in the United States and is expected to be the major source of hydrogen production near to mid-term.
  - Steam methane reforming is the baseline against which other hydrogen production technologies will compete.
  - Domestic natural gas resources can support hydrogen production for a material segment of the transportation sector.
- As compared to other fuels, hydrogen dispensed fuel costs are less sensitive to changes in feedstock commodity costs because capital infrastructure costs and taxes make up a greater proportion of the final fuel cost.

Price and Market Considerations

- Upon commercial introduction, FCEVs are expected to cost ~1.4 times more than a comparable gasoline ICE vehicle; these prices may come down over time and be cost competitive with other LD vehicle options. Ongoing effort will be needed to lower the cost of subsequent generations of vehicles.

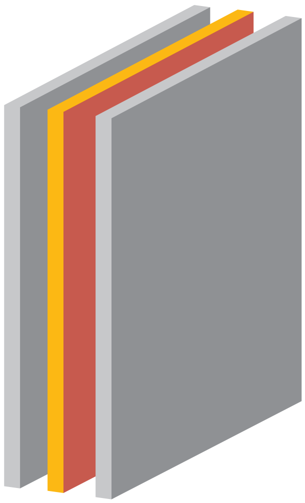
- On a cost-per-mile basis, hydrogen fuel for an FCEV can be comparable to gasoline for a conventional vehicle.
  - The modeled price of dispensed hydrogen (fully taxed) is $9–12/kg in the near term and $6–7/kg in the long term.
  - One kg of hydrogen in an FCEV is equivalent to two to three gallons of gasoline in a conventional vehicle on a miles-driven basis.
- Unsubsidized economic viability can only be reached when sufficient FCEVs are deployed within a geographic region.
- Leveraging of existing hydrogen capacity at centralized production facilities is the most economical option for early fueling infrastructure deployment.
  - Additional hydrogen production capacity will be needed upon mass commercialization of FCEVs.
- Many automotive manufacturers (General Motors, Ford, Toyota, Honda, Nissan, Daimler, and Hyundai) are planning commercial introduction of FCEVs by 2015 in targeted geographies (e.g., United States, Germany, Japan, and South Korea).

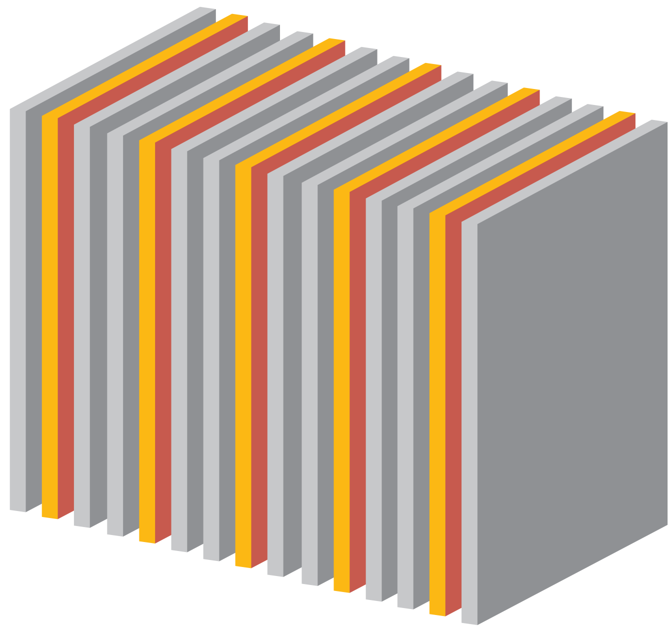
Ongoing Challenges

- Fuel cell durability (life) improvements by a factor of two are needed to be comparable to today's conventional vehicles, based on publicly available fleet demonstration data.
  - Commercial durability targets have been demonstrated in laboratory environments and these improvements will be incorporated into next generation vehicles.
- An early market value proposition for FCEVs is needed because the first generations of commercial FCEVs are not expected to be cost competitive with conventional vehicles.
- As is the case for most fueling infrastructure business models, the economic viability for hydrogen fueling infrastructure is significantly dependent on scale of fueling capacity and utilization of installed fueling capacity (i.e., leveraging economies of scale).
- Technology advancements in compression and on-site storage are needed and can provide further reductions in capital costs, operating costs, and land requirements. They can also improve station reliability.

Significant and sustained investments by industry and government are required for this pathway to achieve commercial success.

APPENDIX 15A:
HOW A FUEL CELL WORKS





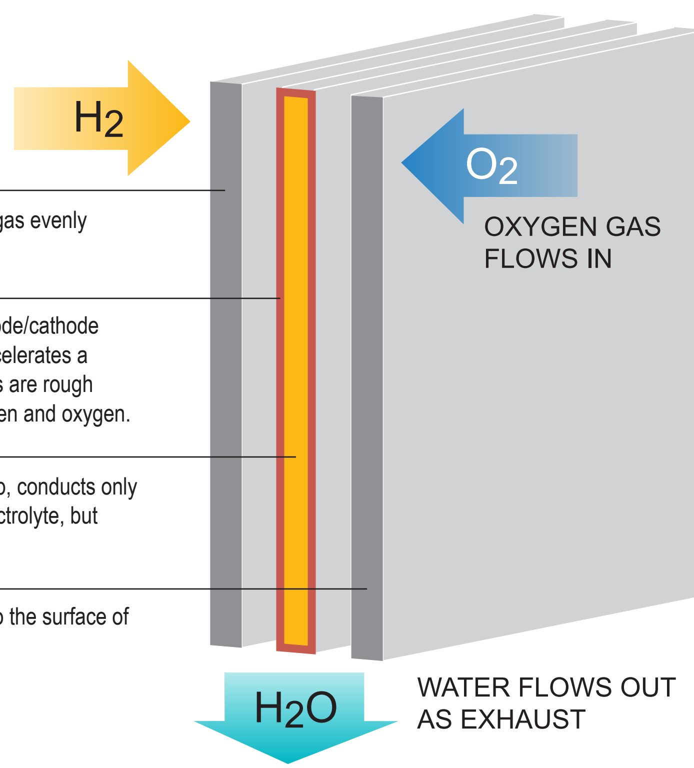
The fuel cell needs two substances to generate power, typically oxygen and hydrogen, though other fuels such as methane or methanol can be used. Oxygen is readily available from the air, but pure hydrogen must be supplied. Hydrogen can be produced from diverse domestic resources, including natural gas, petroleum, and coal, as well as renewables such as biomass, or directly from water using solar, wind, and geothermal energy sources. A fuel cell's only emission is pure water.

Source: General Motors.

A typical PEM fuel cell operates at 0.7 volts at close to one amp per square centimeter current density. To generate enough electricity to power electric motors, individual fuel cells are combined into a fuel cell "stack." A typical fuel cell stack consists of hundreds of fuel cells.

Figure 15A-1. *How a Fuel Cell Works – Cell and Stack*

HYDROGEN GAS
FLOWS IN



OXYGEN GAS
FLOWS IN

ANODE
The negatively charged anode has channels that disperse the hydrogen gas evenly over the surface of the catalyst.

CATALYST
A thin layer of a catalyst coats the proton exchange membrane or the anode/cathode electrode. Current catalysts are comprised of a precious metal which accelerates a chemical reaction between the oxygen and hydrogen. The catalyst layers are rough and porous so that maximum surface area can be exposed to the hydrogen and oxygen.

PROTON EXCHANGE MEMBRANE
The Proton Exchange Membrane, which looks something like plastic wrap, conducts only positively charged protons. The protons pass through the membrane electrolyte, but electrons do not.

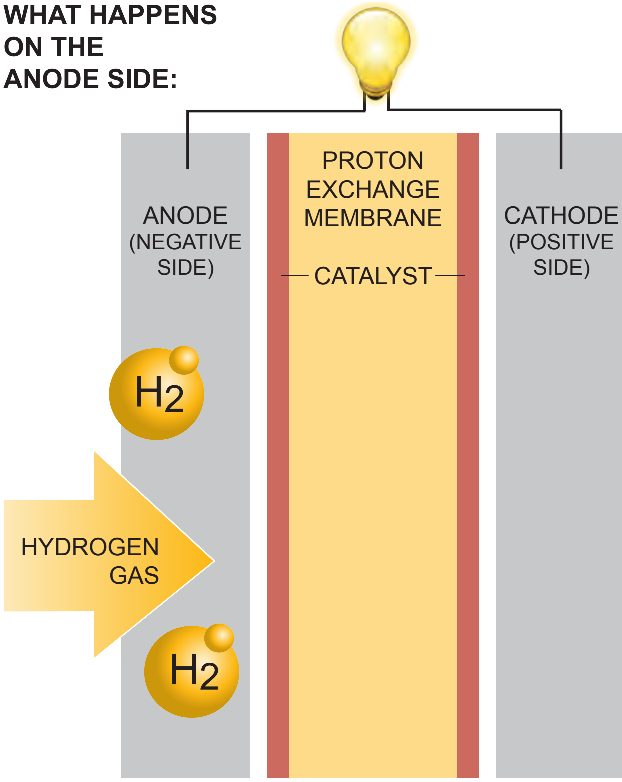
CATHODE
The positively charged cathode has channels that distribute the oxygen to the surface of the catalyst and remove the water produced during the reaction.

WATER FLOWS OUT
AS EXHAUST

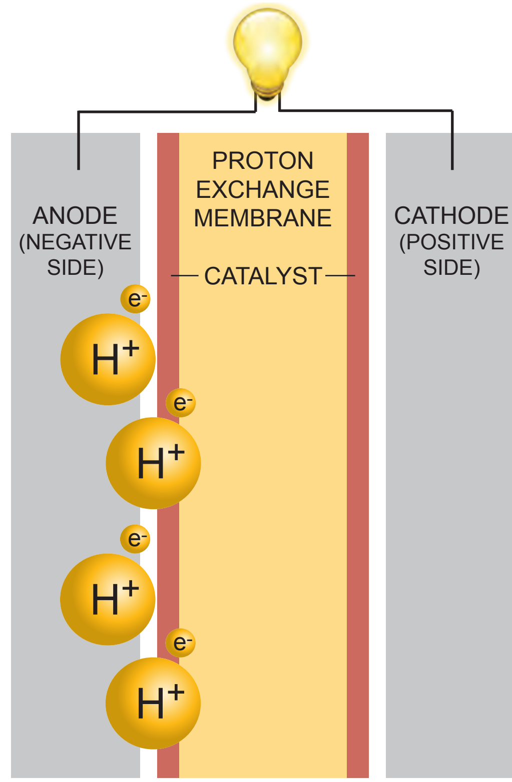
Source: General Motors.

Figure 15A-2. *How a Fuel Cell Works – Cell Detail*

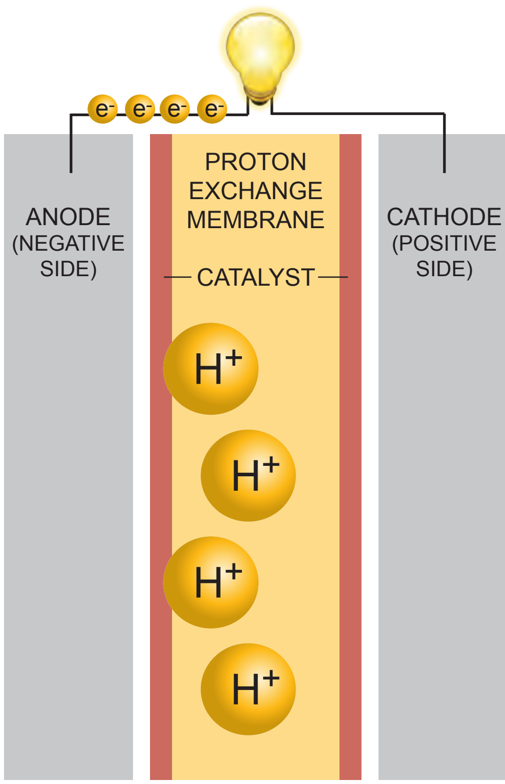
WHAT HAPPENS ON THE ANODE SIDE:



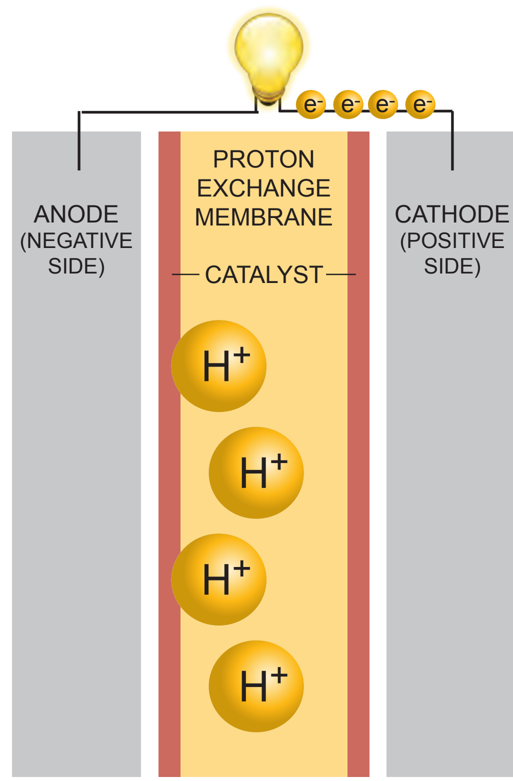
1. Inside the fuel cell, hydrogen gas is pumped through the catalyst.



2. When an H_2 molecule touches the catalyst, it splits into two hydrogen ions (H^+) and two electrons (e^-).



3. The electrons are conducted through the anode. They bypass the membrane and go through an external circuit (where they help turn an electric motor in a vehicle) ...



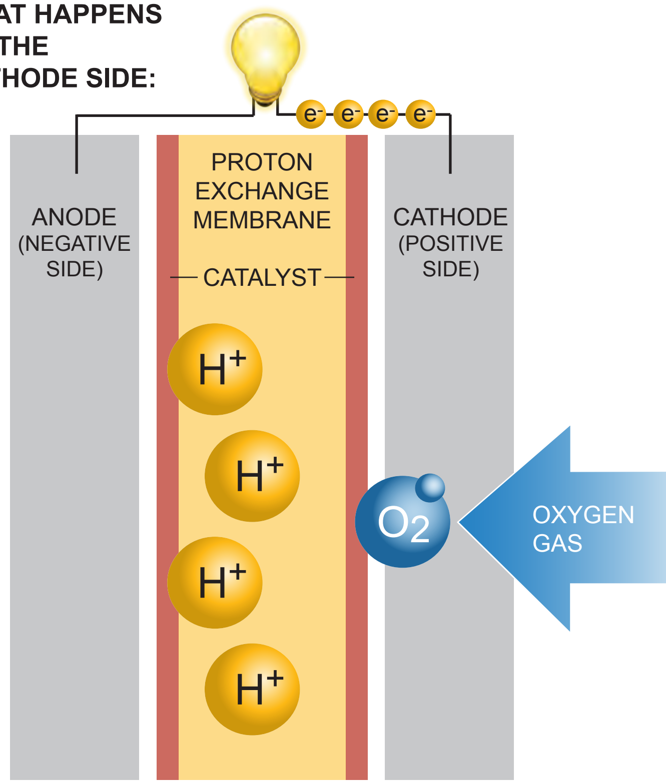
... and return to the cathode side of the fuel cell.

CHEMISTRY: $2H_2 = >4H^+ + 4e^-$

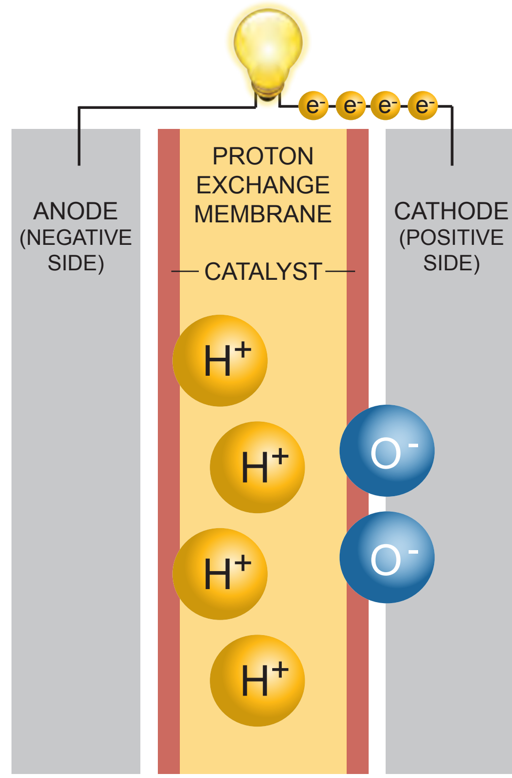
Source: General Motors.

***Figure 15A-3.** Fuel Cell Chemistry – Anode (Hydrogen) Side*

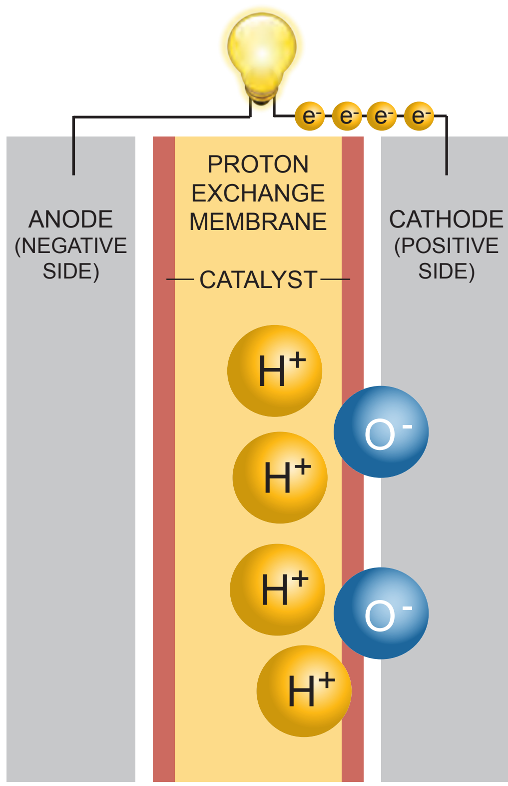
WHAT HAPPENS ON THE CATHODE SIDE:



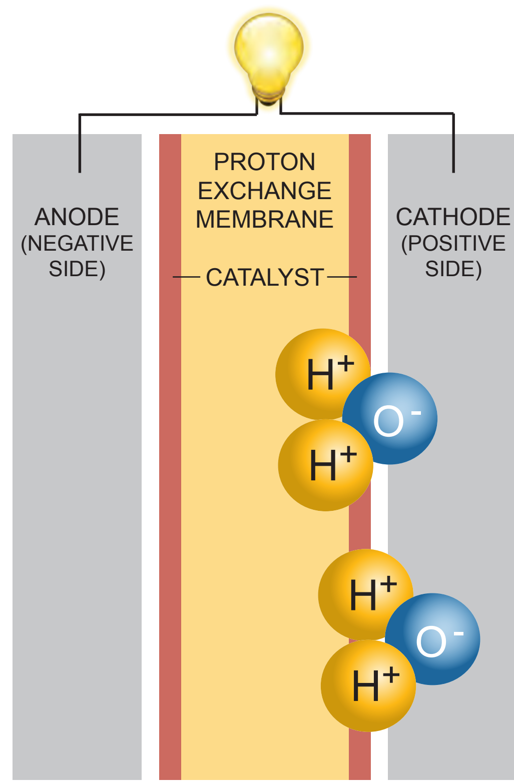
1. Oxygen (O_2) from the air enters the fuel cell on the cathode side. This gas is forced through the catalyst.



2. The catalyst splits the O_2 into two oxygen atoms.



3. Each oxygen atom attracts two H^+ ions through the membrane.



4. Two H^+ ions combine with an oxygen atom and two of the electrons from the external circuit to form a water molecule (H_2O), which is emitted as exhaust.

CHEMISTRY: $\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$

Source: General Motors.

Figure 15A-4. *Fuel Cell Chemistry – Cathode (Oxygen) Side*

APPENDIX 15B:
HYDROGEN PATHWAY PRIORITIZATION CRITERIA

Areas for more comprehensive analysis were selected based on the pathway's ability to materially impact greenhouse gas emissions, energy security, and economic growth ("three pillars").

Some pathways, when considered independently, may not materially contribute towards meeting the three pillars; however, these pathways may have significant ongoing technology development activities and could be direct enablers for other more-significant pathways and therefore were considered.

Other fuel cell markets (e.g., forklifts, auxiliary power units, stationary power) are growing rapidly for hydrogen and fuel cells. However, because the focus of this study is the transportation sector, other fuel cell markets were not considered. These are stand-alone viable markets that are now growing without government incentives; however, even with this rapid growth, these markets are not large enough to make material contributions towards the three pillars at a national level.

Technical merit, by itself, was not a disqualifier for any pathway, and the exclusion of a pathway should not be considered a negative reflection of its technical merits, nor does it indicate that further RD&D efforts are not warranted.

Only the use of hydrogen for direct vehicle propulsion was considered. Vehicle auxiliary power applications do not represent a significant share of U.S. transportation fuel usage and therefore were also not considered.

The use of hydrogen for stationary power was not considered because it is out of scope for this study.

VEHICLE PATHWAYS

Hydrogen Internal Combustion Engines and Fuel Cells

Both hydrogen FCEVs and hydrogen internal combustion engine (HICE) vehicles were evaluated for the light-duty (LD) vehicle, medium-/heavy-duty (MD/HD) vehicle, aviation, rail, and marine market segments.

One significant benefit of using hydrogen as a transportation fuel is the efficiency of a fuel cell, which is significantly more efficient at producing usable energy than internal combustion engines. Fuel cells for automobiles can generate electric power at efficiencies as high as 50% at full power and 60% at partial power; versus 15–20% for most internal combustion engines, or approximately 30% for some advanced diesel engines. The HICE drive train has lower technology hurdles than a fuel cell drive train because combustion engines are a mature technology; however, few manufacturers favor this approach because the lower efficiency of the combustion engine requires significantly greater volumes of hydrogen to be stored onboard the vehicle. Alternatively, due to their lower efficiency, the deployment of HICE vehicles could increase the demand for hydrogen more rapidly, which would help infrastructure economics. HICE vehicles may have applications as a transition technology, but they are not required for successful commercialization of the hydrogen pathway. Since HICE vehicles do not have as material an impact on achieving the three pillars as FCEVs, HICE vehicles were not pursued for further analysis.

Light-Duty Vehicles

Most U.S. and foreign auto manufacturers have substantial ongoing efforts to develop LD hydrogen-fueled vehicles, specifically FCEVs. LD FCEVs offer similar or better performance than conventional engine platforms and other competing technologies; therefore, auto manufacturers see market potential for this vehicle platform. Since LD vehicles are currently the largest transportation market segment for energy use, additional hydrogen technology developments for LD vehicles can have a material impact on achieving the three pillars and are considered in scope and a key priority pathway.

Medium- and Heavy-Duty Vehicles

Although the market segment for MD/HD vehicles is not as large as that for LD vehicles, it is still material and remains a focus area for vehicle manufacturers. Technology providers continue to invest in hydrogen vehicle technologies such as auxiliary power units for long-haul trucks and propulsion systems for buses and delivery trucks. The deployment of a hydrogen fueling infrastructure to support the introduction of buses and delivery trucks can be a significant enabler for hydrogen fuel availability and a catalyst for the LD FCEV market. By providing an early market with steady demand for hydrogen and by driving the implementation of hydrogen delivery and dispensing infrastructure, fuel cell buses and fuel cell delivery trucks can aid and speed the commercialization of LD FCEVs. Although they are not considered a critical path, buses and delivery truck technologies are considered a priority pathway because of the technology developments currently under way and their ability to be a significant enabler for LD vehicle commercialization.

Hydrogen fuel cell buses represent an early market for fuel cell technologies. Fuel cell buses are currently in operation at 12 transit agencies, and another 6 agencies are planning to operate fuel cell buses. There are 14 fuel cell buses currently operating at these transit agencies, with another 22 buses planned.

Each fuel cell transit bus can require several thousand kilograms of hydrogen each year. Fuel cell transit buses thus can provide a regular demand for hydrogen, and transit agencies operating fuel cell buses can help in the development of a nascent hydrogen distribution and dispensing infrastructure.

Similarly, fuel cell electric drivetrains can be developed for delivery trucks, further aiding the growth of hydrogen infrastructure in urban areas. Fleets of delivery trucks that are centrally fueled can be good candidates for converting to fuel cell use.

FUELING INFRASTRUCTURE PATHWAYS

Centralized Hydrogen Production

Large scale centralized hydrogen production is the most common and efficient way to produce hydrogen today and is primarily accomplished via steam reforming of hydrocarbons (namely natural gas). Centralized plants would be located outside the city limits to serve the local market. Other feedstock for the centralized production of hydrogen include, but are not limited to, biomass, renewable natural gas, ethanol, coal, naphtha, ethane, propane, and butane. State of the art large reformers have 70%[84] to 90%[85] system efficiency depending on how a unit's operation can be optimized to use heatpower and hydrogen.

Current commercial centralized hydrogen production technologies and assets can be leveraged to provide fuel for FCEVs in the early period. Therefore, centralized hydrogen production is a priority pathway.

Distributed Hydrogen Production

Significant technology development work has been performed to date to produce hydrogen on site at or near retail fueling stations. Producing hydrogen on a smaller scale on site (or near a retail location) eliminates (or reduces) fuel distribution costs. Distributed hydrogen production technologies have been demonstrated primarily using natural gas and water as feedstock via reformation and electrolysis, respectively, and have efficiencies of over 70% and 60%, respectively.[86] The use of biogas (in place of natural gas) and renewable electricity offer near-term renewable pathways for distributed hydrogen production. Distributed hydrogen production technologies are not as economical as centralized hydrogen production technologies and require land at a station and skilled labor for operation and maintenance. A significant reason for this is the economies of scale and integration of which centralized facilities can take advantage. Distributed hydrogen technologies are also not as mature, and future advancements can make them more economically competitive. Distributed hydrogen production offers a near-term potentially scalable and potentially economically competitive option to leverage existing infrastructure (natural gas, electricity, and/or water utilities) to produce hydrogen at the point of demand; therefore, distributed hydrogen production is a priority pathway.

84 GREET Model v1.8d.

85 Pamela L. Spath and Margaret K. Mann, *Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming,* National Renewable Energy Laboratory, NREL/TP-570-27637, Revised February 2001.

86 GREET Model v1.8d.

Home Fueling

A commercially viable home fueling system can significantly affect the fuels and auto industries and is being pursued by companies and researchers. If home fueling technology is used to power and heat the home, it would also impact the power and public utility industries. Since this pathway is in the early stages of technology development, has numerous and significant technology challenges such as cost, noise, space, and utilities requirements, codes & standards, is not essential for the successful introduction of hydrogen vehicles, and other hydrogen fueling pathways have significantly lower technology challenges, home fueling was not pursued for further analysis.

Combined Heat, Power, and Hydrogen

Stationary fuel cell efficiencies can be optimized to approach 85% by producing and using a combination of heat, power, and hydrogen.[87] A high-temperature stationary fuel cell directly converts the chemical energy in its fuel to electricity, with water, carbon dioxide, and heat as by-products. High-temperature fuel cells typically consume 70 to 80% of their fuel. The unconsumed hydrogen is essentially a waste stream that can be utilized for the production of by-product hydrogen, reducing gas, additional power, or waste heat.[88] The heat and power can be used at the location where the stationary fuel cell is installed and the hydrogen, typically 10 to 20% of the total fuel content, can be used to fuel early deployments of FCEVs.

Power and heat production from stationary fuel cells can be applicable in limited locations where utility prices are relatively high and renewable methane is available (e.g., digester gas). A proof-of-concept of co-production of hydrogen (100 kg/day) from a stationary fuel cell (250 kW net power output) is in operation at a wastewater treatment facility in Southern California under DOE funding and demonstrates that combined heat, power, and hydrogen installations can be feasible. This effort is focused on the development of a solution to produce renewable hydrogen if it is required by regulation (e.g., California SB 1505) or if consumers are willing to pay a premium for renewable hydrogen. Due to limited applicability, this pathway is not considered a priority within this analysis.

87 National Fuel Cell Research Center, University of California, Irvine (website), "Fuel Cell Benefits," 2009, http://www.nfcrc.uci.edu/2/FUEL_CELL_INFORMATION/FCexplained/FC_benefits.aspx.

88 U.S. Department of Energy, Energy Efficiency & Renewable Energy, Industrial Technologies Program, "Ultra Efficient Combined Heat, Hydrogen, and Power System," August 2011, http://www1.eere.energy.gov/industry/distributedenergy/pdfs/fuel_cell_chhp.pdf.

APPENDIX 15C: CALCULATIONS FOR FUTURE HYDROGEN COST VARIABLES AND RATIONALE

Near Term									
Distributed Case	Cost Analysis Background			Inputs		Scaled			
	Key Input Parameters	Nominal Values	Range	kg hydrogen capacity per day	140	250	Low	High	
AEO2010 – 2015(low), 2020(ref), 2025(high)	Natural Gas Feedstock Cost	$6.70	$5.82–$7.44	Total cost	$4,300,000	$5,256,979	$3,628,490	$6,885,469	
Used central near term Opex/Capex ratio applied to direct Capex (no site work)	Total Fixed Operating Cost	$375,000	$200,000–$525,000	Site cost (prep, permits, etc.)	$2,000,000	$2,000,000	$2,000,000	$2,000,000	
NA	Delivery Cost	NA	NA	Equip Capex	$2,300,000	$3,256,979	$1,628,490	$4,885,469	
Mid based on H2A default	Equipment Life	15	10–20 Years	Fixed Opex	$268,333	$379,981	$189,990	$569,971	
Mid is scaled to 250 kg/day; low and high are +/- 50% of equipment cost only (site costs fixed)	Total Station Capital Cost	$5,300,000	$3.5M–$7M	Equip cap/fixed Opex ratio	11.7%		Scaling Factor	0.6	
Mid based on H2A default	Station Demand Factor	85%	50–95%						
2010 FreedomCAR analysis	After-tax IRR	10%	0–20%						
	Station Capacity	250 kg/day	100–400 kg/day						
Tax revenue neutral for per-mile basis	Tax	0.79							

Central Case	Cost Analysis Background			Inputs	
	Key Input Parameters	Nominal Values	Range	kg hydrogen capacity per day	250
AEO2010 – 2015(low), 2020(ref), 2025(high)	Natural Gas Feedstock Cost	$6.70	$5.82–$7.44	Total cost	$1,500,000
From discussion with Air Products	Total CSD Operating Cost	$175,000	$125K–$250K	Site cost (prep, permits, etc.)	$0
2010 FreedomCAR analysis	Delivery Cost	$1.75	$1.25–$2.25	Equip Capex	$1,500,000
Mid based on H2A default	CSD Equipment Life	15	10–20 Years	Fixed Opex	$175,000
CA Energy Comm2010 Stations Awards +/- 50%	Total CSD Capital Cost	$1,500,000	$1M–$2M	CSD cap/fixed Opex ratio	11.7%
Mid based on H2A default	Station Demand Factor	85%	50–95%		
Mid based on H2A default	After-tax IRR	10%	0–20%		
	Station Capacity	250 kg/day	100–400 kg/day		
Tax revenue neutral for per-mile basis	Tax	0.79			

Table 15C. *Calculations for Future Hydrogen Cost Variables and Rationale*

Near Term								
Distributed Case	**Cost Analysis Background**			**Inputs**		**Scaled**		
	Key Input Parameters	**Nominal Values**	**Range**	**kg hydrogen capacity per day**	**140**	**250**	**Low**	**High**
AEO2010 – 2015(low), 2020(ref), 2025(high)	Natural Gas Feedstock Cost	$8.73	$6.92–$13.15	Total cost	$4,300,000	$8,384,304	$3,628,490	$11,576,456
5% of capital cost range	Total Fixed Operating Cost	$325,000	$150,000–$475,000	Site cost (prep, permits, etc.)	$2,000,000	$2,000,000	$2,000,000	$2,000,000
NA	Delivery Cost	NA	NA	Equip Capex	$2,300,000	$6,384,304	$3,192,152	$9,576,456
Mid based on H2A default	Equipment Life	15	10–20 Years	Fixed Opex		$319,215	$159,608	$478,823
Mid is scaled to 1,500 with 1%/yr learning (40 yrs); low and high are +/- 50% of equipment only	Total Station Capital Cost	$8,500,000	$5M–$11.5M	Implied learning factor		0.669		
Mid based on H2A default	Station Demand Factor	85%	50–95%	CSD cap/fixed Opex ratio	5.0%	1% LEARNING over 40 years		
Mid based on H2A default	After-tax IRR	10%	5–15%				Scaling Factor	0.6
	Station Capacity	1,000 kg/day	750–1,500 kg/day					
Tax revenue neutral for per-mile basis	Tax	0.79						

Central Case	**Cost Analysis Background**			**Inputs**				
	Key Input Parameters	**Nominal Values**	**Range**	**kg hydrogen capacity per day**	**250**	**1,500**	**Low**	**High**
AEO2010 – 2025(low), 2035(ref), 2050(high)	Natural Gas Feedstock Cost	$8.73	$6.92–$13.15	Total cost	$1,500,000	$2,940,287	$1,470,144	$4,410,431
5% of capital cost range	Total CSD Operating Cost	$150,000	$75,000–$225,000	Site cost (prep, permits, etc.)	$0	$0	$0	$0
2010 FreedomCAR analysis	Delivery Cost	$1.25	$1.00–$1.50	Equip Capex	$1,500,000	$2,940,287	$1,470,144	$4,410,431
Mid based on H2A default	CSD Equipment Life	15	10–20 Years	Fixed Opex		$147,014	$73,507	$220,522
Mid is scaled to 1,500 with 1%/yr learning (40 yrs); low and high are +/- 50%	Total CSD Capital Cost	$3,000,000	$1.5M–$4.5M	Implied learning factor		0.669		
Mid based on H2A default	Station Demand Factor	85%	50–95%	CSD cap/fixed Opex ratio	5.0%	1% LEARNING over 40 years		
Mid based on H2A default	After-tax IRR	10%	5–15%				Scaling Factor	0.6
	Station Capacity	1,000 kg/day	500–1,500 kg/day					
Tax revenue neutral for per-mile basis	Tax	0.76						

Table 15C. *Calculations for Future Hydrogen Cost Variables and Rationale (continued)*

APPENDIX 15D:
INPUT CHANGES TO GREET 1.8D.1 AND RESULTS

- Assumed 100% gaseous hydrogen production is via centralized steam methane reforming (SMR) from North American natural gas by modifying the 'Fuel_Prod_TS' tab (cells C218:C224 set to 100%).
- Zeroed out pipeline transfer distance. This was accomplished in the 'T&D_Flowcharts' tab. Transfer from the central plant to the bulk terminal was set to 0.001% (cell F949) and distance was set to 1 mile (cell F950). Could not set these parameters to zero due to "divide by zero" error. Pipeline transfer from bulk terminal to the refueling station was set to 0% (cell K945—a valid entry) and 1 mile (cell K946).
- Assumed truck distance of 30 miles, which was entered into cell K953 of the 'T&D_Flowcharts' tab.
- Modified the truck payload from 0.4 tons to 1.1 tons (U.S.) in the 'T&D' tab (cells Q7:Q8) to be consistent with input on new high pressure trailers carrying 1,000 kg.
- Modified the values in the 'Compression' tab of GREET to reflect the pressures and refueling temperature (-40 C/F during). Refueling to 700 bar would require compression to 12,500 psi. This value was entered in cell H5. The temperature of -40 was entered into cell H6. Assumed that fueling the tube trailers to 500 bar at the central plant would require the same degree of over-pressure as fueling the vehicle. Hence, the compression value used for the tube trailers was 12,500 psi * (500 bar/700 bar) = 8,900 psi. This was entered into cell G5. (Note that if one simply used 500 bar * 14.5 psi/bar = 7,250 psi, the result is about 0.13 million metric tons of carbon equivalent (MMTCe)/quadrillion BTU lower.)
- Added emissions to reflect chilling the gas to -40 during refueling based on input of 2 kWh per kg of hydrogen. Used U.S. electricity mix emission factors from the 'Electric' tab: cells B65 (HC), B66 (CO), B71 (CH_4), B72 (N2O), and B73 (CO_2) were used to derive the CO_2e values. The U.S. electricity mix was used throughout this pathway. This was a separate calculation.

The results of the above modifications are presented in Table 15D-1 in terms of MMTCe/quadrillion BTU on a higher heating value basis. The emissions from cooling hydrogen have been shown separately.

	Impact of Δ to Distribution and Compression	Impact of Δ to Cooling	New Total Value for 2020
Centralized SMR	0.871	2.636	29.248
Distributed SMR	Not Applicable or Negligible	2.636	29.505
Centralized Biomass	0.871	2.636	11.146
Centralized Solar	0.871	2.636	7.767
Centralized Wind	0.871	2.636	7.767
Nuclear Electrolysis	0.871	2.636	8.470
Distributed Electrolysis	Not Applicable or Negligible	2.636	70.960

Table 15D-1. *Results of NPC Modifications to GREET 1.8d.1 Model (Million Metric Tons of Carbon Equivalent per Quadrillion BTU)*