Quadrennial Technology Review 2015

Chapter 8: Advancing Clean Transportation and Vehicle Systems and Technologies

Technology Assessments

Connected and Automated Vehicles

Fuel Cell Electric Vehicles

Internal Combustion Engines

Lightweight Automotive Materials

Plug-in Electric Vehicles

U.S. DEPARTMENT OF ENERGY

Quadrennial Technology Review 2015

Fuel Cell Electric Vehicles

Chapter 8: Technology Assessments

Introduction to the Technology/System

Overview of Fuel Cell Electric Vehicles

Energy planning models demonstrate that electric drive vehicles and low-carbon fuels are needed to address climate change, energy security, and criteria pollutant emissions goals, among others.[1,2,3,4,5] Hydrogen fuel cell electric vehicles (FCEVs) are a promising electric vehicle technology that could meet petroleum and emission reduction goals and be cost-competitive with advanced gasoline internal combustion engine vehicles (ICEVs).[6] In a recent report on fuel transitions, the U.S. National Academy of Sciences[7] stated the following:

> "Fuel cells, batteries, biofuels, low-GHG [greenhouse gas] production of hydrogen, carbon capture and storage, and vehicle efficiency should all be part of the current R&D [research and development] strategy. It is unclear which options may emerge as the more promising and cost-effective… The committee believes that hydrogen/fuel cells are at least as promising as battery electric vehicles in the long term and should be funded accordingly (p. 7)."

There are several benefits to expanding FCEV use. FCEVs have the potential to lower per-mile greenhouse gas (GHG) emissions compared to gasoline ICEVs owing to their higher efficiency and ability to use renewable and low carbon hydrogen. Additionally, FCEVs could be used as a medium for energy storage and transmission, and thus can help facilitate the expansion of renewable power generation by storing energy at times when electricity production is greater than demand. Lastly, FCEVs provide quiet operation, no tailpipe emissions (except water), 300+ mile range, rapid refueling, and the ability to act as a source of portable electrical power generation for off-vehicle use.

A number of companies (e.g., Toyota, Hyundai) have begun to commercialize FCEVs while others (e.g., Honda, Daimler) plan to do so within a few years, but mainly in Europe, Asia, California, the northeastern United States, and Hawaii, where governments are coordinating efforts to build hydrogen infrastructure. Within the United States, several thousand fuel cell forklifts are already deployed, enabling real-life experience with hydrogen fueling.[8] Other potential markets for FCEVs include medium-duty and heavy-duty vehicles. Many of these vehicles have duty cycles that are not suitable for pure battery electric or plug-in electric technology.

Summary of Challenges

Despite the potential benefits of FCEVs, there are four main technical challenges that need to be addressed before they can become widely adopted, each of which requires further research and development (R&D) if it is to be addressed. These challenges are fuel cell durability, fuel cell efficiency, fuel cell cost and performance, and hydrogen storage, and are detailed below:

- **Fuel Cell Durability**: The average durability of fuel cells on the road is 2,500 hours based on laboratory technology that is several years old in early-generation vehicles, but levels of over 4,000 hours have been reached in the laboratory and recent on-road data are nearing 3,900 hours[9] maximum durability. To reach vehicle lifetimes similar to gasoline ICEVs (about 150,000 miles), durability of over 5,000 hours is necessary. Specific durability barriers include the following:

- Low durability of current catalysts and electrodes, which are not yet capable of 5,000 hours of durable operation at low platinum group metal (PGM) loading
- Low durability of current ultrathin membranes, which are not yet capable of withstanding 5,000 hours of operation with humidity cycling and exposure to contaminants
- Tolerance of fuel cells to a range of fuel quality conditions as well as automotive cycling, such as start-stop conditions

- **Fuel Cell Efficiency**: Currently the electrical efficiency of fuel cell systems is approximately 60%, but increasing this efficiency would be beneficial: higher efficiencies mean that less onboard hydrogen is needed to go the same distance. Decreasing the weight of the hydrogen tank then leads to greater vehicle efficiency. This benefit motivates research to push electrical efficiencies of fuel cell systems to 65% in the near-term and up to 70% in the long-term.[10]
- **Fuel cell cost and performance**: Automotive fuel cell systems at a cost of $30/kW or less will be competitive with gasoline internal combustion engines.[11] To achieve this goal further cost reductions will be needed from the currently projected $55/kW cost for today's state-of-art laboratory technology with high volume production (500,000 per year). The current high cost of the automotive fuel cell system motivates research to improve:
  - Sub-optimal utilization of PGM content in current catalysts
  - Current catalysts' and electrodes' performance to reduce platinum group metal loadings[12] and balance-of-plant[13] requirements
  - Performance of membranes under the hot and dry conditions that occur when operating near the peak power point without humidification
  - Understanding of the role of electrode composition and microstructure at low platinum group metal loadings on fuel cell performance and durability
- **Hydrogen Storage**: On-board hydrogen storage should provide a driving range of more than 300 miles on one fill at a cost of $8/kWh or less, without compromising performance, safety, or interior space:
  - **Composites**: Low-cost, high-performance composites are needed to reduce total costs while maintaining performance
  - **Materials**: Alternative, high-strength, low-cost materials are needed for balance-of-plant components in high-pressure hydrogen service applications
  - **Conformability**: Systems capable of having non-cylindrical shapes are desirable as they could be packaged onboard vehicles more efficiently

Technology Assessment and Potential

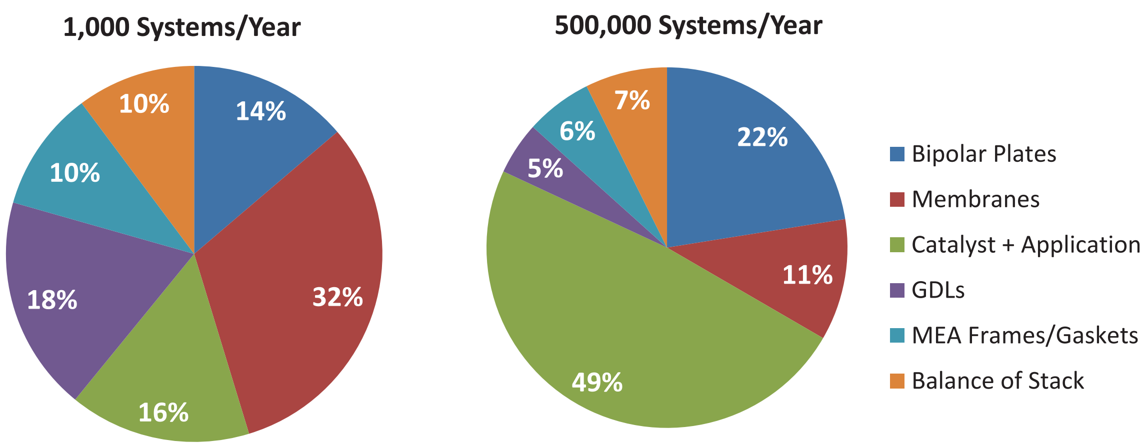
Performance Advances of Fuel Cells

Fuel cells convert the chemical energy in fuels such as hydrogen directly into electricity. They do so without combustion by electrochemically combining the fuel with oxygen from air in an electrochemical cell. The only product when hydrogen is used, besides electricity and heat, is water vapor—with no other emissions from the vehicle. In an FCEV, the fuel cell stack, composed of a number of individual cells, replaces the entire engine, and a small battery is typically included to provide additional power and take advantage of regenerative braking. FCEVs can be refueled in a few minutes, can be used for a wide range of vehicle sizes, and can achieve a driving range of more than 300 miles. However, the availability of a hydrogen production, distribution, and fueling infrastructure is a key barrier (hydrogen fuel is discussed in Chapter 7 and Technology Assessment 7.D).

The classification of a fuel cell is based on its electrolyte (e.g., phosphoric acid, molten carbonate, solid oxide, alkaline, and polymer electrolyte membrane [PEM] fuel cells). The most widely used fuel cell for automotive applications is the PEM fuel cell (PEMFC). This is primarily owing to their low temperature operation (roughly 80°C), which allows for rapid start-up and shutdown and the good transient response required for a range of automotive operating conditions.

Fuel cell technologies continue to improve, and costs continue to decline. Emerging technologies often experience the highest reductions in weight, volume, and cost between successive early generations of the technology and less so as the technology matures.[14] For instance, reductions of 2.3% per year in high volume cost in early generations of a technology, and 1% per year in later generations have commonly been observed.[15] Figure 8.B.1 shows the breakdown of component costs for low- and high-volume production of fuel cells in 2014. As shown, at low volumes the catalyst plus application costs only account for 15% of the fuel cell cost, while at high volume they account for 46% of a much lower total cost. Even at high manufacturing rates, catalyst cost is a major contributor to total cost, pointing to a need for further catalyst R&D. Currently, the highest production capacity of a single automaker is approximately 1,000 units per year.[16]

Figure 8.B.1 Breakdown of the 2014 Projected Fuel Cell Stack Cost at 1,000 and 500,000 Systems Per Year [17]



Costs were estimated at $273/kW at 1000 systems per year and at $55/kW at 500,000 per year. Further R&D could reduce fuel cell costs to $30/kW (high volume beyond 2030) and double the durability to make FCEV life-cycle costs (vehicles + fuel) comparable to those of other advanced vehicle technologies (Figure 8.B.2). Additional fuel cell R&D is needed to: (a) reduce catalyst loading; (b) develop low-cost, high-temperature membranes with high proton conductivity and chemical stability, and low-cost durable membrane electrode assemblies; and, (c) produce corrosion-resistant bipolar plates.

Figure 8.B.3 shows the performance of 700 bar Type IV compressed hydrogen storage system at 300 K against DOE's 2020 onboard vehicle storage targets. The blue space indicates current performance and the white space indicates the areas in which 700 bar compressed systems currently fall short of DOE's 2020 targets.

Figure 8.B.2 Cost Reduction Target For Automotive Fuel Cell

Credit: Fuel Cell Technologies Office analysis - update of SAinc (B. James) 2015 Annual Merit Review presentation (report to be published in 2016)

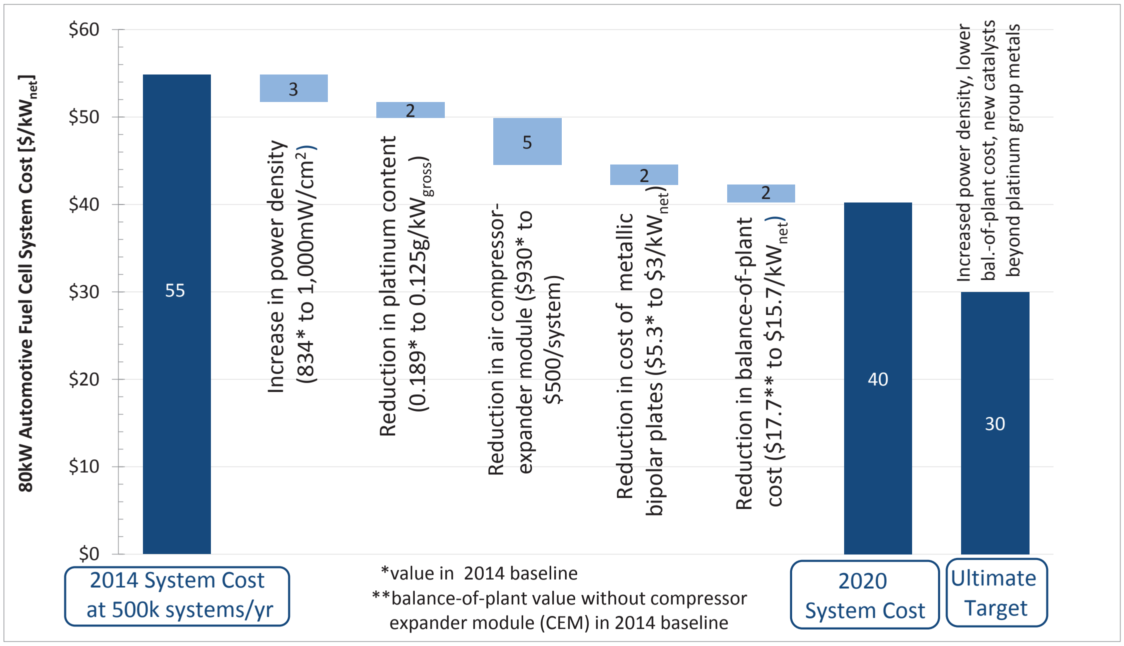
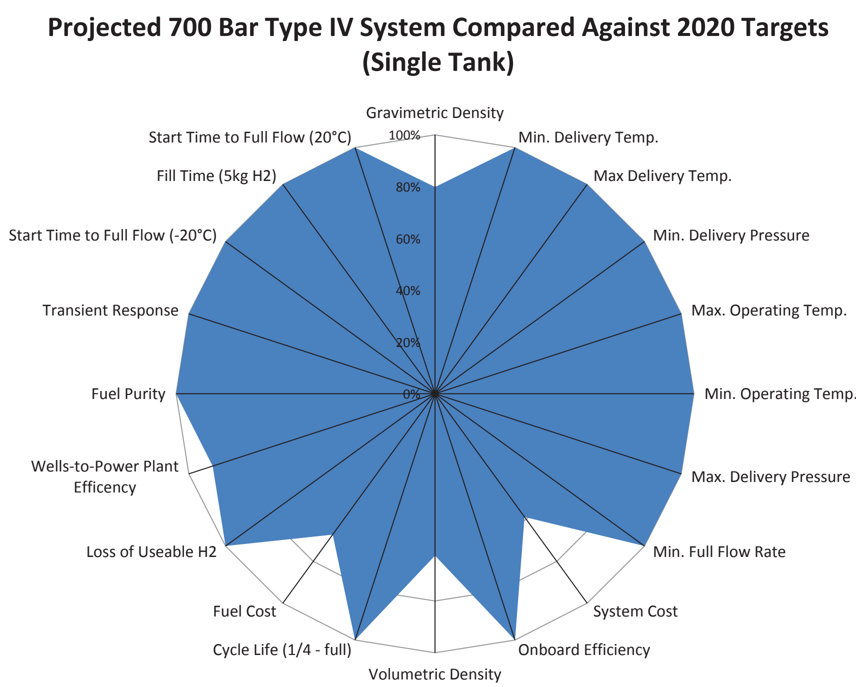


Figure 8.B.3 Projected 700 Bar Type IV System Compared Against DOE's 2020 Targets (Single Tank)[19,20,21]

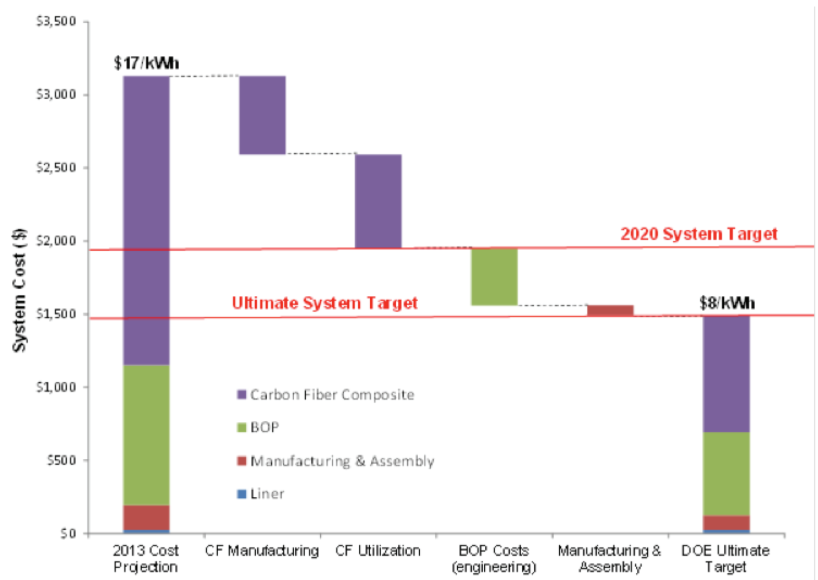


Performance Advances of Hydrogen Storage

Hydrogen storage costs are a significant element in the overall costs of an FCEV. The current near-term technology for onboard hydrogen storage is focused on 350 bar (for fuel cell buses) and 700 bar (for fuel cell cars) nominal working-pressure compressed hydrogen vessels (i.e., "tanks"). The compressed gas storage capacity, and hence the vehicle driving range, is limited by the volume and cost of tanks that can be packaged in vehicles. The tanks within these systems have been certified worldwide. The high-pressure hydrogen storage tanks for LDVs consist of either a metallic (Type III) or nonmetallic (Type IV) liner overwrapped with a carbon fiber reinforced composite.

High Pressure Tanks: To provide a 300-mile driving range for LDVs, current cost projections for a 700 bar Type IV system would be approximately $2,800 ($17/kWh) if manufactured at 500,000 systems per year but approximately $5,500 ($33/kWh) if manufactured at only 10,000 systems per year.[22] Additionally, the system would require a volume roughly three to four times that typical for current gasoline tanks. While automakers have demonstrated the ability to package these systems onboard some vehicle platforms to offer a driving range close to 300 miles,[23] this cannot be accomplished across the full range of vehicle platforms at acceptable costs. The ultimate cost target for high pressure tanks is $8/kWh, as shown in Figure 8.B.4.

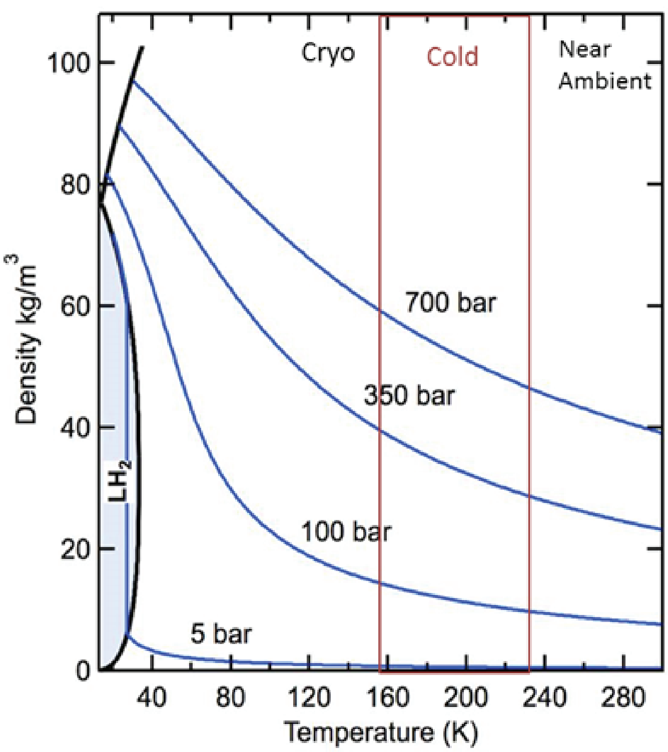
Figure 8.B.4 Potential Cost Reduction Strategy for Compressed Hydrogen Tanks [24]



The Type III and IV compressed gas systems used for hydrogen are similar to those used for compressed natural gas (CNG). Hydrogen is typically stored at 700 bar for LDVs in Type IV systems and 350 bar for buses and off-road vehicles (e.g., forklifts) in Type III or IV systems. CNG is typically stored at 200–250 bar in Type III or IV systems. As shown in Figure 8.B.4, the main cost driver for the Type III and IV systems is the carbon fiber composite. Long continuous lengths of high-strength "aerospace-grade" carbon fiber are required to fabricate the composite over-wraps for the tanks. Efforts to reduce the cost of the carbon fiber composite include developing low-cost alternative fibers, developing lower-cost precursors for producing the carbon fiber, developing fillers to improve the composite performance, and improving winding patterns and manufacturing processes for the tanks (see also QTR Technology Assessment 6.E). The second highest cost driver for compressed hydrogen systems is the balance-of-plant components (e.g., fittings, valves, and pressure regulators); R&D efforts to reduce their cost is also needed.

Advanced hydrogen storage technologies include sub-ambient temperature compressed storage and materials-based storage. As shown in Figure 8.B.5, the density of hydrogen is increased at reduced temperature; therefore, the use of cold (150 K to near-ambient) or cryogenic (<150 K) temperatures offers the potential to reduce the overall system volume for a given pressure and quantity of hydrogen stored. These storage tanks require insulation to minimize heat leakage into the stored hydrogen.

Figure 8.B.5 Density Versus Temperature for H_2 Storage[25]



Materials-based Storage: Materials-based storage technologies take advantage of the fact that significantly higher hydrogen densities at lower pressure (typically 100 bar or less) can be obtained when hydrogen is adsorbed on the surface of porous solids or bonded to other elements within compounds. The three primary classes of materials are hydrogen adsorbents, reversible metal hydrides, and chemical hydrogen storage materials. Basic as well as applied research is required for all three classes of materials to meet temperature, capacity, and kinetics requirements.

Metal Hydrides: Reversible metal hydride hydrogen storage using certain materials is fairly mature and well proven; it is the basis of NiMH battery technology, but the conventional intermetallic alloys used are considered too expensive and too heavy for LDV hydrogen storage applications. Therefore, development of hydrides composed primarily of lighter elements is required. A second class of reversible metal hydrides is the "complex" hydrides, where the hydrogen is bound to a metal, typically through covalent bonds, forming a multi-element anion, also called a "complex anion." The complex anion coordinates with cations, typically alkaline or alkaline earth metals, through ionic or saline interactions. Because many complex hydrides are composed of lightweight elements, higher hydrogen capacities by mass are possible (e.g., $Mg(BH_4)_2$, ~14% hydrogen by mass), and this is an active area of current investigation. However, the temperature required for hydrogen release needs to be lowered.

Sorbents: In hydrogen adsorption, the diatomic hydrogen molecule adheres to the surface of a solid material through low energy van der Waals interactions. High-surface area microporous materials, such as activated carbons and metal organic frameworks, are being developed as sorbents for hydrogen and natural gas storage.

While many of the preferred material characteristics are similar for hydrogen and natural gas adsorption, a key difference is that the van der Waals binding strength for hydrogen is much lower, resulting in the need for cryogenic temperatures for significant adsorption. Therefore, development of materials with high micropore density as well as higher hydrogen binding strengths is required.

Chemical Hydrogen Storage Materials: Chemical hydrogen storage materials are compounds with strongly bound hydrogen, where the hydrogen is released through non-equilibrium processes and thus cannot be recharged simply through application of pressurized hydrogen. Examples of potential chemical hydrogen storage materials include ammonia borane (NH_3BH_3), ammonia (NH_3), aluminum hydride (AlH_3), and sodium borohydride (Na(BH4)). Chemical hydrogen storage materials can have very high hydrogen capacities by mass (e.g., ammonia borane: 19.6% by mass). While materials in this class have been developed for several niche applications, the materials need to be easily filled onboard for automotive use and the spent product must be easily removable from the vehicle. In addition, the spent materials will need to be regenerated efficiently at low cost. The need for a two-way infrastructure complicates the use of chemical hydrogen storage materials in automotive applications. Onboard the vehicle, the system may be complicated by the need for post-release cleanup to remove volatile components (e.g., B_2H_4 and NH_3) that could negatively impact the fuel cell performance from the released hydrogen.

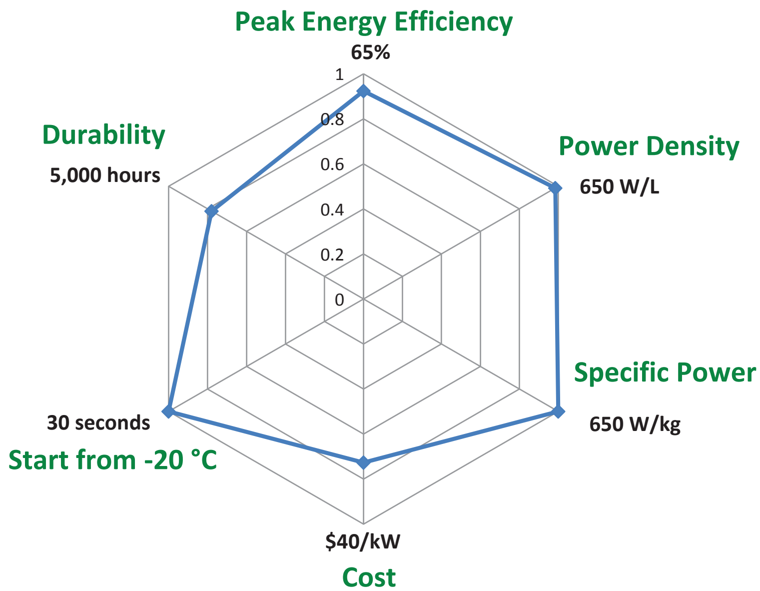
Long-Term Research Needs: In the longer term, R&D is needed on advanced storage materials because, while some promising storage materials have been identified, no single material meets all storage targets simultaneously. To support and accelerate the advancement of hydrogen storage materials R&D, DOE has developed a database[26] to provide the research community with easy access to searchable, comprehensive, up-to-date materials data on adsorbents, chemicals, and metal hydrides in one central location. The database includes information from DOE-funded research, pulled from a number of sources, including the historical Hydride Information Center database, DOE-funded research projects, and the former DOE Centers of Excellence. The database currently includes approximately 3,000 unique material entries and has had close to 20,000 page views, with visitors from 121 countries in its first three years available online. Furthermore, hydrogen storage materials must be integrated into a system that meets the cost, safety, and performance requirements of current and future vehicle markets. Complete system models developed through the DOE-supported Hydrogen Storage Engineering Center of Excellence are available online so materials developers can project how their developed materials would perform when incorporated into a complete system for automotive application.[27]

Figure 8.B.6 shows progress toward the DOE's fuel cell targets relative to current performance. The figure demonstrates that durability and cost are the primary challenges to fuel cell commercialization.

Potential Benefits of FCEVs

As shown in Figures 8.B.7 and 8.B.8, by the mid-2030s FCEVs with hydrogen produced from distributed natural gas reforming could offer greater than 50% reduction in GHG emissions and nearly a complete reduction in petroleum consumption compared to today's gasoline ICEVs.[30] These benefits can be improved

Figure 8.B.6 2020 Fuel Cell Targets Relative to Current Performance (Laboratory data). Sources: Targets are from the Fuel Cell Technologies Office (FCTO)'s Multi-Year Research, Development, and Demonstration Plan;[28] current performance data are from DOE assessments and/or FCEV evaluations compiled by NREL.[29]



by using carbon capture. Reductions in GHG emissions of more than 80% can be reached by using low-carbon hydrogen from renewable sources. Additionally, biogas from sources such as wastewater treatment plants and landfills is already available as feedstock to hydrogen, and there could be other low-carbon pathways in the future (e.g., hydrogen from biomass, nuclear, and microbiological pathways) that would enable fuel cells to achieve even greater reductions in GHG emissions. Note that in both Figures 8.B.7 and 8.B.8, the wind electricity (central) bar for FCEVs has a nonzero value in some cases because the hydrogen transportation and distribution

Figure 8.B.7 Well-To-Wheels GHGs Emissions from Advanced Light-Duty Vehicle/Fuel Pathways, Year 2035[31]

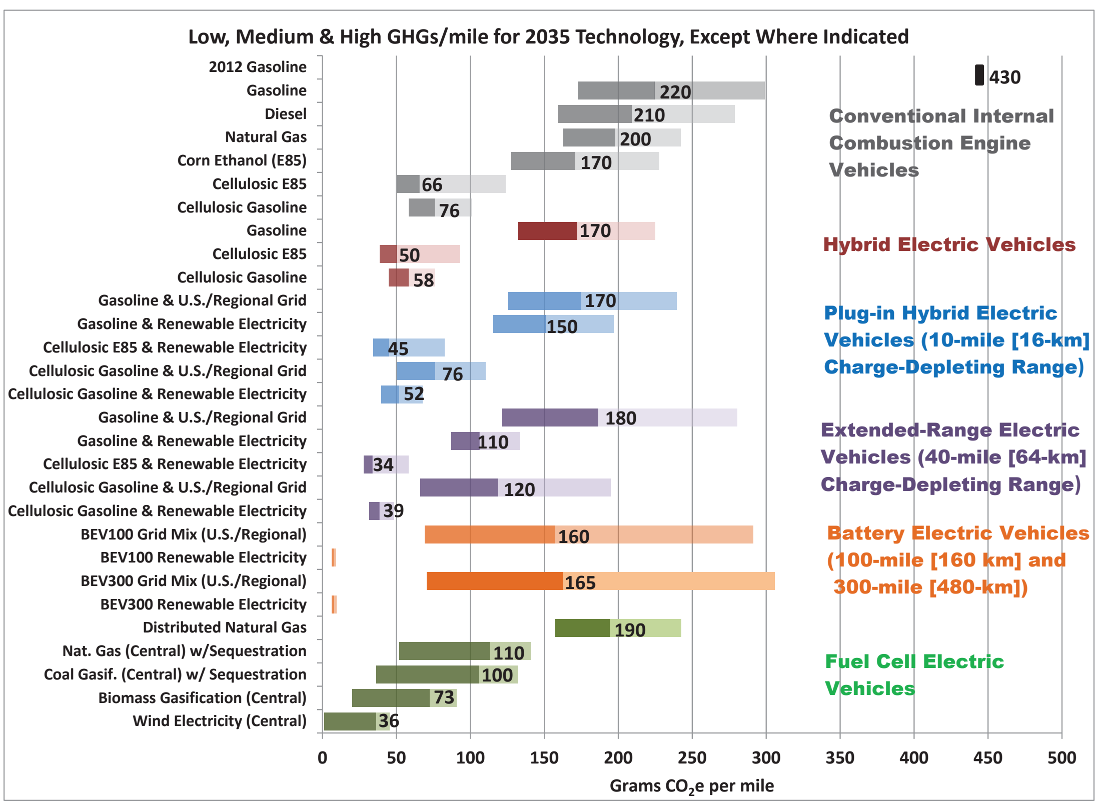
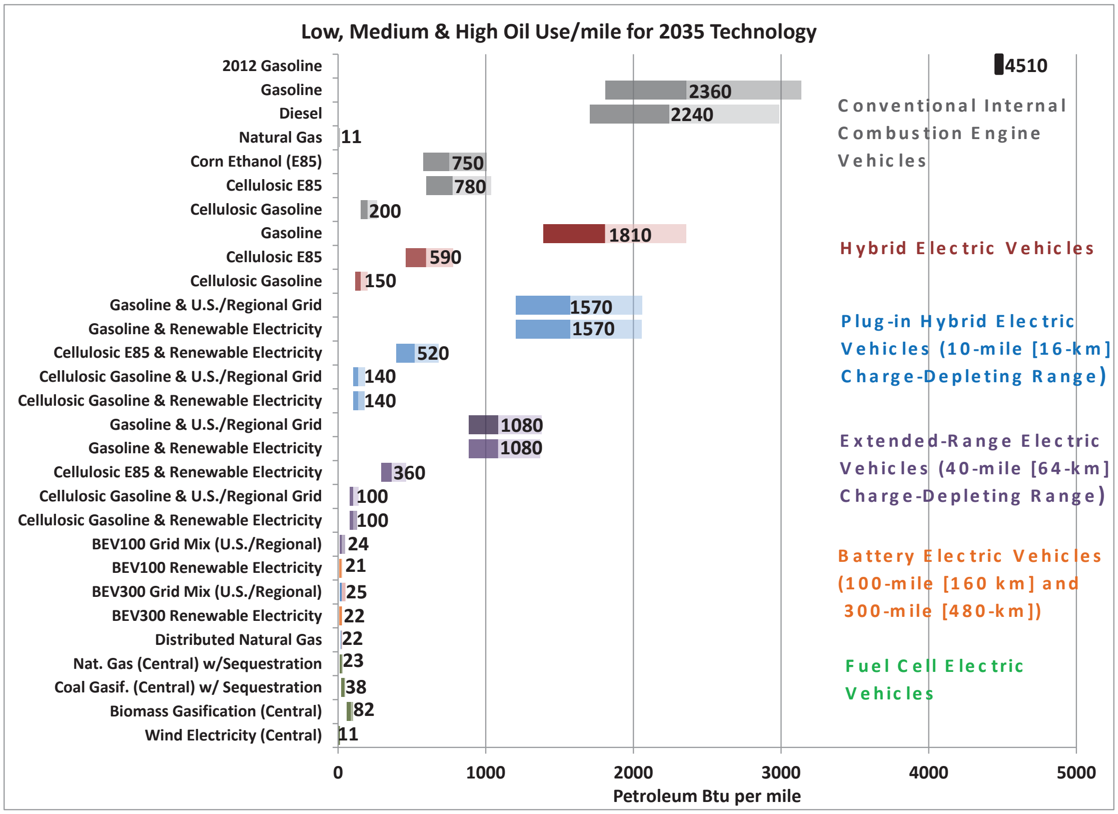


Figure 8.B.8 Life-Cycle Oil Consumption from Advanced Light-Duty Vehicle/Fuel Pathways, Year 2035[32]



are assumed to use some fossil fuels (e.g., grid electricity to run a compressor at a refueling station, using the EIA-projected U.S. mix of electricity sources for Year 2035 rather than a potential low-carbon future electric power system). The water footprints of several FCEV/hydrogen pathways are smaller than that of the typical passenger car on gasoline with 10% ethanol by volume. The environmental and energy benefits of hydrogen and fuel cells in different sectors are discussed in Chapters 3, 4, and 7 of the QTR and their accompanying Technology Assessments.

Analysis by Oak Ridge National Laboratory indicates that by 2050, the market penetration of FCEVs could reach 20%–70% percent of LDV stocks (not just sales) if program targets are met, and the resulting benefits of the DOE efforts could therefore include reductions in national oil consumption of 2–4 million barrels per day and reductions in GHG emissions of 200–450 million metric tons per year.[33]

Figure 8.B.9 is adapted from the National Research Council report,[34] *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen*, and illustrates that significant reductions in GHG emissions can be achieved through the use of hydrogen fuel cells—making substantial gains toward the goal of 80% reduction in CO_2 emissions by 2050. The portfolio approach shown in the figure assumes a significant introduction of FCEVs to the market, the maximum practical rate of improvements in gasoline ICEVs efficiency (including hybrid electric vehicles), and large-scale use of biofuels.

FCEVs have cost reduction potential relative to ICEVs as the technology matures and higher production volumes are reached. Figure 8.B.10 shows the projected total cost of ownership of four power trains, as estimated by McKinsey & Company (2010).[36] After the year 2020, the total cost of ownership converges as costs of the advanced power trains benefit from learning and economies of scale. This finding that FCEVs become cost-competitive with plug-in electric vehicles (PHEVs), battery-electric vehicles (BEVs), and ICEVs is also projected by the National Research Council report.[37]

Figure 8.B.9 The Role of Hydrogen FCEVs in a Portfolio Approach to Achieve GHG Emission Goals[35]

Credit: National Research Council. The graph is a result of combining different graphs from the source reference to save space.

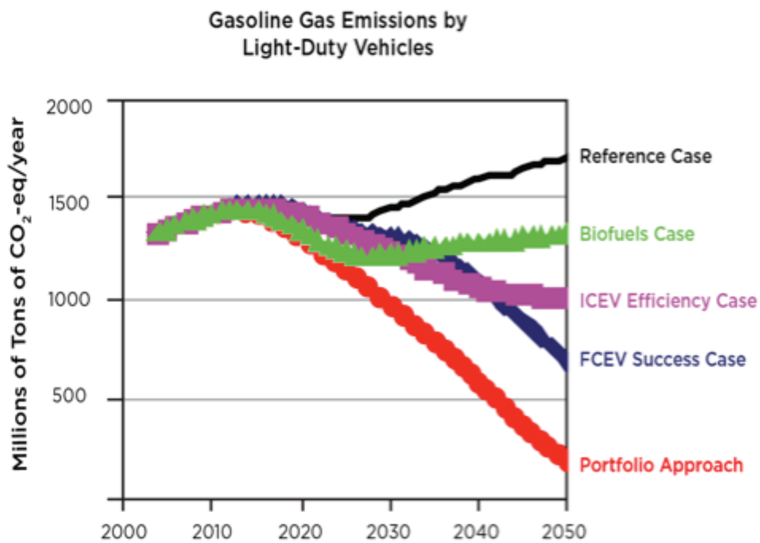
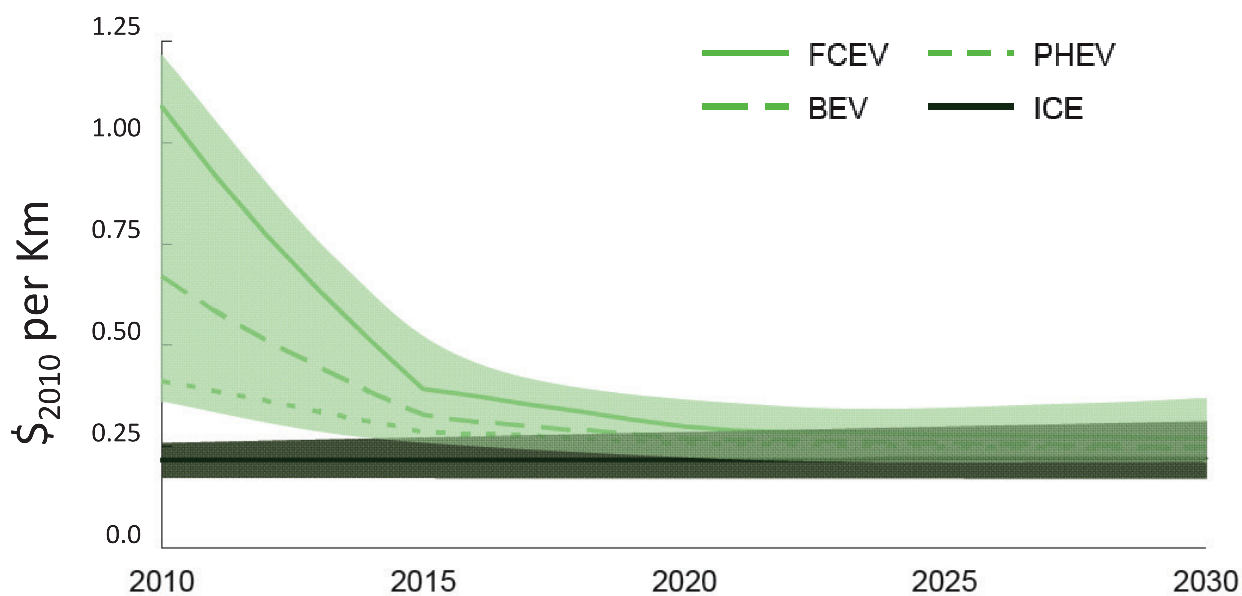


Figure 8.B.10 Total Cost of Ownership by Power Train for Generic FCEVs, PHEVs, BEVs, and ICEVs[38]

Credit: McKinsey and Company



Public and Private R&D Activities

A number of challenges still hinder the widespread adoption of FCEVs. As highlighted above, hydrogen fuel cell and storage technologies continue to rapidly improve, but more progress is needed to reach cost and performance parity with incumbent vehicle technology. A broader challenge is the so-called "chicken and egg problem" in which vehicle manufacturers are reluctant to build FCEVs due to a lack of hydrogen refueling infrastructure but fuel providers are reluctant to build hydrogen refueling stations due to a lack of vehicles to supply. Successful entry into new markets will also require overcoming certain institutional and economic barriers, such as the need for codes and standards, the lack of public awareness and understanding of the technologies, and the lack of a supply base that many new technologies face in their critical early stages.

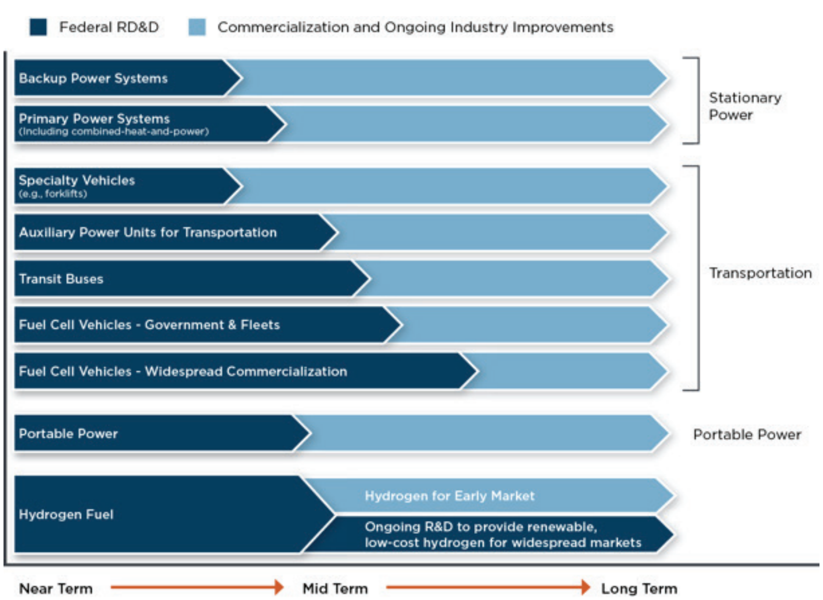
While private companies often focus on relatively low-risk, incremental improvements to existing technology, the long-term nature and high risk in overcoming the barriers listed above motivates a strong public role. Specifically, government can play an important role in supporting R&D activities to lower fuel cell, battery, and storage costs and in helping coordinate hydrogen infrastructure expansion. In the text below, this technology assessment examines the DOE role in addressing technical and other barriers to FCEV adoption.

Role of DOE

Program Considerations to Support R&D

There are potential synergies between fuel cell systems used for transportation and those used for buildings (e.g., manufacturing learning benefits), with a public role important in capturing and leveraging these synergies (Figure 8.B.11). Specifically, this includes market-acceleration strategies that integrate technology demonstration and validation, codes and standards development, and early market deployments to test technologies and capture economies of scale and learning in technology production. Demonstration and validation ensures that pre-commercial technologies are ready for the deployment phase and can provide critical feedback to R&D efforts, revealing issues that come to light when technologies are operated in complete systems under real-world conditions. Efforts in safety, codes and standards enable development of codes and standards that are necessary for commercial deployments and help reduce permitting times. Early market deployment activities focus on key markets for commercial-ready technologies, where a modest number of new orders will have a significant impact on long-term commercialization by reducing costs through economies of scale and catalyzing growth of domestic manufacturing.

Figure 8.B.11 Federal Role in Fuel Cell and Hydrogen R&D. It is desirable to pursue advances in hydrogen and fuel cell technologies in the early stages of development for a variety of applications[39]



A number of workshops have helped inform DOE's program strategies in these areas. Table 8.B.1 presents the workshop names and dates in 2014 that added to program strategies for fuel cells, hydrogen storage, safety codes and standards, technology validation, manufacturing R&D, and market transformation (see also QTR Supplemental Information for Chapter 1 "Representative DOE Applied Energy Program workshops").

Fuel Cells

Public-private fuel cell R&D is focused on materials, stack components, balance-of-plant components and subsystems,

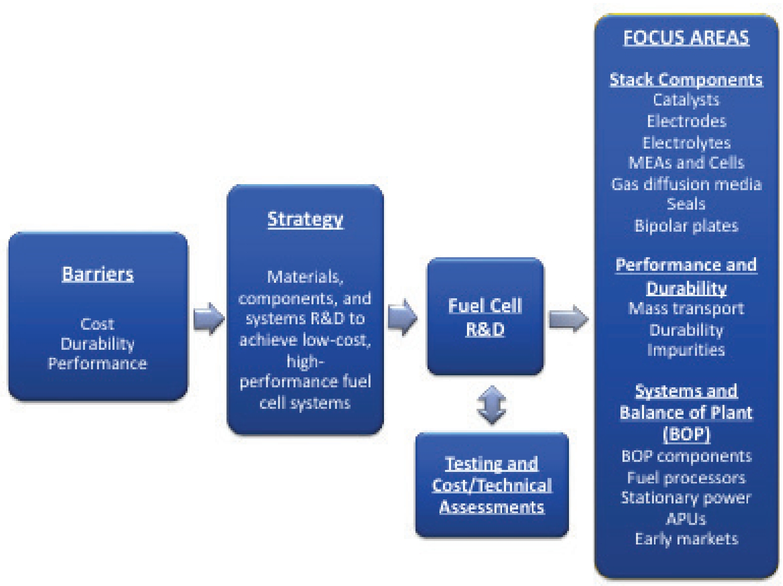
Table 8.B.1 Examples of DOE Workshops and Request for Information in 2014 that Generated Information in Support of the Quadrennial Technology Review

Workshop	Date	Location
Gas Clean-up for Fuel Cell Applications	March 6–7, 2014	Argonne National Lab, IL[40]
Hydrogen Energy Storage	May 5, 2014	Sacramento, CA[41]
International Hydrogen Infrastructure	May 8-9, 2014	Torrance, CA[42]
Hydrogen Contamination Detector	June 12, 2014	Troy, MI[43]
DOE Pre-solicitation: R&D needs and technical barriers for PEMFC	June 16, 2014	Washington, DC[44]
Fuel Cells for Continuous On-Board Recharging Application for Battery Electric Light-Duty Vehicle	July, 2014	Request for Information issued online [45]

and integrated fuel cell systems targeting lower cost and enhanced durability, with an emphasis on science and engineering at the cell level, and from a systems perspective, on integration and component interactions (Figure 8.B.12). Examples of key R&D activities include the following:

- Developing improved fuel cell catalysts and electrolytes
- Identifying degradation mechanisms and approaches for mitigating the effects
- Improving membrane electrolyte assemblies and fuel cells through integration of state-of-the-art components
- Characterizing and optimizing transport phenomena, improving cell and stack performance
- Developing low-cost, durable system balance-of-plant components

Figure 8.B.12 DOE Strategy for R&D of Fuel Cells[48]

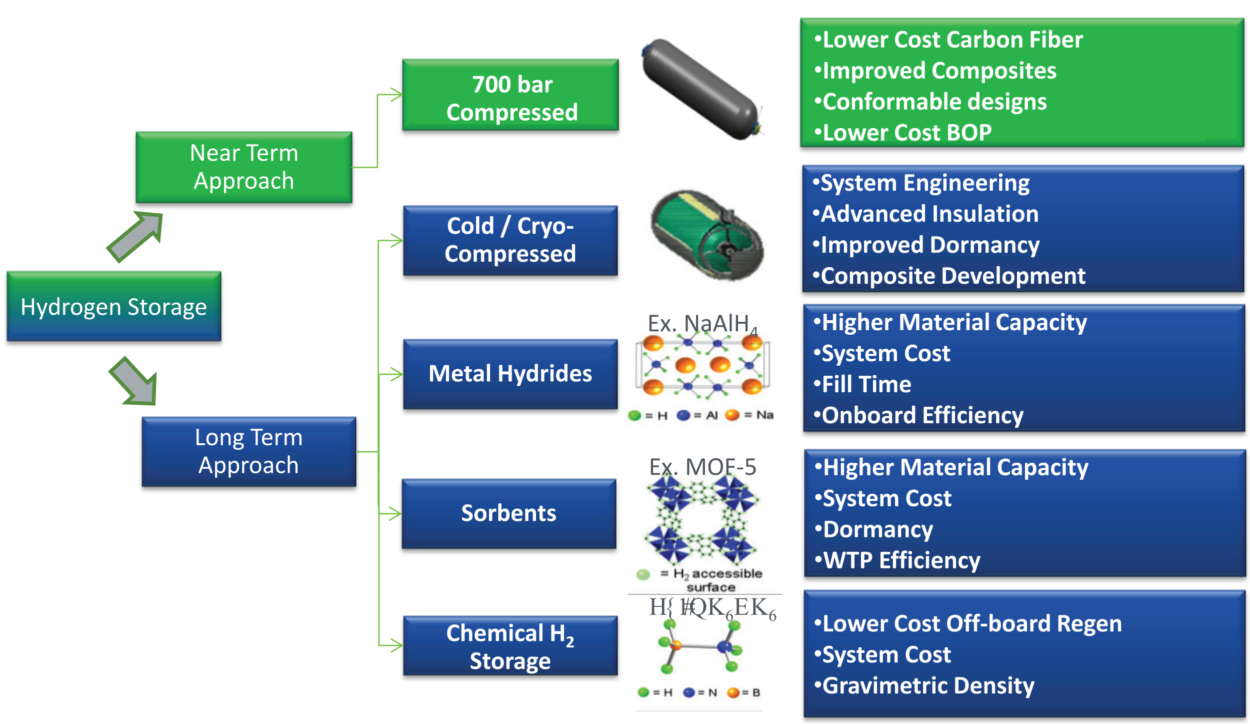


The DOE perspective on FCEV pathways and costs[46] has arisen through numerous workshops and technical team meetings through the industry/federal partnership U.S. DRIVE; it is consistent with, and incorporates external assessments.[47] The specific targets identified by DOE have been developed with broad stakeholder input (automobile industry, fuel cell technology developers, industrial gas companies, university, national laboratory, and private sector researchers).

Hydrogen Storage

Hydrogen storage R&D is needed to lower the cost of near-term physical storage options and to develop longer-term advanced hydrogen storage technologies that meet the full set of onboard system targets and that can enable the widespread commercialization of hydrogen fuel cell systems for diverse applications across a number of sectors. A near-term focus exploring low-cost carbon fiber composites for high-pressure storage will not only benefit hydrogen fuel cell vehicles but will also be applicable to CNG vehicles. By addressing R&D needs for both gaseous fuels simultaneously, advancements can be made for both at an accelerated pace and at lower overall R&D costs. Figure 8.B.13 depicts the DOE strategy developed with stakeholders to address hydrogen storage challenges.

Figure 8.B.13 Hydrogen Storage R&D Strategy[49]



Safety Codes and Standards

The development of safety codes and standards is an important aspect of hydrogen technology R&D and has an important public component. Safety codes and standards are necessary for the widespread commercialization and safe deployment of hydrogen and fuel cell technologies, and require R&D in the areas of hydrogen risk, behavior, materials compatibility, and fuel quality. The development of robust data to underpin this work is essential. For example, a data-driven science-based approach enabled an update to the hydrogen bulk storage separation distances used in key codes (e.g., National Fire Protection Association (NFPA) 52[50] and NFPA 2[51]). As a result, required separation distances were reduced by as much as 50% in some instances. Risk management measures can reduce the risk and mitigate the consequences of potential incidents that could hinder the commercialization of these technologies. These activities require collaborative efforts among government, industry, standards development organizations, universities, and national laboratories in an effort to harmonize regulations, codes, and standards, both domestically and internationally. Because the development of safety codes and product standards is not a static event but a continuing process, these efforts will continue as technologies mature.

In addition to activities supporting codes and standards development, activities focused on development of information resources and best practices for safety are necessary. Extensive stakeholder input from automobile manufacturers and the energy, insurance, and aerospace sectors, as well as the fire protection community and academia, to enhance and create safety knowledge tools for emergency responders and authorities having jurisdiction (AHJs) is essential for successful development of these best practices. Continual availability of safety knowledge tools, distributed via an array of media outlets to reach the largest number of safety personnel possible, is a priority. The development and implementation of best practices and procedures to ensure safety in the operation, handling, and use of hydrogen and fuel cell technologies is an important aspect of success. These issues, with strong stakeholder engagement, have been key considerations in the development of the DOE Safety Codes and Standards program. As a result, the Safety Codes and Standards program activities and goals include the following:

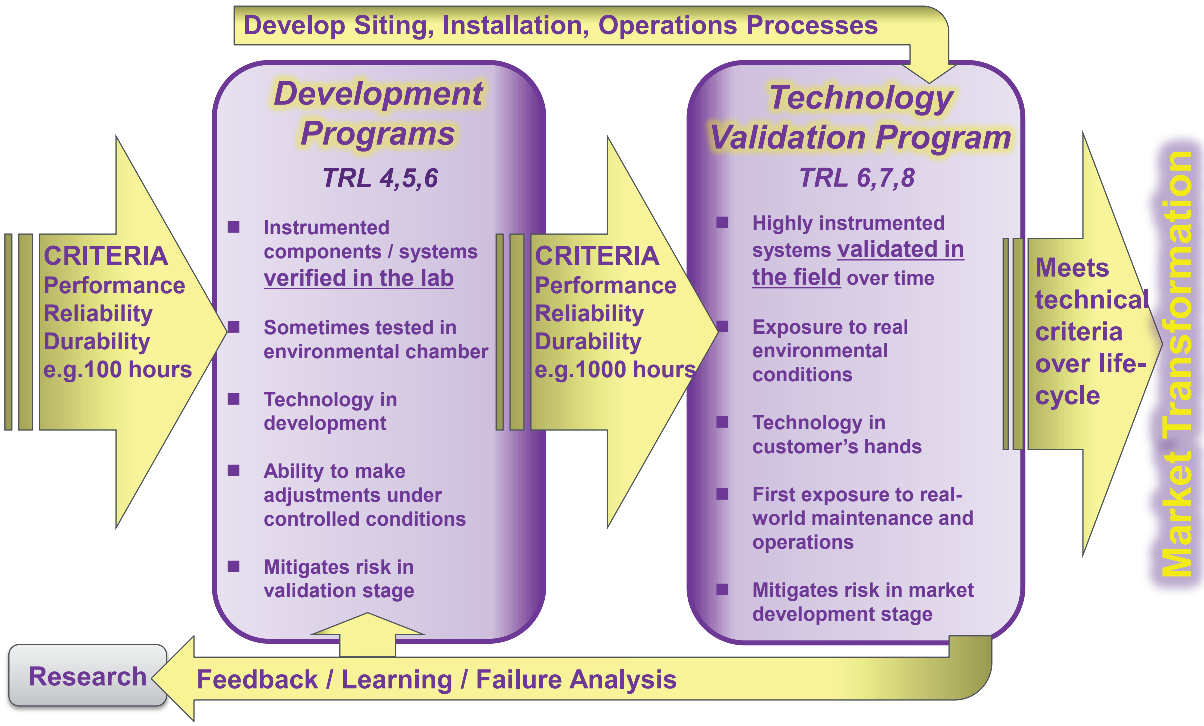
- Ensure that safety is a critical priority in research, technology development, and market deployment
- Promote widespread sharing of safety-related information, procedures, and lessons-learned with first responders, AHJs, and other stakeholders
- Understand and mitigate risk to facilitate the safe use of hydrogen and fuel cell technologies and improve insurability
- Conduct R&D to provide critical data needed to define requirements in codes and standards
- Conduct research to support the development of codes and standards and facilitate international harmonization of codes and standards (e.g., fuel quality and quality assurance)
- Support and facilitate the continued promulgation of essential codes and standards and support the international harmonization of regulations, codes and standards to enable the widespread commercialization and market entry of hydrogen and fuel cell technologies
- Support and facilitate the completion of essential domestic and international regulations, codes, and standards by 2020
- Develop appropriate test methodologies, such as methods to allow materials to be used in hydrogen service, at both the material and component testing levels
- Complete critical assessment of indoor refueling and system operation and recommend relevant code modifications

Although transportation fuel cells have different requirements than stationary fuel cells, there are synergies in cost reduction that would benefit both applications (see QTR Technology Assessment 4.Q). Large-scale deployment of PEM fuel cells for other applications, such as backup power, forklifts, and small-scale combined heat and power, would improve manufacturing learning and help drive down the cost of automotive fuel cells.

Technology Validation

Technology Validation aims at reducing deployment risks through careful validation of the performance of pre-commercial prototypes and disseminating the information (after roll up and harmonization to protect companies' identities) to the wider community of technology developers and systems integrators (Figure 8.B.14). To enable the automotive, energy, and utility industries to determine whether technology readiness has been achieved, vehicles and hydrogen infrastructure components are validated under real-world operating conditions against their technical targets. These activities provide critical data to predict whether FCEVs can meet the 2020 targets of 65% peak efficiency, 5,000-hour fuel cell durability, a range greater than 300 miles, five-minute fill time, and hydrogen fuel costs of less than $4 per gasoline gallon equivalent. These requirements

Figure 8.B.14 Technology Validation Strategy[52]

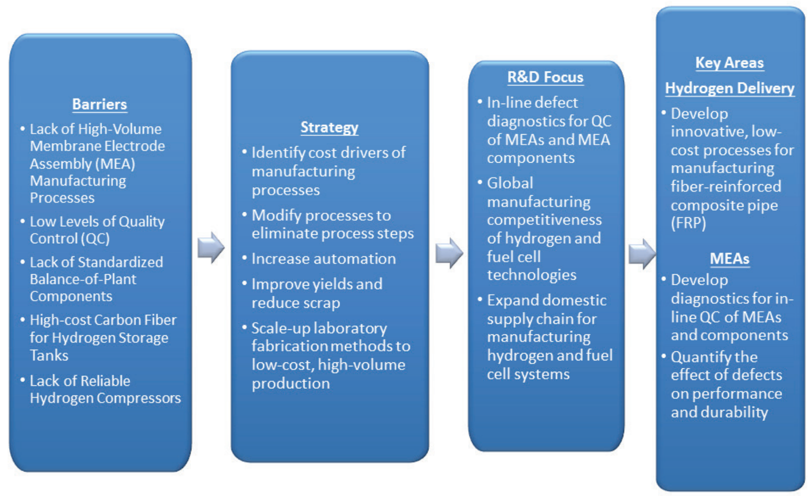


to meet real-world competition with conventional vehicles has driven public-private efforts to develop these FCEV technologies and validate their performance. DOE efforts include validating the performance of FCEVs to demonstrate an increase in durability from roughly 2,500 hours in 2012 with a goal of 5,000 hours by 2020. Technology Validation also provides information in support of codes and standards development as well as for the development of best practices regarding safety.

Manufacturing R&D

Increasing the scale of manufacture of today's hydrogen and fuel cell components and systems from laboratory-scale fabrication to high-volume commercially available products can have significant coordination and logistical challenges. Manufacturing R&D is needed to develop advanced fabrication technologies and processes to meet the cost targets of hydrogen and fuel cell technologies. Enabling large-scale production also requires the development and expansion of the domestic supply chain of hydrogen- and fuel-cell-related components in the United States because a nimble supply chain can help reduce cycle time in production and ensure a constant flow of raw materials. These factors have driven DOE to support appropriate R&D in fuel cell, hydrogen storage, hydrogen delivery, and manufacturing, and to facilitate the supply chain development process. Extensive coordination across DOE ensures effective and appropriate use of the limited resources through competitive cost-shared support of R&D with industry, universities, national laboratories, and other organizations. Figure 8.B.15 summarizes the Program's strategy.

Figure 8.B.15 DOE Competitive Cost-Shared Manufacturing R&D Strategy with Industry, Universities, National Laboratories, and Other Organizations[53]



Diagnostics for quality control in the production of hydrogen and fuel cell components and systems will help achieve the hydrogen and fuel cell portion of the FCEV's "levelized" cost per mile target of $0.13 per mile by 2020. Quality control diagnostics on electrode material have been demonstrated on a web-line at 60 feet/minute by DOE-supported R&D.[54] Diagnostics for defect detection as well as experiments and modeling that quantify the effect of defects generated during the manufacturing process on fuel cell performance are important areas of R&D supported by DOE. DOE coordinates with the Department of Defense (DOD) and the Department of Commerce (National Institute of Standards and Technology) to leverage other activities.

Market Transformation

Market transformation strategies identify opportunities to grow early markets for hydrogen and fuel cells, and directly assist in the conversion of technology to an operational state for near-commercial hydrogen and fuel cell systems. Market transformation activities are a key final phase in the comprehensive strategic timeline for moving technologies from the lab to self-sustaining commercialization in the marketplace. These considerations help drive DOE FCEV market transformation activities, which are closely integrated with DOE demonstration and education and outreach efforts.

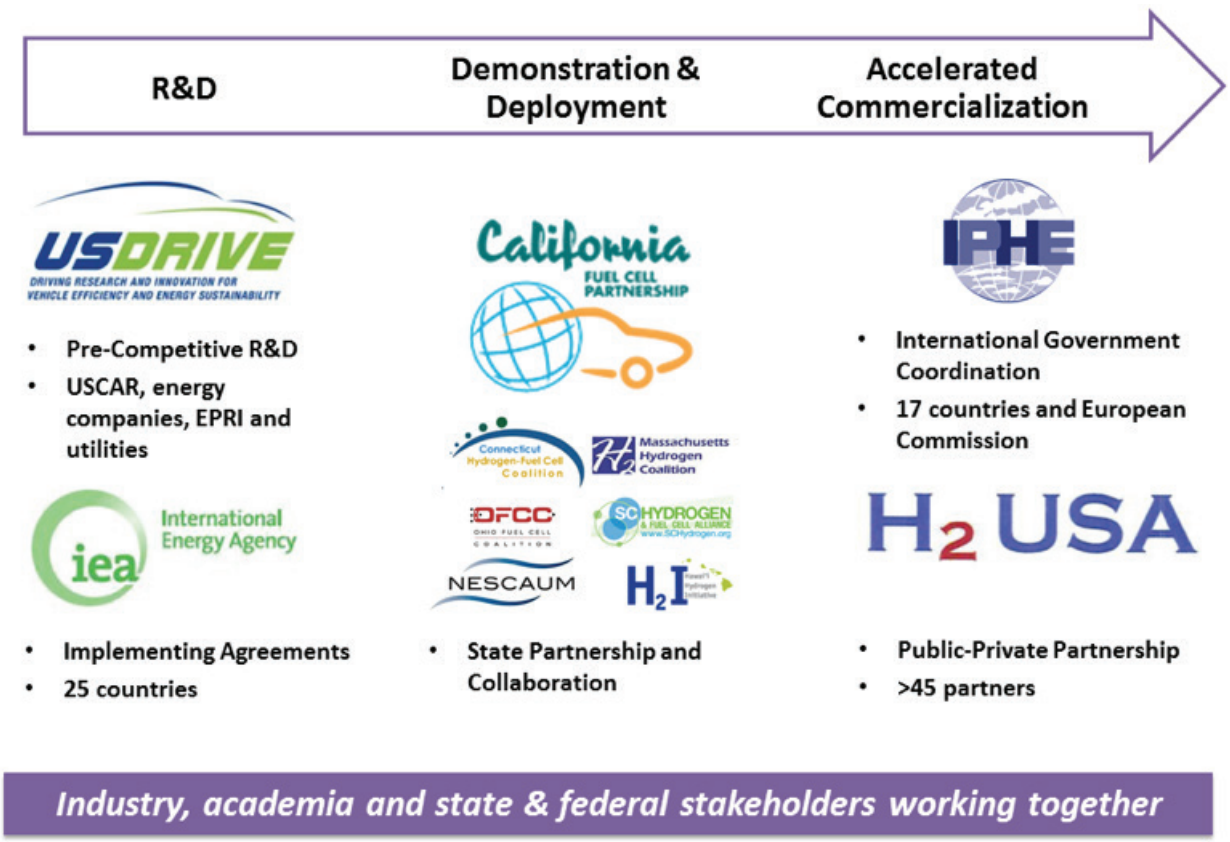
The primary goal of market transformation is to stimulate operational use of hydrogen and fuel cell technologies where a modest production volume will have a significant impact on reducing costs through economies of scale. This approach is aligned with national laboratory and market research studies that outline necessary operational testing to reach cost goals to be competitive with conventional vehicles. Near commercial ready technology usage can also stimulate further early adoption activity by supporting the growth of a domestic industry, overcoming some of the logistical and other nontechnical challenges associated with using a new technology, and establishing key elements of the infrastructure that will be essential for volume growth. In addition to their direct positive impact on user acceptance, such activities can provide valuable data on the performance of the technologies in real-world operation, lessons learned from early adopters, and information that will be used to validate the benefits of the technologies. Such considerations drove DOE's work with fuel cell forklifts and resulted in their deployment at multiple commercial sites.

Early market activities have also focused on identifying opportunities for usage of fuel cells by federal agencies and facilitating this through technical and financial support. DOE has actively collaborated with other agencies to facilitate federal adoption of hydrogen and fuel cells in key early applications, including specialty vehicles, backup/remote power, portable power, primary power for critical applications, and renewable hydrogen production (including the use of hydrogen for energy storage). Current opportunities include battery/fuel cell applications for ground support vehicles at airports, drayage trucks at seaports, medium-duty delivery vans in urban areas, and heavy-duty fleet battery electric vehicles with a fuel cell range extender. There are potentially significant benefits to the user in each of these applications; conversely, use of fuel cells in these applications offers near-term scale-up to help drive costs down and performance up. Federal agency partnerships are supported by the Hydrogen and Fuel Cell Interagency Working Group and the Hydrogen and Fuel Cell Interagency Task Force (establishment of the task force was mandated by the Energy Policy Act of 2005).[55] To date, the Program has collaborated on deployment projects with several agencies, including the Federal Aviation Administration, the National Parks Service, and DOD. Substantial opportunities for further collaboration and coordination were created with a memorandum of understanding between DOE and DOD, signed in July 2010.

Partnerships

A key challenge to the successful deployment of FCEVs in the U.S. is the diverse set of private and public stakeholders and accompanying interests that comprise the fuel cell industry. Figure 8.B.16 shows examples of DOE's key partnerships along the continuum between research and commercialization.

Figure 8.B.16 DOE Partnerships Along Continuum of Research to Commercialization



As shown in the figure, U.S. DRIVE (Driving Research and Innovation for Vehicle Efficiency and Energy sustainability) focuses on pre-competitive, high-risk research needed to reduce the dependence of the nation's personal transportation system on imported oil and to minimize harmful vehicle emissions. A major goal of the partnership is to accelerate the development of pre-competitive and innovative technologies to enable a full range of affordable and clean advanced light-duty vehicles (LDVs) as well as related energy infrastructure. Partners include DOE, the U.S. Council for Automotive Research (whose members are Ford Motor Company, General Motors Corporation, and Fiat Chrysler Automobiles), Tesla Motors Company, five major energy companies (BP, Chevron, Phillips66, ExxonMobil, and Shell), the Electric Power Research Institute, and two utilities (DTE Energy and Southern California Edison).[56]

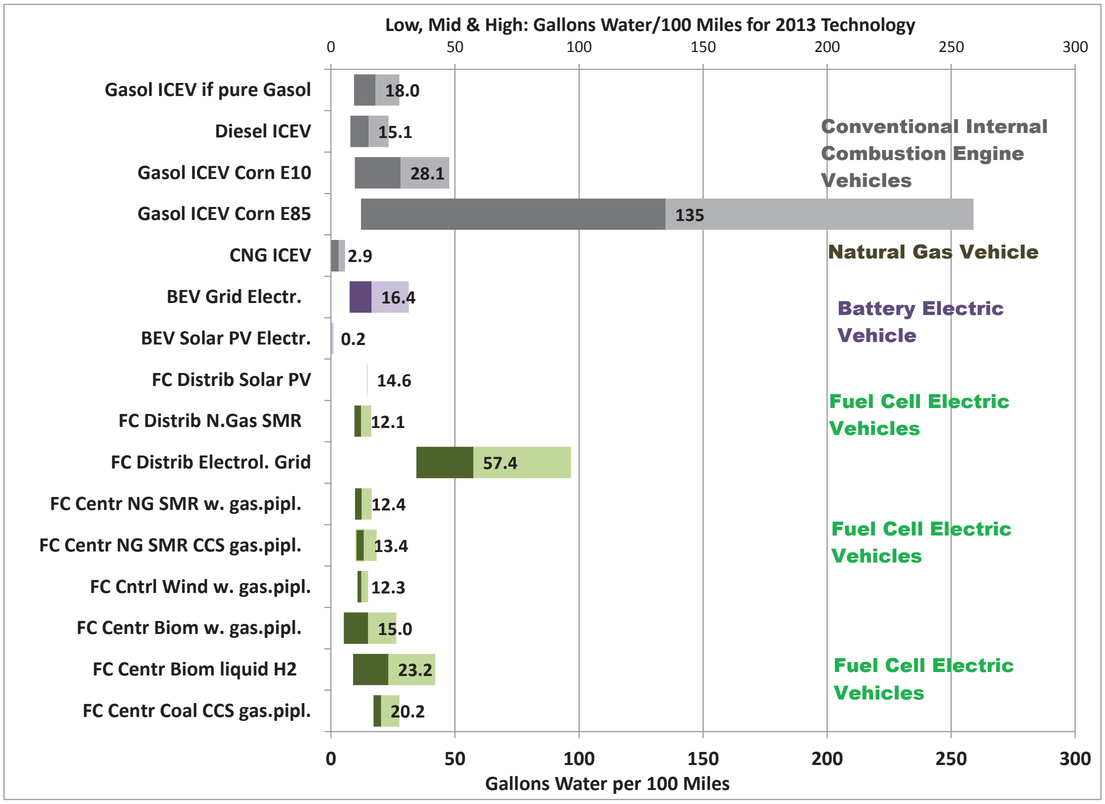
In addition, several international R&D activities are being carried out on fuel cells, hydrogen storage and delivery, and hydrogen production technologies, primarily through the International Energy Agency's Hydrogen Implementing Agreement (IEA-HIA)[57] and Advanced Fuel Cells Implementing Agreement.[58] Additionally, DOE and the U.S. Department of Transportation, in coordination with the U.S. State Department, founded the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)[59] to organize and implement effective, efficient, and focused international research, development, demonstration, and commercial utilization activities related to hydrogen and fuel cell technologies. Participation in these organizations' activities allows for regular exchange of information and diffusion of knowledge across national borders.

Other examples of successful partnerships seeking to advance fuel cell and FCEV commercialization include the following:

- **The Fuel Cell and Hydrogen Energy Association (FCHEA)**: FCHEA is a trade association dedicated to the commercialization of fuel cells and hydrogen energy technologies and created from a merger between the United States Fuel Cell Council and the National Hydrogen Association. FCHEA's membership represents a broad range of stakeholders, including manufacturers of fuel cell components, systems, and materials; hydrogen producers and fuel distributors; universities; government laboratories; and others.[60]
- **State-level partnerships and alliances:** These are collaborations of public and private organizations that seek to advance the use of FCEVs in a given state (e.g., California Fuel Cell Partnership,[61] Ohio Fuel Cell Coalition,[62] Connecticut Hydrogen-Fuel Cell Coalition,[63] and South Carolina Hydrogen and Fuel Cell Alliance).[64]
- **The California Stationary Fuel Cell Collaborative:** The Collaborative is a public-private partnership working to advance the commercialization of stationary fuel cells for distributed generation throughout the state of California.[65]

Water consumption during the production of fuels is an important consideration in evaluating vehicle/fuel combinations. A recent EERE analysis is summarized in Figure 8.B.17. The water intensity of several hydrogen fuel pathways is within 25% of conventional E10 (10% corn ethanol in gasoline).

Figure 8.B.17 Water Consumption by Light-Duty Vehicles, per 100 Miles Driven[66]



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Acronyms

AHJ	Authorities having jurisdiction
BEV	Battery electric vehicle
BOP	Balance of plant
CNG	Compressed natural gas
DARPA	Defense Advanced Research Project Agency
DOE	Department of Energy
DOD	Department of Defense
EIA	Energy Information Administration
FCHEA	Fuel Cell and Hydrogen Energy Association
GDL	Gas diffusion layer
GHG	Greenhouse gas
ICEV	Internal combustion engine vehicle
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
kW	Kilowatt
LDV	Light duty vehicle
MEA	Membrane electrode assembly
MOF	Metal organic framework
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technologies
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
PEM	Polymer electrolyte membrane
PGM	Platinum group metals
R&D	Research and development
SDO	Standards development organizations
US DRIVE	US Driving Research and Innovation for Vehicle efficiency and Energy sustainability

Glossary

GDL	Gas diffusion layer is the porous structure made by weaving carbon fibers into a carbon cloth or by pressing carbon fibers into a carbon paper. The GDL helps diffuse reactants across the catalyst-coated membrane.
MEA	The membrane electrode assembly (MEA) is the core component of a fuel cell. The MEA is composed of a polymer electrolyte membrane (PEM), catalyst layers (CL) and gas diffusion layers (GDL) attached on the outer surface of the catalyst layers.
MOF	Metal organic frameworks are highly crystalline, often highly porous materials that can be used as electro-catalysts, electrolyte membranes, and fuel storage materials.
PEM	Polymer electrolyte membrane fuel cells are a common type of fuel cell under development. PEM fuel cells are built from MEAs which include electrodes, electrolyte, and gas diffusion layer.
PGM	Platinum group metals are six elements clustered in the periodic table: Ru, Rh, Pd, Os, Ir, and Pt.