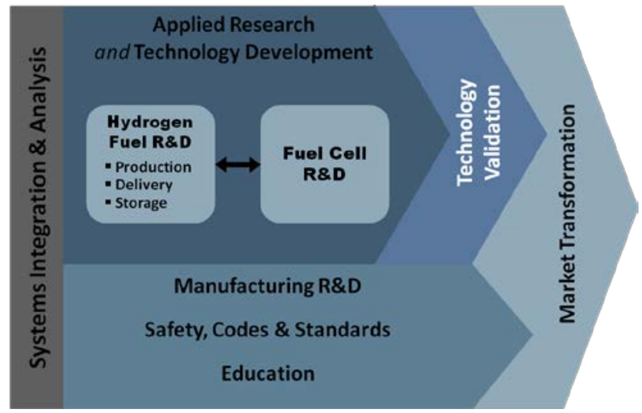
3.6 Technology Validation



The Technology Validation sub-program tests, demonstrates, and validates hydrogen (production, delivery, storage) and fuel cell systems and their integrated components in real-world environments. Feedback provided to the DOE hydrogen and fuel cell research and development (RD&D) projects, industry partners, and end users helps determine the additional RD&D required to move the technologies forward or to determine whether the technologies are ready for commercialization. Evaluations conducted include the following:

- Applications – transportation; primary power; combined heat and power (CHP); combined hydrogen, heat, and power (CHHP); auxiliary power; back-up power; material handling applications;
- Distributed production – natural gas reforming, electrolysis and bio-derived liquids;
- Central production – natural gas, electrolysis, biomass gasification, photo-electrochemical, photo-biological, and solar thermochemical technologies; and
- Storage systems – high-pressure or cryogenic tanks, high surface area adsorbents, metal hydrides, or chemical hydrogen storage materials.

No specific plans to validate portable power fuel cells have been identified.

3.6.1 Technical Goal and Objectives

Goals

Validate the state-of-the-art of fuel cell systems in transportation and stationary applications as well as hydrogen production, delivery and storage systems. Assess technology status and progress to determine when technologies should be moved to the market transformation phase.

Objectives

- By 2012, publish the final report on the National Hydrogen Fuel Cell Electric Vehicle and Infrastructure Learning Demonstration.
- By 2014, validate durability and efficiency of stationary fuel cell systems against fuel cell targets (40,000 hours, 40%).
- By 2017, complete the validation of commercial fuel cell combined heat and power (CHP) systems target (50,000 hours).
- By 2017, validate durability of auxiliary power units (APUs) against fuel cell systems target (15,000 hours).

- By 2019, validate hydrogen fuel cell electric vehicles with greater than 300-mile range and 5,000 hours fuel cell durability. Validate a hydrogen fueling station capable of producing and dispensing 200 kg H_2/day to cars and/or buses.
- By 2020, validate large-scale systems for grid energy storage that integrate renewable hydrogen generation and storage with fuel cell power generation by operating for more than 10,000 hours with a round-trip efficiency of 40%.

3.6.2 Technical Approach

Hydrogen and fuel cell technology projects share a common approach for demonstration and validation. Projects in Technology Validation are both "learning demonstrations" to help guide and manage the hydrogen and fuel cell component and materials research and development activities, and a validation of the technology under real-world operating conditions against durability and performance targets. The projects are 50/50 cost-shared between the government and industry, which may include fuel cell system manufacturers, automobile manufacturers, energy companies, suppliers, universities, state governments, and end-users. Extensive data are collected on systems operated in real-world conditions as they would be if they were sold or leased commercially. Laboratory data may be collected only to augment real-world data collection. Data collected through Technology Validation provides the most accurate assessment of technology readiness and the risks facing continued government and industry investment.

The Technology Validation sub-program focuses its efforts on both stationary applications for residential and commercial power and transportation applications including fuel cell buses, fuel cell electric vehicles, and support equipment. Technology Validation is also involved in the demonstration and validation of hydrogen fueling equipment. The sub-program leverages its testing and demonstration projects to obtain important data and provide technical analyses. In working with other sub-programs and maintaining strong collaborations with government agencies and industry, Technology Validation is able to provide critical data and feedback to the Program and industry to direct research and development.

3.6.2.1 Stationary Fuel Cell Applications

There is a need to evaluate stationary fuel cell systems for residential and commercial applications, including CHP and combined cycle operation.

Natural gas-fed fuel cells provide cleaner power than the U.S. grid average. As electricity from the grid is predominantly derived from coal power, on-site power generation with fuel cells typically reduces total greenhouse gas emissions by up to 60%[1]. In addition to the cleanliness associated with using natural gas feedstock, fuel cells can convert fuel into electricity with more than 50% efficiency on a lower heating value (LHV) basis. Fuel cells also allow for the waste heat from the

[1] http://www.epa.gov/cleanenergy/documents/egridzips/eGRID2010V1_1_year07_GHGOutputrates.pdf
http://www.fuelcellenergy.com/files/FCE3000%20Product%20Design-lo-rez%20FINAL.pdf

electrochemical process to be used for heating, resulting in total thermal and electrical efficiencies up to 85% (LHV basis).[2]

Stationary fuel cells also have a significant benefit in reducing criteria pollutants. Traditional power generation technologies burn raw fuel and generate nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter and unburned hydrocarbon emissions. Fuel processors in fuel cell systems or in hydrogen production systems remove sulfur from the fuel, preventing the SO_X formation and fuel cells operate at lower temperature, preventing the NO_x formation from the nitrogen in the air. Low-temperature operation also prevents the formation of particulate matter in the exhaust, and fuel cell systems have minimal hydrocarbon emissions.

While fuel cells are currently expensive relative to conventional technologies, they are being deployed in niche markets that provide industry and their supply chain with orders that will increase production volume, lower costs, and increase market-share. For example, stationary fuel cell technologies are desirable especially in highly congested environments where air quality is an issue, such as Environmental Protection Agency (EPA) non-attainment zones. Additionally, noise emissions of fuel cells are typically less than equivalently-sized internal combustion systems, which also allow them to operate in populated environments.

Commercial Power

Commercial applications vary widely in size. Buildings can range from small offices that consume 100 kW to large multi-megawatt facilities. Large-scale fuel cell systems are commercially available today to compete with mainstream technologies. In larger applications, fuel cells may provide heat for driving absorption chillers or reformate that may be used to produce hydrogen for material handling, vehicular, or other applications. Fuel cells may be configured to serve multiple buildings in district heating and cooling arrangements. In these applications fuel cells could be economically competitive with incumbent technologies because multiple heat, electricity, cooling, or fuel demands can be super-imposed to allow the fuel cell system to be more fully utilized.

Residential Power

Currently, residential fuel cells are fueled by natural gas and being built in the 0.5 kW - 5 kW range. Small-scale residential fuel cells are the most challenging market for stationary fuel cells. Small-scale residential fuel cells are similar to large scale fuel cells in their services; however they are challenged by two economic drivers: economy of scale and variability of demand. The economics of fuel cell systems are impacted by the "fixed cost" in fuel cell system installations and equipment, causing system cost per kilowatt to be greater for smaller systems, while the benefit of fuel and energy cost savings remains proportional to the size of the system. The variability of demand is the result of how individual (power) loads in the building are aggregated, and impacts the fuel cell system's utilization and response. Small residential systems have fewer individual loads than a large building, and thus do not benefit from the smoother and more gradually changing total building load that results from aggregating many individual loads. A total building load for a small residential building is aggregated from fewer individual loads and thus, has abrupt changes that result from an individual load (e.g., an appliance) being turned on or off. If the fuel cell system does not have adequate response to transient loads, the system must then be supplemented by batteries or the electrical grid.

[2] http://www.hydrogen.energy.gov/pdfs/doe_h2_fuelcell_factsheet.pdf

Additionally, larger transients in operation result in an increased frequency of thermal expansion and contraction, resulting in mechanical fatigue and lower durability.

Combined Heat and Power

Primary power fuel cell systems use natural gas to produce electricity and produce heat that can be utilized for the following:

- Direct heating (steam generation, water heating, condensate preheating, space heating, industrial heat needs).
- Cooling (through absorption chillers, can provide a coefficient of performance (COP) of 0.7 to 1.35 for chilled water and space cooling).[3]
- Electricity production (through bottoming cycles such as Rankine cycles, where waste heat is used to produce additional electricity. Typically, such cycles have efficiency of ~10-15%, and require large scale to be economical).

Typically, the most economic means of utilizing the heat is to provide direct heating, but in absence of significant heat demand, other applications may be economical.

3.6.2.2 Transportation Fuel Cell Applications

Fuel Cell Buses

Fuel cell bus development and demonstration activities have been primarily funded by the Department of Transportation's Federal Transit Administration through the National Fuel Cell Bus Program (NFCBP) as well as a number of congressionally directed fuel cell bus (FCB) projects. Other projects have been funded by a combination of state and local government agencies. The Technology Validation sub-program collaborates with these agencies by providing third-party assessment of these buses once they are placed in service. The FCB data — including operational, maintenance, reliability, and cost — are compared to data from conventional buses (diesel or compressed natural gas (CNG)) to track progress over time. The results are used to identify key areas of RD&D focus to speed the progress toward full market introduction.

In 2010, a collaboration of five San Francisco Bay Area transit agencies began operating a fleet of 13 fuel cell buses. SunLine Transit in Palm Springs and the City of Burbank will also operate fuel cell buses. To meet the California Air Resources Board (CARB) zero-emission bus (ZBus) regulation requirements, 10 California transit agencies are expected to start purchasing zero-emission buses as 15% of their fleet purchases in just a few years. Table 3.6.1 shows the number of fuel cell buses expected in each phase, based on the numbers required in regulation and transit agencies' reported plans.

[3] U.S. Department of Energy Gulf Coast Clean Energy Application Center http://files.harc.edu/sites/gulfcoastchp/webinars/absorptionchillers.pdf

Table 3.6.1: Number of Fuel Cell Buses Based on Transit Agency Plans and ZBus Regulation[4]

	Field Testing	Full-scale Demonstration	Commercialization
	2009-2011	2012-2014	2015-2017
Number of FCBs*	15 to 17	20 to 60	60 to 150

** Total number project on the road at the end of each timeframe*

Fuel Cell Electric Vehicles

A major emphasis of the Technology Validation sub-program has been the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation project, also known as the National Hydrogen Fuel Cell Electric Vehicle Learning Demonstration. This project was initiated in 2004 and concluded in 2011. The project's objective was to implement complete integrated systems including hydrogen production facilities and hydrogen fuel cell electric vehicles (FCEVs) and collect data to determine whether the technical targets have been met under real-world conditions. The project brought together teams of automotive and energy companies that worked to address FCEV and hydrogen infrastructure interface issues and to identify future research needs. The results of the Learning Demonstration provided feedback on progress and identified problems that could be addressed through additional research and development.

Many automotive original equipment manufacturers (OEMs) have announced production plans for fuel cell electric vehicles for retail sale or lease as early as 2015 in the U.S. and other countries. A follow-on validation project similar to the Phase 1 Learning Demonstration will continue to track the progress of fuel cell electric vehicles leading up to and through their introduction. Data will be collected from sample sets of FCEVs as they are introduced to enable DOE to track the status and technical progress of the fuel cell systems to provide feedback to its research and development efforts.

A significant amount of activity has been occurring in California relating to new hydrogen fueling stations and planned FCEV deployments that help satisfy California's zero-emission vehicle emission regulations. The California Fuel Cell Partnership (CaFCP) compiles information from automaker members to project the planned vehicle deployments in the coming years. Individual automakers would not normally make this information publicly available given the highly competitive environment of new vehicle development and commercialization. In 2010, the CaFCP collected this information a second time. The results show trends similar to 2009, confirming automaker plans for hundreds, thousands and then tens of thousands of fuel cell electric vehicles. Table 3.6.2 presents a summary of CaFCPs 2010 information for passenger FCEVs, which are consistent with the California Energy Commission (CEC) and CARB's recently collected information.

[4] Source: CaFCP "Hydrogen Fuel Cell Vehicle and Station Deployment Plan: A Strategy for Meeting the Challenge Ahead, Progress and Next Steps" April 2010", http://www.cafcp.org/sites/files/FINALProgressReport.pdf

Table 3.6.2: 2010 CaFCP FCEV Deployment Results: Passenger FCEVs in Operation (cumulative on the road)[5]

	Hundreds	Thousands	Tens of thousands
	Through 2013	2014	2015-2017
Total Passenger Vehicles*	430	1,400	53,000

**Total number projected on the road at the end of each timeframe*

Specialty Vehicles

Hydrogen fuel cells provide the opportunity to power several other transportation applications in addition to cars and buses. The fuel cells provide zero tailpipe emissions propulsion for small vehicles such as airport ground support equipment, lift trucks, and grounds maintenance vehicles.

Auxiliary Power Units

Fuel cells can also provide auxiliary power units (APUs) for trucks, ships and aircraft, where the electric power does not move the vehicle but instead provides electrical needs of the vehicle to avoid running the large motive power plant at inefficient operating points during idling or low-power operation. Since there is little real-world experience placing fuel cells in this application, Technology Validation will gather data from early deployments to determine whether any technology gaps remain before recommending this application for deployments related to the Market Transformation sub-program of the FCT Program.

3.6.2.3 Hydrogen Fueling

In the past decade, approximately 60 stations supported a few hundred vehicles in the United States. Of these stations, 24 supported the 155 DOE Learning Demonstration vehicles.[6] As OEMs are gearing up fuel cell bus, forklift and car production, States and industry plan to build additional stations, increase individual station output and cluster stations to cover the area where vehicles are located. The current hydrogen fueling infrastructure in the U.S. is depicted in Figure 3.6.1.

California has been a leader in supporting additional hydrogen infrastructure through multiple state agencies, including CARB and CEC. As of 2011, there are 7 stations funded by CARB that will be coming online. The CEC recently announced support for 11 hydrogen stations (3 upgrades and 8 new stations) in California, moving the state towards the CaFCP goal of 40 stations by 2015 when the vehicles will be introduced in larger numbers.

[5] Source: CaFCP "Progress and 2011 Actions for Bringing Fuel Cell Vehicles to the Early Commercial Market in California" February 2011", http://cafcp.org/sites/files/CaFCPProgressand2011Actions_0.pdf
[6] http://www.nrel.gov/hydrogen/pdfs/49639.pdf

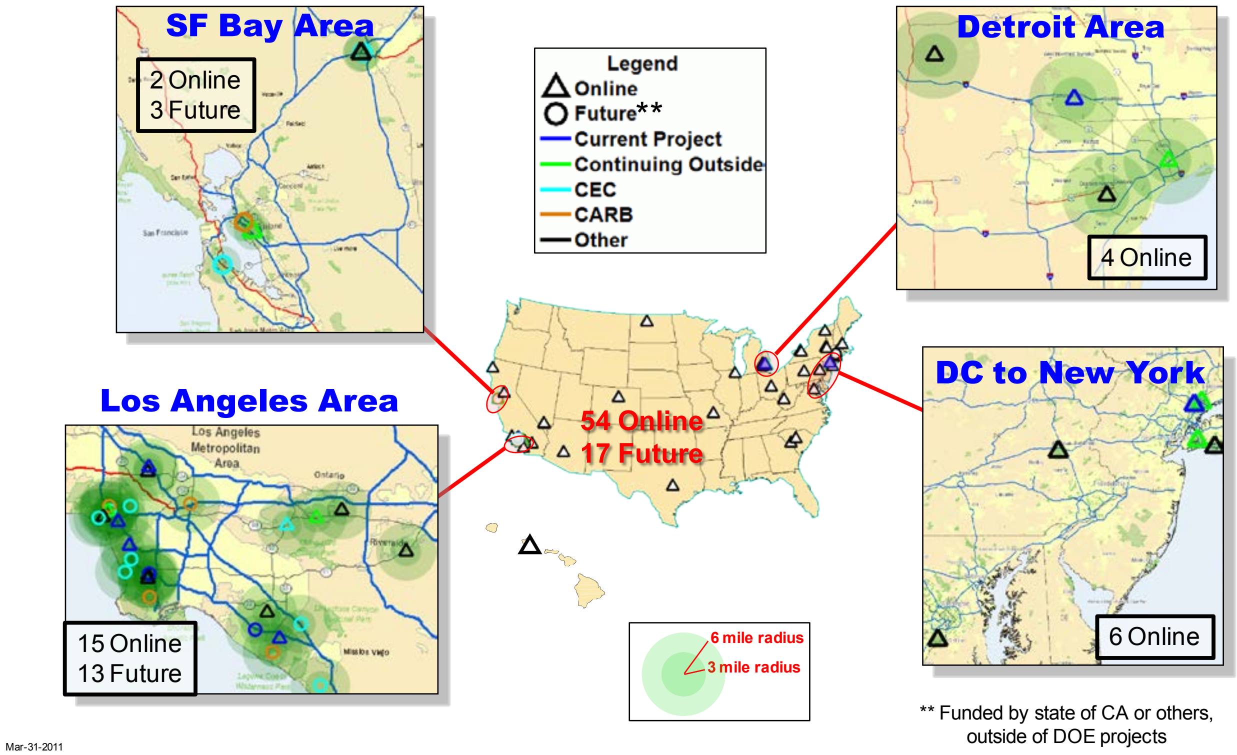


Figure 3.6.1 Current Hydrogen Infrastructure – Online and Planned Hydrogen Fueling Stations in the United States.

When planning for the upcoming vehicles, it is essential to account for the long lead time to site and commission fueling stations. Some stations will support multiple types of applications including forklifts, buses and cars. A multitude of methods will exist for providing hydrogen to the fueling stations: on-site production from waste-water treatment plants, on-site reforming of natural gas, renewable water electrolysis, and centrally-produced and delivered liquid or gaseous hydrogen. As these pathway technologies are developed, progress and future technology development needs are determined through data collection and analysis. Statistics on usage patterns, safety, availability, and maintenance will also be useful in determining the next steps to make FCEVs a commercial reality.

Distributed On-Site Hydrogen Production

Small-scale (i.e., 100 - 500 kg H_2/day) distributed hydrogen production from natural gas is currently one of the most economical ways to produce hydrogen and the most mature technology compared to hydrogen from renewables. However, costs at low volume are still high. Electrolyzer technology is available today, but using electricity produced from fossil fuels to make hydrogen creates significant greenhouse gases and is less efficient than the more direct chemical conversions of coal or natural gas to hydrogen. For areas where renewable or nuclear sources of energy are abundant, electrolyzers may be used to produce hydrogen. Progress in on-site production at fueling stations will continue to be validated as the technology improves and is scaled-up.

Two integrated hydrogen production and electricity generation options are being validated: 1) energy stations that use natural gas, bio-derived liquid, or biomass resources to thermo chemically produce hydrogen as a fuel for vehicles and generate stationary electric power; and 2) energy stations that incorporate renewable energy options such as wind, solar, and/or geothermal through the process of water electrolysis.

Co-Production of Hydrogen and Electricity Options

Because high-temperature fuel cells provide internal fuel reformation, they can be used to economically produce two forms of high-grade energy. By using the heat that they produce while generating electricity, high-temperature fuel cells configured for combined hydrogen and power (CH_2P) can simultaneously produce electric power and hydrogen from natural gas, bio-derived liquids, or other biomass resources such as landfill gas, wastewater treatment gases, and agricultural waste. The electricity can be used on-site and exported to the grid, and the hydrogen can be dispensed for material handling equipment, vehicular applications, backup power or other specialty equipment. High-temperature fuel cells may also be configured for combined heat, hydrogen, and power (CHHP) for applications where heat may be needed.

The energy station concept in Figure 3.6.2 includes production of hydrogen for FCEVs or forklifts from natural gas, bio-derived liquids, or biomass and can also produce electricity. The system can be programmed to monitor the reserve of hydrogen, the demand for hydrogen, and the demand for electricity so that the system's electricity vs. hydrogen output is tuned to provide maximum value. For example, if hydrogen reserves are adequate and there is high demand for electricity, the system can switch to fuel cell-mode and produce electricity. By serving two markets, the equipment's capital cost can be recovered more quickly.

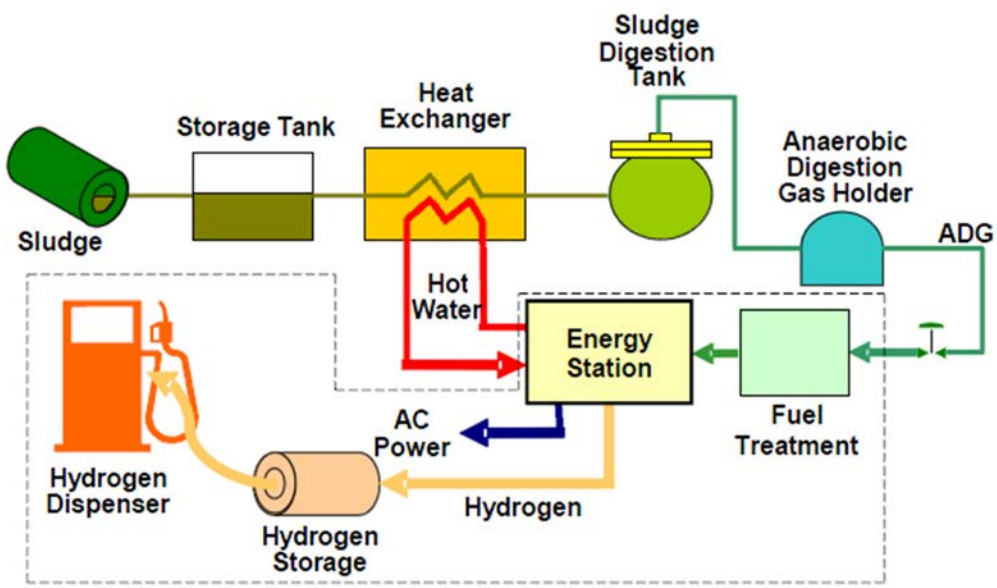


Figure 3.6.2 Hydrogen Energy Station - The Energy Station using thermo chemical processes for continuous hydrogen generation as well as heat and electrical power (figure credit: Air Products)

Water Electrolysis and Reversible Fuel Cells

Distributed water electrolysis allows hydrogen to be produced from renewable wind, solar and geothermal energy sources as well as nuclear power. Additionally, the electrolyzers can be used to produce and subsequently store hydrogen from grid electricity during off-peak periods. Electrolyzers and hydrogen storage may be sited with renewable sources, however, with appropriate communication; the electrolyzer does not need to be located in the immediate vicinity of the renewable resource to effectively use it. Electrolyzers may be controlled remotely to use inexpensive electricity that is produced when intermittent renewable sources are available, but demand is not.

Reversible fuel cells may be integrated with various scales of hydrogen storage to provide load-leveling for an intermittent renewable energy source, an intermittent electric demand, or for the fluctuations of the larger electric grid, in addition to providing fuel for vehicles or other fuel cell applications. Figure 3.6.3 shows an integrated renewable energy station which can accept energy and store it as hydrogen when it is generated in off-peak periods, such as wind turbines that generate electricity at night. The stored energy can then be used during peak demand periods when there is a higher value for such deployable power generated from the hydrogen or as a fuel for vehicles.

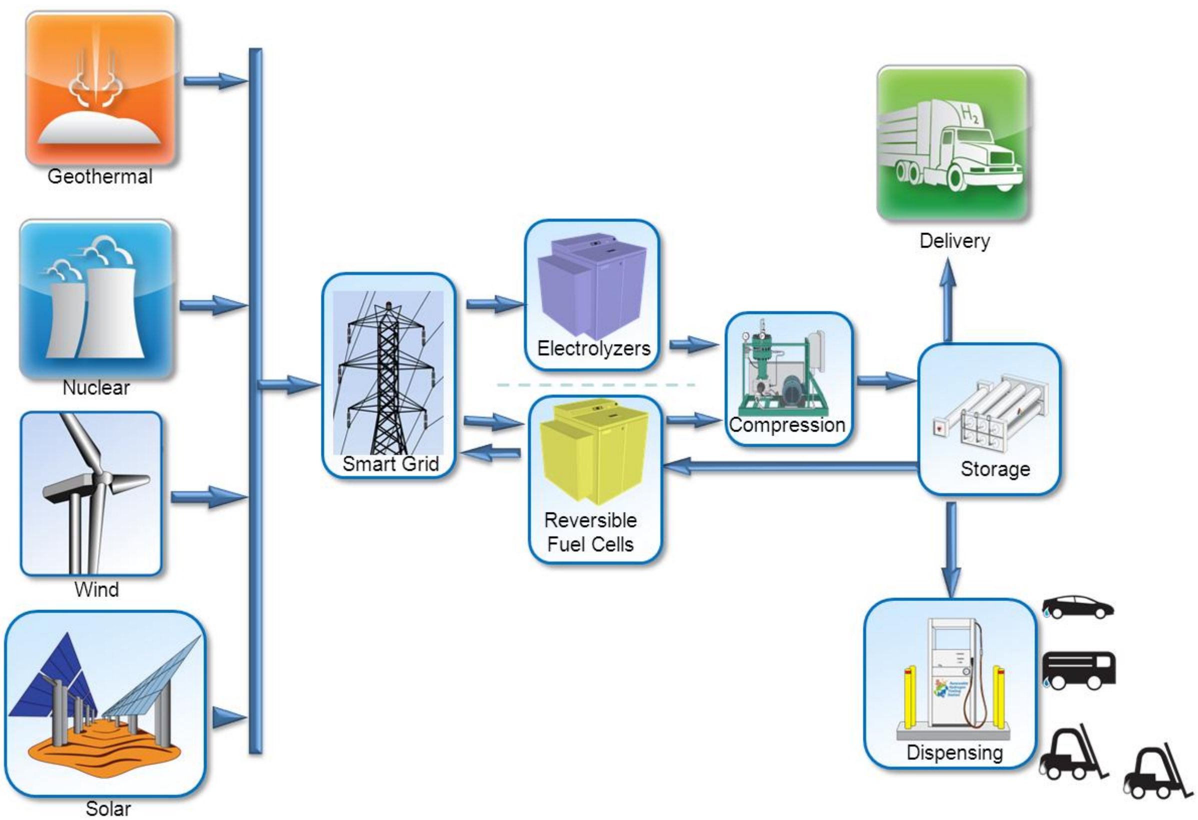


Figure 3.6.3 Electrolyzers and reversible fuel cells provide expanded market for base load and surplus renewable and zero-GHG power.

Delivered Hydrogen through Trucks and Pipelines

Currently, one of the most economical ways to provide hydrogen for fueling stations is by truck, with hydrogen as liquid or gas. This method takes advantage of large central hydrogen production facilities that make hydrogen for other purposes, such as oil refining or food processing. This pathway also has the benefit that increases in demand can often be met simply by scheduling more frequent truck deliveries without needing to change the footprint of the original equipment.

While initial capital costs are higher, hydrogen pipelines can provide one of the lowest ongoing costs for hydrogen, due to the same economies of scale as large central hydrogen facilities. In 2011, the first example of a hydrogen pipeline fueled station was opened in Torrance, California (see Figure 3.6.4).

Figure 3.6.4 Fueling station using pipeline hydrogen - If a hydrogen pipeline is located nearby, the cost of building the hydrogen production system can be avoided, lowering the cost of dispensed hydrogen (photo source: NREL).

3.6.2.4 Technical Analysis

The Hydrogen Secure Data Center (HSDC) at the National Renewable Energy Laboratory (NREL) is currently the central location for Technology Validation data collection and analysis. The HSDC was established under the Learning Demonstration project to report composite data products (CDPs) that aggregate data across numerous industry teams. Detailed data products (DDPs) are shared with each individual data supplier and provide valuable information regarding an individual data supplier's contribution to CDPs, as well as summary and system specific performance results. The HSDC typically receives and processes operational data every 3 months and publishes CDPs every 6 months.

Periodic analyses and reporting from the HSDC include results on performance of individual fuel cell applications, multiple applications compared to each other (e.g., fueling rates of cars, buses, and forklifts plotted on the same graph), and the value application for fuel cells in a specific application.

The following are the primary functions of the HSDC:

- Evaluating baseline (incumbent) technologies that hydrogen or fuel cell technologies supplement or replace
- Evaluating scalability of technology from current size or application to larger size or other applications
- Assessing technology readiness levels (TRLs)
- Comparing hydrogen and fuel cell technology status across applications to identify RD&D needs that may be specific to one or more technology applications.
- Publishing composite data products that aggregate results across multiple sites, manufacturers, and applications.
- Providing a readily available objective source of information on the current status of hydrogen and fuel cell technologies for key stakeholders and decision-makers.

3.6.2.5 Relationship to Other Sub-Programs

The Technology Validation sub-program validates hydrogen and fuel cell technology under real-world conditions to determine whether it meets the anticipated requirements of the marketplace. Technology Validation assesses technical and manufacturing readiness levels which are required for high market penetration. Technology Validation also validates progress toward technical targets established and researched in the RD&D program (fuel cells, storage, production), most of which were derived from anticipated application-specific market requirements. The Market Transformation sub-program takes the technology that has already been field-validated in limited numbers and encourages potential end-users to gain experience with the technology and evaluate whether it can be part of a viable value proposition. The Hydrogen Codes and Standards sub-program takes technology validation data to improve the quality of code requirements, collect real-world lessons learned, and assist in the implementation of these technologies. Technology Validation works in concert with Market Transformation and the RD&D activities. Technology Validation provides Market Transformation with data to be used to help develop business cases for a particular technology. Education uses information from Technology Validation to help in educating the public about the state-of-the-art of fuel cell technologies.

3.6.2.6 Evaluation Across Applications

Technical performance aspects, like durability and efficiency, are important to the validation of multiple applications. The Technology Validation analyses include performance comparisons to highlight the similarities and differences of systems and real-world applications. Possible outcomes of comparison applications, as well as field and lab data, are the creation of testing protocols and summaries of real-world influences on fuel cell system performance. Figure 3.6.5 shows an example of a cross-application comparison of fueling rates for cars, buses, and forklifts.[7]

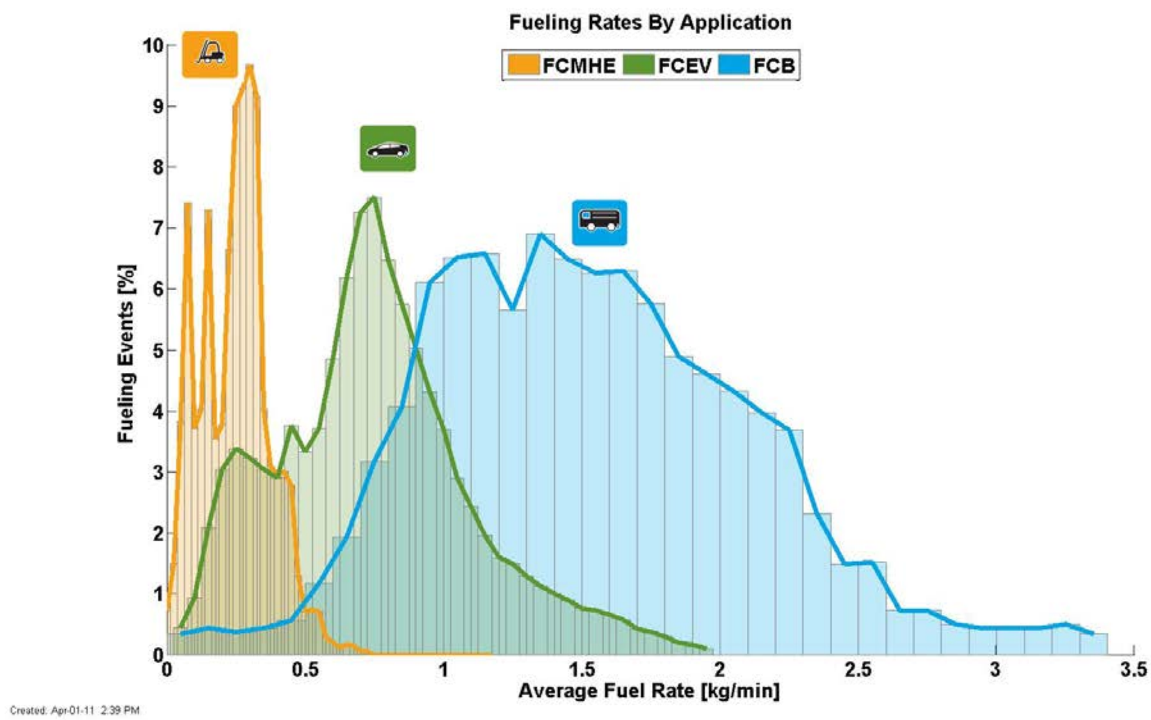


Figure 3.6.5 An example of a cross-application CDP, comparing fueling rates for fuel cell cars, buses, and forklifts.

3.6.2.7 Coordination

Communication of results and collaboration between the Technology Validation sub-program and the RD&D, Codes and Standards, Education, and Market Transformation sub-programs and industry stakeholders is important for advancing hydrogen and fuel cell technology. The composite data products in the HSDC will be updated every 6 months (http://www.nrel.gov/hydrogen/proj_tech_validation.html) and presented at relevant industry conferences. At least every 6 months, individual results will be shared with the data suppliers prompting collaboration on performance and analyses important for technology assessment. Results will also be highlighted for different applications via semi-annual briefings to the FCT Program. Other partnerships with industry and government include Department of Defense (DoD), CEC, the CARB, and the CaFCP.

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[7] Source: NREL Technology Validation cross-application CDP, published in 2011 Annual Merit Review presentation TV001, Controlled Hydrogen Fleet and Infrastructure Analysis, Wipke, etc. al, May 13, 2011. http://www.nrel.gov/hydrogen/pdfs/tv001_wipke_2011.pdf (slide 14).

3.6.3 Programmatic Status

Current Activities

Table 3.6.3 summarizes current technology validation activities, which focus on hydrogen vehicles and infrastructure, energy stations, and integrated renewable/hydrogen system demonstrations.

Table 3.6.3 Current Activities

Organization	Activities
Hydrogen Pipeline Infrastructure	
Air Products and Chemicals Inc. – California Hydrogen Infrastructure (CHIP) Project	Demonstration of 700-bar pipeline-based hydrogen fueling station and evaluation of actual costs of dispensed hydrogen.
GM, Hawaii, NREL	Validation of hydrogen delivery through methane gas pipeline with separation at the hydrogen fueling station. Verify the quality of dispensed hydrogen and that there is no impact on the durability of fuel cell electric vehicles.
Natural Gas-to-Hydrogen Fueling Stations	
NREL - Hydrogen Frontiers	Validation of long-term durability and performance of an on-site steam methane reforming system producing 100 kg H_2/day in Burbank, CA.
Co-Production of Hydrogen and Electricity at Energy Stations	
Air Products and Chemicals Inc.	Validation of a high temperature fuel cell as an energy station at Fountain Valley, CA.
Renewable Hydrogen Production Systems	
State of Hawaii	Installation of a hydrogen fueling station at Volcanoes National Park to refuel hydrogen fuel cell buses and to provide hydrogen to a fuel cell for power to the Park's visitors' center.
NREL - Wind-to-Hydrogen Facility	Validation of hydrogen as an energy storage medium for intermittent renewable electricity from wind and solar. Includes optimization of electrical pathway (power electronics) between renewable source and electrolyzer and storage of hydrogen at various pressures. Validation of water electrolysis from hydrogen production RD&D.
Hydrogen System and Component Validation	
NREL - Energy and Systems Integration Facility (ESIF)	Validation of full-size hydrogen and fuel cell components and systems using NREL's wind-to-hydrogen facility and a new state-of-the-art test facility, ESIF, scheduled for completion in 2012.

Table 3.6.3 Current Activities (continued)	
Organization	**Activities**
Technical Analysis	
NREL - Vehicle and Infrastructure	Evaluation of hydrogen fueling infrastructure from novel stations being commissioned in California by the CEC and CARB.
NREL – Early Market Analysis	Evaluation of fuel cell and hydrogen infrastructure data for early markets, such as material handling equipment (fork trucks), backup power, residential power, and primary/commercial power.
NREL – evaluation of Department of Transportation (DOT) fuel cell buses	Collection and analysis of performance and operational data on fuel cell buses in real-world service and comparing them to conventional buses. Data include fueling, maintenance, availability, reliability, durability, cost, and descriptions of the fleet's experience with the technology. (Fuel cell buses and their operation are being funded by DOT)

3.6.4 Technical Challenges

In addition to the technical barriers being addressed through research, development and demonstration in the other sub-programs of the FCT Program, there are several obstacles to successful implementation of stationary fuel cells for residential and commercial applications, APUs for trucks, ships and aircraft as well as FCEVs and fueling infrastructure. The primary technical challenge is that of integration of complex systems. For example, unless stationary fuel cells are installed in new buildings they need to be integrated into existing thermal and electrical systems in a safe and economical way. For hydrogen fueling stations, the hydrogen dispensers and hardware will likely be integrated into existing refueling stations for economic reasons, requiring that the systems be fully integrated in with existing hardware and footprints.

To reduce technology risk, multiple units are evaluated to acquire sufficient data for statistical significance. Further, the systems must be able to meet local, national, and international codes and standards. All integrated systems will have to meet safety regulations. A by-product of this technology validation approach is that technical and system problems and issues are revealed and component requirements are assessed.

Technical Targets

The Technology Validation sub-program bases its targets on a combination of technical needs identified by the RD&D sub-programs (fuel cells, storage, production, etc.) and market needs identified by current validation projects and industry partners. The Technology Validation sub-programs technical targets are listed in the following tables:

Table 3.6.4 Fuel Cell Durability – Staged (2015, and 2020) Evaluation of Fuel Cell Durability and Operating Periods Against Specific Application Targets			
Application	Current Status[a]	2015	2020
Light Duty Passenger Durability (Hours)	2,521	3,600	5,000
Residential Power Durability (Hours)	12,000[b]	25,000	50,000
Commercial Power Durability (Hours)	40,000-80,000[b,c]	45,000	65,000
APU Durability (Hours)	3,000[b]	10,000	15,000[d]

Table 3.6.5 Fuel Cell System Availability – Staged (2015, 2020) Evaluation of Fuel Cell System Reliability and Availability Against Specific Application Targets			
Application	Current Status[a]	2015	2020
Residential Power Availability[e]	97%[b]	97%	98%
Commercial Power Availability[d]	95%[b]	97%	98%
APU availability[f]	97%[b]	97.5%	98%

Table. 3.6.6 Electrical Efficiency – Staged (2015, 2020) Evaluation of Fuel Cell System Efficiency Against Specific Application Targets			
Application	Current Status[a]	2015	2020
Light Duty Passenger Vehicles – FC System Efficiency[g] @ 25% Power	59%	60%	60%
1 -10 kW Residential Power[h] System Efficiency	34-40%[b,c]	40%	42%
100 kW – 3 MW Commercial Power System Efficiency[g]	42-47%[b,c]	43%	48%
APU System Efficiency[f]	25%[b]	33%	38%

[a] Fiscal Year 2011
[b] From Fuel Cell Systems sub-program. Not validated by Technology Validation sub-program.
[c] Range represents multiple developers and multiple technologies.
[d] The 15,000 hour APU durability target will be met in 2017.
[e] Percentage of time the system is available for operation under realistic operating conditions and load profile. Unavailable time includes time for scheduled maintenance.
[f] Percentage of time the system is available for operation under realistic operating conditions and load profile. Scheduled maintenance does not count against system availability.
[g] Electrical energy (direct current) output per lower heating value of fuel input.
[h] Electrical energy (alternating current) output per lower heating value of fuel input.

3.6.5 Technical Barriers

The following barriers will be addressed by the Technology Validation sub-program to allow fuel cell technologies to progress toward technology readiness.

A. Lack of Fuel Cell Electric Vehicle and Fuel Cell Bus Performance and Durability Data

In the public domain, statistical data for vehicles that are operated under both controlled and real-world conditions have been successfully collected over the last seven years. Data need to continue to be collected to determine if targets are being met and to determine the state-of-the-art of the technology, such as FCEV system fuel efficiency and economy, thermal/water management integration, fuel cell stack durability, and system durability. Data related to vehicle drivability, operation, and survivability in extreme climates (particularly low temperature start-up and operation in hot/arid climates), should also be collected. Development and testing of complete integrated fuel cell power systems is required to benchmark and validate targets for component development.

B. Lack of Data on Stationary Fuel Cells in Real-World Operation

In the last decade, installation of fuel cells for CHP applications has grown tremendously worldwide, with the number of new small stationary fuel cells doubling between 2007 and 2008[8]. However, the number of installations in the U.S. has not grown as quickly. As a result, there is a gap in knowledge of the performance of these systems operating under real-world conditions in the U.S. under multiple usage patterns.

C. Hydrogen Storage

Innovative packaging concepts, durability, fast-fill, discharge performance, and structural integrity data of hydrogen storage systems that are garnered from user sites need to be provided to the community. Current technology does not provide reasonable cost, efficiency and volume options for stationary applications. An understanding of composite tank operating cycle life and failure mechanisms and the introduction of potential impurities is lacking. Cycle life, storage density, fill-up times, regeneration cycle costs, energy efficiency, and availability of chemical and metal hydride storage systems need to be evaluated in real-world circumstances.

D. Lack of Hydrogen Refueling Infrastructure Performance and Availability Data

The high cost of hydrogen production from renewable resources, low availability of the hydrogen production systems, and the challenge of providing safe systems including low-cost, durable sensors are early market penetration barriers. Shorter refueling times need to be validated for all the on-board storage concepts including those using up to 700 bar pressure, particularly with hydrogen pre-cooling. Integrated facilities with footprints small enough to be deployed into established refueling infrastructures (existing gasoline stations) need to be designed and implemented. New station technologies (such as composite tank delivery and new compressor technologies) should be evaluated for their performance and cost-effectiveness. Interface technology to fast-fill high pressure tanks requires reliable demonstrations. Small factory-manufactured, skid-mounted refueling systems need to be proven as reliable options in low-volume production systems for sparsely populated areas with low anticipated vehicle traffic. Other concepts for energy stations and mid-sized plants (i.e.,

[8] http://www.fuelcelltoday.com/online/survey?survey=2009-03%2FSmall-Stationary-2009

5,000 - 50,000 kg H_2/day), including pipelines or mobile refuelers, needs to be verified with respect to system performance, efficiency, and availability.

E. Codes and Standards

Lack of adopted or validated codes and standards that will permit the deployment of refueling stations in a cost-effective and timely manner must be addressed. Technology Validation projects will be closely coordinated with Safety, Codes and Standards so that the experience and learning gained in siting systems for technology validation purposes can be captured and disseminated for the benefit of future installations. Additionally, data on the impact of constituent hydrogen impurities on fuel cell and storage systems need to be validated under real-world operating conditions.

F. Centralized Hydrogen Production from Fossil Resources

There are limited data on the cost, efficiencies, and availabilities of integrated coal-to-hydrogen/power plants with carbon sequestration options. In collaboration with DOE's Office of Fossil Energy, hydrogen delivery systems from such centralized production systems need to be validated and operated. Hydrogen separations at high temperature and high pressure and the integrated impact on the hydrogen delivery system need to be demonstrated and validated.

G. Hydrogen from Renewable Resources

There is little operational, cost, durability, and efficiency information for large integrated renewable electrolyzer systems that produce hydrogen. The integration of biomass, solar thermochemical and other renewable electrolyzer systems needs to be evaluated. These activities will be conducted in collaboration with other EERE programs.

H. Hydrogen and Electricity Co-Production

Cost and durability of hydrogen fuel cell or alternative-power production systems and reformer systems for co-producing hydrogen and electricity need to be validated at user sites. Permitting, codes and standards, and safety procedures need to be established for hydrogen fuel cells located in or around buildings and refueling facilities. These systems have no commercial availability, or operational and maintenance experience.

3.6.6 Technical Task Descriptions

The technical task descriptions for the Technology Validation sub-program are presented in Table 3.6.7. Concerns regarding safety and environmental effects will be addressed within each task in coordination with the appropriate sub-program. The barriers associated with each task are listed in the "Technical Barriers" section.

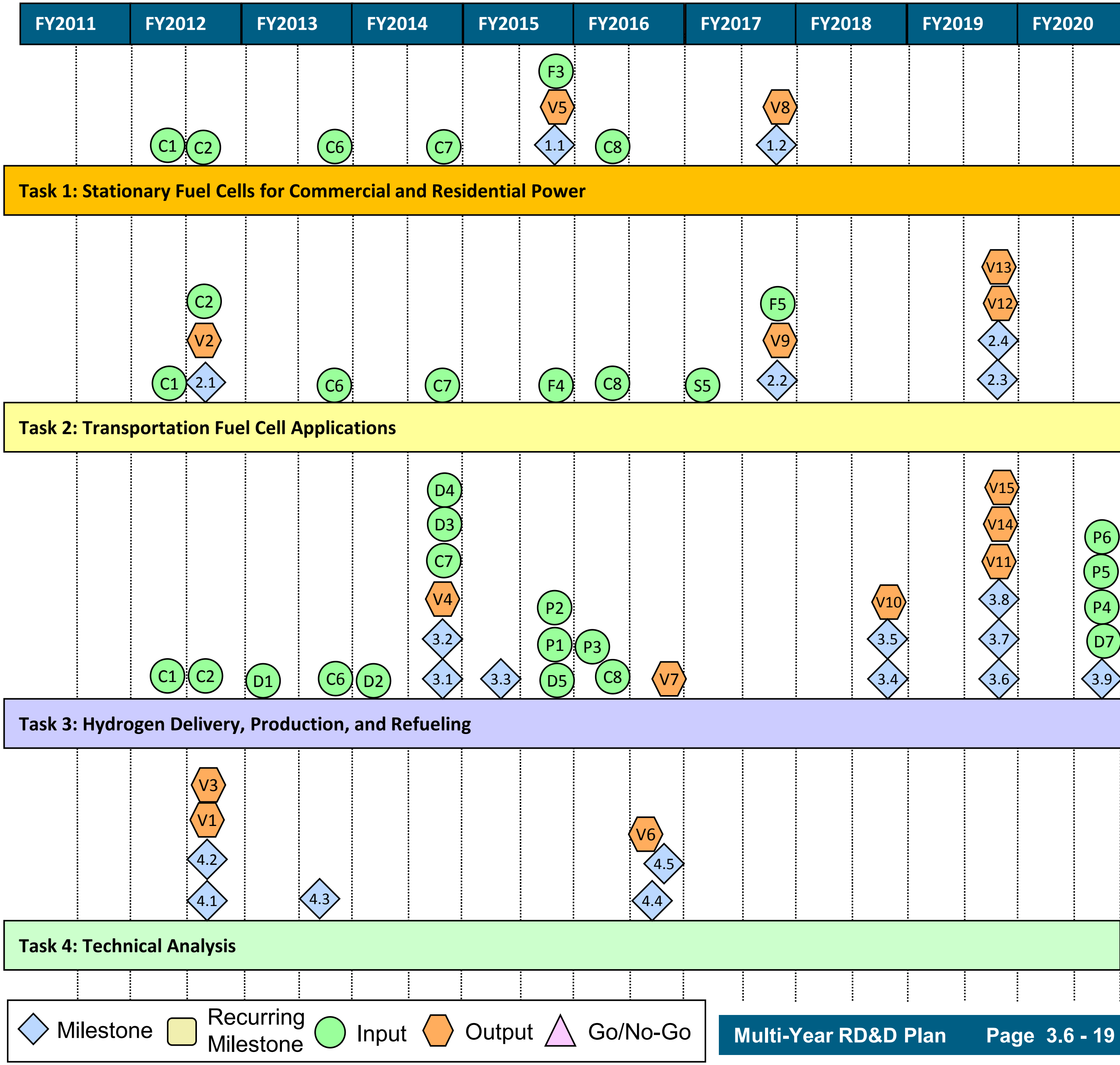
Table 3.6.7 Technical Task Descriptions

Task	Description	Barriers
1	**Stationary Fuel Cells for Commercial and Residential Power** • Validate performance of stationary fuel cells for commercial and residential power in real-world operation; includes multiple fuel cell technologies, such as polymer electrolyte membrane, solid-oxide, molten carbonate, and phosphoric acid. • Perform competitive assessment of performance of fuel cells produced by North American companies compared with the rest of the world.	B, E, H
2	**Transportation Fuel Cell Applications** • Validate performance of state-of-the-art fuel cell electric vehicles. • Determine the current status of fuel cell bus technologies supported by DOT. Analyze performance and operational data of fuel cell buses in real-world service and compare to conventional technology buses as a baseline. Data include fueling, maintenance, availability, reliability, cost, and descriptions of the fleet's experience with the technology. • Validate fuel cell APUs for trucks, ships, and aircraft.	A, C, D, E
3	**Hydrogen Delivery, Production, and Refueling** • Validate integrated systems and their ability to deliver low-cost hydrogen, which includes system performance, operation and maintenance, durability, and reliability under real-world operating conditions. • Validate and improve H2A economic models to provide feedback to RD&D. • Analyze infrastructure data from hydrogen refueling sites to assess technology readiness • Analyze advanced energy stations for production of both hydrogen and electricity from renewable and natural gas sources to assess technology readiness.	D, E, F, G, H
4	**Technical Analysis** • Collect and analyze data from multiple applications of fuel cell and hydrogen technologies demonstrated with support from and outside of the FCT Program. • Publish bi-annual composite data product results to make visible the progress and the remaining technological challenges. • Feed current status into cross-cut analysis studies performed by the Systems Analysis sub-program.	A, B, C, D, E, F, G, H

3.6.7 Milestones

The following charts show the interrelationship of milestones, tasks, supporting inputs from sub-programs, and outputs for the Technology Validation sub-program. The chart covers the time period FY 2011-2020.

Technology Validation Milestone Chart



Task 1: Stationary Fuel Cells for Commercial and Residential Power	
1.1	Complete validation of residential fuel cell micro CHP systems that demonstrate 40% efficiency and 25,000 hour durability. (4Q, 2015)
1.2	Complete validation of commercial fuel cell CHP systems that demonstrate 45% efficiency and 50,000 hour durability. (4Q, 2017)

Task 2: Transportation Fuel Cell Applications	
2.1	Validate achievement of a refueling time of 3 minutes or less for 5 kg of hydrogen at 5,000 psi using advanced communication technology. (3Q, 2012)
2.2	Validate a fuel cell system for APUs with 15,000-hour durability. (4Q, 2017)
2.3	Validate fuel cell electric vehicles achieving 5,000-hour durability (service life of vehicle) and a driving range of 300 miles between fuelings. (4Q, 2019)
2.4	Validate onboard storage system achieving 5.5% weight capacity and an energy density of 1,300 Wh/L. (4Q, 2019)

Task 3: Hydrogen Delivery, Production, and Refueling	
3.1	Validate stationary fuel cell system that co-produces hydrogen and electricity with 40,000-hour durability while maintaining a minimum of 40% overall efficiency. (4Q, 2014)
3.2	Validate novel hydrogen compression technologies or systems capable of >200 kg/day that could lead to more cost-effective and scalable (up to 500 kg/day fueling station solutions for motive applications. (4Q, 2014)
3.3	Validate large scale (>100 kg/day) integrated wind-to-hydrogen production system. (2Q, 2015).
3.4	Validate station compression technology provided by delivery team. (4Q, 2018)
3.5	Validate distributed production of hydrogen from renewable liquids at a projected cost of $5.00/gge and from electrolysis at a projected cost of $3.70 with an added delivery cost of <$4/gge. (4Q, 2018)
3.6	Validate liquefaction technology provided by the delivery team. (4Q, 2019)
3.7	Validate pipeline technology provided by the delivery team. (4Q, 2019)
3.8	Validate reduction of cost of transporting hydrogen from central production to refueling sites to <$0.90/gge. (4Q, 2019)
3.9	Validate large-scale system for grid energy storage that integrates renewable hydrogen generation and storage with fuel cell power generation by operating for more than 10,000 hours with a round-trip efficiency of 40%. (4Q, 2020)

Task 4: Technical Analysis	
4.1	Final Learning Demonstration final summary report published. (3Q, 2012),
4.2	Updated composite data products for material handling and backup power published. (3Q, 2012)
4.3	Report safety event data and information from ARRA projects. (3Q, 2013)
4.4	Complete evaluation of 700-bar fast fill fueling stations and compare to SAE J2601 specifications and DOE fueling targets. (3Q, 2016)
4.5	Based on field validation data, publish assessment of remaining fuel cell technology gaps requiring additional RD&D to satisfy residential/commercial fuel cell CHP markets. (4Q, 2016)

Outputs

V1 Output to Program: Final learning demonstration summary report published. (3Q, 2012)

V2 Output to Delivery, Storage, Safety, Codes and Standards, and Systems Analysis: Validate achievement of a refueling time of 3 minutes or less for 5 kg of hydrogen at 5,000 psi using advanced communication technology. (3Q, 2012)

V3 Output to Safety, Codes and Standards, Market Transformation, and Systems Analysis: Publish/post composite data products for material handling and backup power, including safety event data. (3Q, 2012)

V4 Output to Market Transformation and Systems Analysis: Validate stationary fuel cell system that co-produces hydrogen and electricity and report on durability and efficiency. (4Q, 2014)

V5 Output to Fuel Cells and Market Transformation: Report on the validation of residential fuel cell micro combined heat and power systems' efficiency and durability. (4Q, 2015)

V6 Output to Delivery and Safety, Codes and Standards: Validate 700-bar fast fill fueling stations against DOE fueling targets. (3Q, 2016)

V7 Output to Delivery and Systems Analysis: Validate novel hydrogen compression technology durability and efficiency. (4Q, 2016)

V8 Output to Fuel Cells and Market Transformation: Complete validation of commercial fuel cell combined heat and power systems' efficiency and durability. (4Q, 2017)

V9 Output to Fuel Cells and Market Transformation: Validate status of truck auxiliary power unit durability. (4Q, 2017)

V10 Output to Production and Systems Analysis: Validate distributed production of hydrogen from electrolysis at a projected cost of $3.90/kg with an added delivery cost of <$4/gge. (4Q, 2018)

V11 Output to Delivery and Systems Analysis: Validate station compression technology provided by the delivery team. (4Q, 2019)

V12 Output to Fuel Cells and Systems Analysis: Validate light duty fuel cell vehicle durability. (4Q, 2019)

V13 Output to Storage: Validate onboard storage system weight capacity and energy density. (4Q, 2019)

V14 Output to Delivery and Systems Analysis: Validate liquefaction technology provided by the delivery team. (4Q, 2019)

V15 Output to Delivery and Systems Analysis: Validate pipeline technology provided by the delivery team. (4Q, 2019)

Inputs

C1 Input from Safety, Codes and Standards: NFPA2: Hydrogen code document. (2Q, 2012)

C2 Input from Safety, Codes and Standards: Hydrogen fuel quality standard (SAE J2719). (3Q, 2012)

C6 Input from Safety, Codes and Standards: Updated materials compatibility technical reference manual. (4Q, 2013)

C7 Input from Safety, Codes and Standards: Materials reference guide and properties database. (4Q, 2014)

C8 Input from Safety, Codes and Standards: National indoor fueling standard. (2Q, 2016)

D1 Input from Delivery: Delivery pathways that can meet an as-dispensed hydrogen cost of <$4/gge ($1/100ft3) for emerging fuel cell powered early markets. (1Q, 2013)

D2 Input from Delivery: Provide candidate station compression technologies for potential technology validation. (1Q, 2014)

D3 Input from Delivery: Provide candidate liquefaction technologies for potential validation. (4Q, 2014)

D4 Input from Delivery: Recommended pipeline technology for validation. (4Q, 2014)

D5 Input from Delivery: Provide options that meet <$4/gge for hydrogen delivery from the point of production to the point of use for emerging regional consumer and fleet vehicle markets. (4Q, 2015)

D7 Input from Delivery: Provide options that meet <$2/gge for hydrogen delivery from the point of production to the point of use in consumer vehicles. (4Q, 2020)

F3 Input from Fuel Cells: Provide micro-combined heat and power system test data from documented sources indicating performance status. (4Q, 2015)

F4 Input from Fuel Cells: Provide auxiliary power unit system test data from documented sources indicating performance status. (4Q, 2015)

F5 Input from Fuel Cells: Provide automotive stack test data from documented sources indicating performance status. (4Q, 2017)

P1 Input from Production: Hydrogen production system based on centralized biomass gasification technology producing hydrogen at a projected cost of $2.10/kg at the plant gate. (4Q, 2015)

P2 Input from Production: System based on distributed production of hydrogen from electrolysis at a projected cost of $3.90/kg without compression, storage and dispensing. (4Q, 2015)

P3 Input from Production: Hydrogen production system based on centralized electrolysis technology producing hydrogen at a projected cost of $3.00/kg at the plant gate. (1Q, 2016)

P4 Input from Production: Solar hydrogen production system based on centralized high-temperature thermochemical conversion technology producing hydrogen at a projected cost of $3.10/kg at the plant gate. (4Q, 2020)

P5 Input from Production: Solar hydrogen production system based on photolytic biological hydrogen production from water at a solar to hydrogen conversion efficiency of 5%. (4Q, 2020)

P6 Input from Production: Solar hydrogen production system based on photoelectrochemical hydrogen production from water at a solar to hydrogen conversion meeting 2020 targets. (4Q, 2020)

S5 Input from Storage: Projected performance of materials-based systems for onboard hydrogen storage. (1Q, 2017)