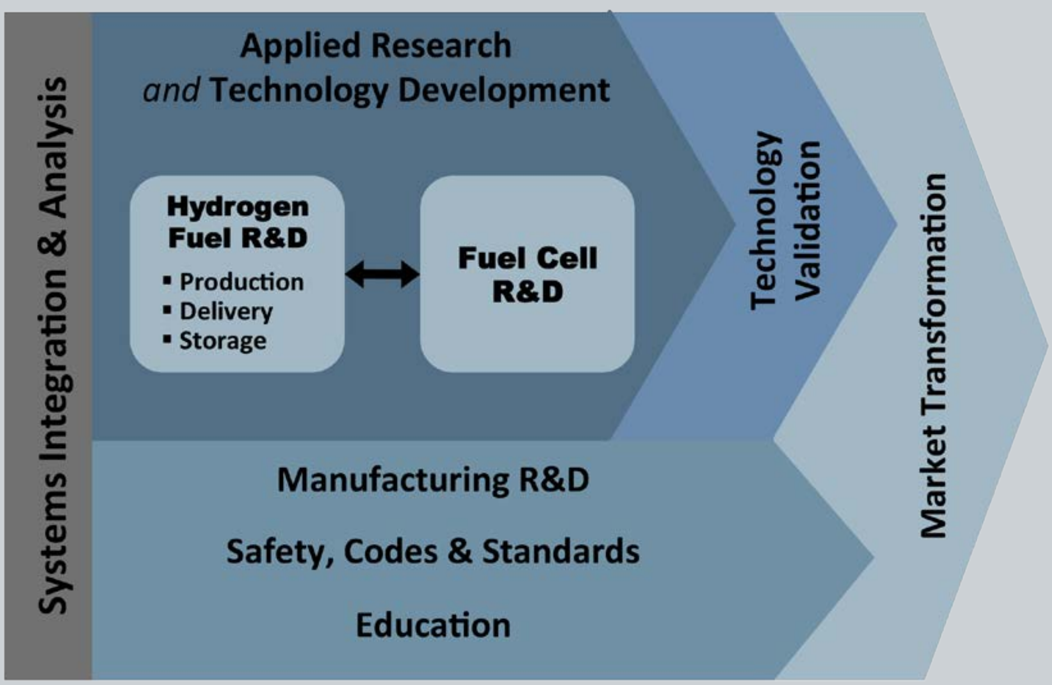
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Fuel Cell Technologies Office

Multi-Year Research, Development, and Demonstration Plan

Planned program activities for 2011-2020



Preface

The *Fuel Cell Technologies Program Multi-Year Research, Development, and Demonstration Plan (MYRD&D Plan)* describes the goals, objectives, technical targets, tasks, and schedules for all activities within the Fuel Cell Technologies Program (FCT Program), which is part of U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE). The Fuel Cell Technologies Program (FCT Program) is also part of the DOE Hydrogen and Fuel Cells Program (the Program), which integrates hydrogen and fuel cell–related activities in the offices of Science, Fossil Energy, and Nuclear Energy. Detailed plans for hydrogen and fuel cell–related activities in the offices of Science and Fossil Energy can be found at http://hydrogen.energy.gov/roadmaps_vision.html; and an integrated plan for the DOE-wide hydrogen and fuel cell activities can be found at http://hydrogen.energy.gov/pdfs/program_plan2011.pdf. Details on every project funded by the FCT Program can be found in the Program's annual progress reports, which are available at: http://www.hydrogen.energy.gov/ annual_progress.html.

This edition of the *MYRD&D Plan* reflects a number of changes in the Department's overall strategy for hydrogen and fuel cells, which have evolved since the previous edition, including:

- Reducing emphasis on a single "technology-readiness" milestone for light-duty vehicles and pursuing a vision of technology advancement that involves continuous improvement in many technology areas and for many applications, with new applications reaching technology readiness at different times. Technology and market success in several applications can enable a domestic supply base and pave the way for fuel cell electric vehicles in the longer term
- Adopting a technology-neutral approach toward fuel cell RD&D, with efforts focused on the most appropriate fuel cell technology for a given application
- Adopting a more comprehensive approach to market transformation—including expanded efforts to leverage the work of other DOE activities, state programs, and other federal agencies—to ensure that the early market successes of certain applications can have the most beneficial impact on the advancement of all hydrogen and fuel cell technologies and the industry as a whole

Document Revision History

The *MYRD&D Plan* is a living document, which is revised periodically to reflect progress in the technologies, revisions to developmental timelines and targets, updates based on external reviews, and changes in the scope of the FCT Program. An initial draft was released in June 2003 and was reviewed by the National Research Council and the National Academy of Engineering, leading to the first edition, published in January 2005. Subsequent revisions to the *MYRD&D Plan* were made in 2007, 2009, and 2012. All revisions were conducted through a rigorous Change Control process as documented in the Systems Integration section.

Executive Summary

The United States pioneered the development of hydrogen and fuel cell technologies, and we continue to lead the way as these technologies emerge from the laboratory and into commercial markets. A tremendous opportunity exists for the United States to capitalize on this leadership role and apply these technologies to reducing greenhouse gas emissions, reducing our dependence on oil, and improving air quality.

Fuel cells can address our critical energy challenges in all sectors—commercial, residential, industrial, and transportation. They can use diverse fuels, including biomass-based fuels, natural gas, and hydrogen produced from renewable resources. And, they can be used in a wide range of applications, including near-term markets such as distributed primary and backup power, lift trucks, and portable power; mid-term markets such as residential combined-heat-and-power (CHP) systems, auxiliary power units, and fleet vehicles; and longer-term markets such as light-duty passenger vehicles.

The central mission of the U.S. Department of Energy's (DOE's) Hydrogen and Fuel Cells Program (the Program) is to enable the widespread commercialization of a portfolio of hydrogen and fuel cell technologies through basic and applied research, technology development and demonstration, and diverse efforts to overcome institutional and market challenges. The Program integrates activities across four DOE offices–Energy Efficiency and Renewable Energy (EERE), Science, Fossil Energy, and Nuclear Energy–and works with partners in state and federal agencies, foreign governments, industry, academia, non-profit institutions, and the national laboratories. This document describes the status, challenges, and activities of the DOE Fuel Cell Technologies Program [(FCT Program) which is the EERE portion of the DOE-wide Hydrogen and Fuel Cells Program] and how these activities relate to the Program's mission. The current focus of the Program is to address both key technical challenges (for fuel cells and hydrogen production, delivery, and storage) and institutional barriers (such as hydrogen codes and standards). These activities include cost-shared, public-private partnerships to accelerate the development of higher-risk technologies essential to the widespread use of hydrogen and fuel cells.

Key Benefits of Hydrogen and Fuel Cells

- **Reducing greenhouse gas emissions**
- **Reducing oil consumption**
- **Advancing renewable power using hydrogen for energy storage and transmission**
- **Highly efficient energy conversion**
- **Fuel flexibility—use of diverse, domestic fuels, including clean and renewable fuels**
- **Reducing air pollution**
- **High reliability and grid support capabilities**
- **Suitability for diverse applications**
- **Quiet operation**
- **Low maintenance needs**
- **Opportunities for economic growth and leadership in an emerging high-tech sector**

Challenges for Hydrogen and Fuel Cell Technologies

While fuel cells are becoming competitive in a few markets, the range of these markets can be greatly expanded with improvements in durability and performance and reductions in manufacturing cost, as well as advances in technologies for producing, delivering, and storing hydrogen. Successful entry into new markets 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 high initial costs and lack of a supply base that many new technologies face in their critical early stages.

Technology Challenges

- For fuel cells to be competitive with incumbent technologies their cost must be reduced and their durability must be improved.
- Some aspects of fuel cell performance must be addressed, including: improvements in operation in wide ranges of temperature and humidity; higher operating temperatures and improvements in efficiency for stationary fuel cells; and higher energy density for portable fuel cells.
- The cost of producing and delivering hydrogen from zero- or near-zero-carbon sources must be reduced.
- Compact, lightweight, and low-cost hydrogen storage systems must be developed. For vehicles, technologies must enable greater than a 300-mile driving range across all vehicle platforms without reducing performance or interior space.
- Improvements in manufacturing technologies and processes will be required to achieve the necessary cost reductions.
- Hydrogen and fuel cell technologies need to be demonstrated in complete, integrated systems operating under real-world conditions.

Economic and Institutional Challenges

- There is a high investment risk for developing and expanding manufacturing capacity for hydrogen and fuel cell technologies.
- There is a high investment risk for developing a hydrogen delivery infrastructure, given the current absence of demand for hydrogen from the transportation sector.
- Additional codes and standards need to be developed and harmonized (nationally and internationally) to ensure safety and insurability of the technologies.
- There is a general lack of understanding and awareness of hydrogen and fuel cells, which is particularly important to address in certain key audiences, including safety and code officials, policy makers, and potential early adopters.
- Deployment costs such as siting, permitting, installation, and financing remain too high and hinder the widespread market penetration of fuel cells in early market applications.

Program Progress

The DOE FCT Program has been integral to the important progress in hydrogen and fuel cell technologies in recent years. Specific examples of accomplishments and progress resulting from Program-funded projects include the following:

- Reduced the cost of automotive fuel cells by more than 30% since 2008 and 80% since 2002 (from \$275/kW in 2002 to \$49/kW in

2011, based on projections of high-volume manufacturing costs).

- More than doubled the durability of automotive fuel cell systems operating under real-world conditions, with more than 2,500-hour durability (about 75,000 miles) that can be demonstrated on the road (membrane durability has exceeded 5,000 hours at the single-cell level, with load cycling and less than 0.2 g/kW of platinum group metal.)
- Reduced the projected high-volume cost of producing hydrogen (untaxed and not including delivery or dispensing costs) through several pathways, including distributed electrolysis ($4.20/kg), central electrolysis ($4.10/kg), and central biomass gasification ($2.20/kg).
- Reduced the capital cost of electrolyzer stacks by more than 80%—from over $2,500/kW in 2001 to less than $500/kW in 2011.
- Independently produced and verified two new sorbent materials with specific surface areas in excess of 6,000 square meters per grams with excess hydrogen capacities exceeding 8 wt.% and 28 g/L at 60 bar and 77K, a greater than 13% increase in gravimetric capacity over the prior best known hydrogen sorbent.
- Developed an integrated model consisting of vehicle, fuel cell, and hydrogen storage system units, allowing for rapid and consistent evaluation of hydrogen storage system concepts and designs against the full set of 20 onboard storage performance targets.
- Demonstrated 25 fueling stations and more than 180 fuel cell electric vehicles operating under real-world conditions (these vehicles have traveled 3.6 million miles, demonstrating efficiencies of up to 59%—more than twice the efficiency of today's gasoline vehicles—and refueling times of approximately 5 minutes for 4 kg of hydrogen).
- Validated vehicles with more than 250-mile driving range, and one vehicle capable of 430 miles on a single fill of hydrogen.
- Collected and analyzed data from second generation fuel cell buses, demonstrating fuel economies more than 100% higher than diesel internal combustion engine (ICE) buses and more than 80% higher than natural gas ICE buses.
- Demonstrated combined efficiency of 54% for co-producing hydrogen and power from a stationary fuel cell.
- Demonstrated the potential for a 25% cost reduction of membrane electrode assemblies through a novel three-layer manufacturing process.
- Conducted safety research and development to provide a sound technical basis for development of critical codes and standards—including the comprehensive hydrogen code, NFPA 2.
- Developed online resources to disseminate best practices and safety information and to facilitate and streamline the permitting process for hydrogen installations.
- Educated more than 9,600 teachers about hydrogen and fuel cells.
- Completed "well-to-wheels" analysis, which shows the potential for significant reductions in emissions and petroleum use through the use of fuel cells in multiple applications.
- Supported deployments of fuel cell lift trucks, which have led to more than 3,500 additional fuel cell lift truck deployments by industry, purchased or on order—with no DOE funding.

Many of the advances that the Program has made can be seen in the marketplace today—commercial customers are choosing fuel cells for the benefits they offer. Success in early markets such as material handling equipment and stationary and portable power can help pave the way for transportation fuel cells by accelerating the development of manufacturing capacity, spurring the growth of localized infrastructure, developing and implementing codes and standards, and facilitating customer acceptance.

Hydrogen and fuel cells are also being demonstrated in growing fleets of automobiles, transit buses, and supporting refueling infrastructure. These demonstrations show strong and steady improvements in performance and durability, confirming progress toward commercial viability in these important markets. By pursuing innovative concepts and promising pathways for research, development, and demonstration, DOE has made significant technological advances; and by working to ease the transition of technologies into the marketplace, DOE has moved hydrogen and fuel cells substantially closer to the crucial role they can play in our energy economy. The successful development of hydrogen and fuel cell technologies will help to ensure that the United States has an abundant, reliable, and affordable supply of clean energy.

1.0 Introduction

The U. S. Department of Energy's (DOE's or the Department's) hydrogen and fuel cell efforts are part of a broad portfolio of activities to build a competitive and sustainable clean energy economy to secure the nation's energy future. Reducing greenhouse gas emissions 80 percent by 2050[1] and eliminating dependence on imported fuel will require the use of diverse domestic energy sources and advanced fuels and technologies in all sectors of the economy. Achieving these goals requires a robust, comprehensive research and development (R&D) portfolio that balances short-term objectives with long-term needs and sustainability.

Fuel cells, which convert diverse fuels directly into electricity without combustion, and hydrogen, a zero-carbon fuel when produced from renewable resources, comprise key elements of the DOE portfolio. DOE's efforts to enable the widespread commercialization of hydrogen and fuel cell technologies form an integrated program—the DOE Hydrogen and Fuel Cells Program (the Program), as reflected in the Hydrogen and Fuel Cells Program Plan.[2] The Program is coordinated across the Department and includes activities in the offices of Energy Efficiency and Renewable Energy (EERE), Science, Nuclear Energy, and Fossil Energy.

The Fuel Cell Technologies Program (FCT Program), situated within EERE, addresses key technical challenges for fuel cells and hydrogen production, delivery, and storage and the institutional barriers, such as hydrogen codes and standards, training, and public awareness that inhibit the widespread commercialization of hydrogen and fuel cell technologies. The FCT Program conducts applied research, technology development and learning demonstrations, as well as safety research, systems analysis, early market deployments, and public outreach and education activities. These activities include cost-shared, public-private partnerships to address the high-risk, critical technology barriers preventing extensive use of hydrogen as an energy carrier. Public and private partners include automotive and power equipment manufacturers, energy and chemical companies, electric and natural gas utilities, building designers, standards development organizations, other Federal agencies, state government agencies, universities, national laboratories, and other national and international stakeholder organizations. The FCT Program encourages the formation of collaborative partnerships to conduct research, development and demonstrations (RD&D) and other activities, such as deployment, that support program goals.

The FCT Program addresses the development of hydrogen energy systems for transportation, stationary power, and portable power applications. Transportation applications include fuel cell vehicles (such as buses, automobiles and heavy duty vehicles), niche markets (such as lift trucks), and hydrogen refueling infrastructure. Hydrogen used for back-up emergency power, commercial/ industrial power and heat generation, and residential electric power generation is included in stationary power applications. Consumer electronics such as mobile phones, laptop computers, and recharging systems are among the portable power applications. The DOE is funding RD&D efforts that will provide the basis for the near-, mid-, and long-term production, delivery, storage, and use of hydrogen derived from diverse energy sources, including renewable, fossil fuels, and nuclear

[1] The Obama-Biden Plan, available at http://change.gov/agenda/energy_and_environment_agenda/.
[2] Available at http://www1.eere.energy.gov/hydrogenandfuelcells/program_plans.html.

energy as coordinated within the Program. This document primarily describes the status, challenges, and RD&D activities of the FCT program but also the overall DOE Hydrogen and Fuel Cells Program.

1.1 Background

In the early 1970s, concern over the United States' growing dependence on imported petroleum, coupled with concerns about our deteriorating air quality resulting from combustion of fossil fuels, prompted initial DOE activity supporting hydrogen technology. In the late 1980s, DOE initiated the Fuel Cells for Transportation Program to develop polymer electrolyte membrane fuel cells (PEMFCs) for automotive use. This was followed by subsequent efforts in the 1990s and 2000s resulting in steady progress. The FCT Program utilizes the results of these past efforts and incorporates the direction and guidance of the *DOE Strategic Plan*[3], the *U.S.DRIVE Partnership Plan*[4], the *National Hydrogen Vision*[5], the *National Hydrogen Energy Roadmap*[6], the *Energy Policy Act of 2005 (EPACT)*, *the Energy Independence and Security Act of 2007 (EISA) and the American Recovery and Reinvestment Act of 2009 (Recovery Act)*. In addition, the FCT Program has incorporated the contributions and ideas of hundreds of experts from U.S. and international industry, government, and academia.

Key Drivers

Three major factors require new approaches to the way the United States produces, delivers, and uses energy. These drivers are as follows:

- Energy security
- Environmental quality
- Economic vitality.

Energy Security

The need to expand the supply of domestically produced energy is significant. America's transportation sector relies almost exclusively on refined petroleum products. Approximately 52% of the petroleum consumed for transportation in the United States is imported,[7] and that percentage is expected to rise steadily for the foreseeable future (Figure 1.1). On a global scale, petroleum supplies will be in higher demand as highly populated, developing countries expand their economies and become more energy-intensive. Hydrogen-powered fuel cell vehicles would virtually eliminate imports of foreign oil, because the hydrogen fuel can be produced almost entirely from the diverse domestic energy sources of renewable resources, fossil fuels, and nuclear power. Hydrogen's role as a major energy carrier would also provide the United States with a more efficient and diversified

[3] Available at http://energy.gov/sites/prod/files/2011_DOE_Strategic_Plan_.pdf
[4] Available at http://www1.eere.energy.gov/vehiclesandfuels/about/partnerships/roadmaps-other_docs.html.
[5] Available at http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/vision_doc.pdf.
[6] Available at http://www.hydrogen.energy.gov/pdfs/national_h2_roadmap.pdf.
[7] Sources: Oak Ridge National Laboratory, *Transportation Energy Data Book: Edition 29, ORNL-6985,* July 2010, http://info.ornl.gov/sites/publications/files/Pub24318.pdf; Energy Information Administration, *Petroleum Supply Annual 2009*, July 2010, http://205.254.135.24/petroleum/supply/annual/volume1/archive/2009/pdf/volume1_all.pdf.

energy infrastructure that includes a variety of options for fueling central and distributed electric power generation systems.

U.S. Petroleum Consumption

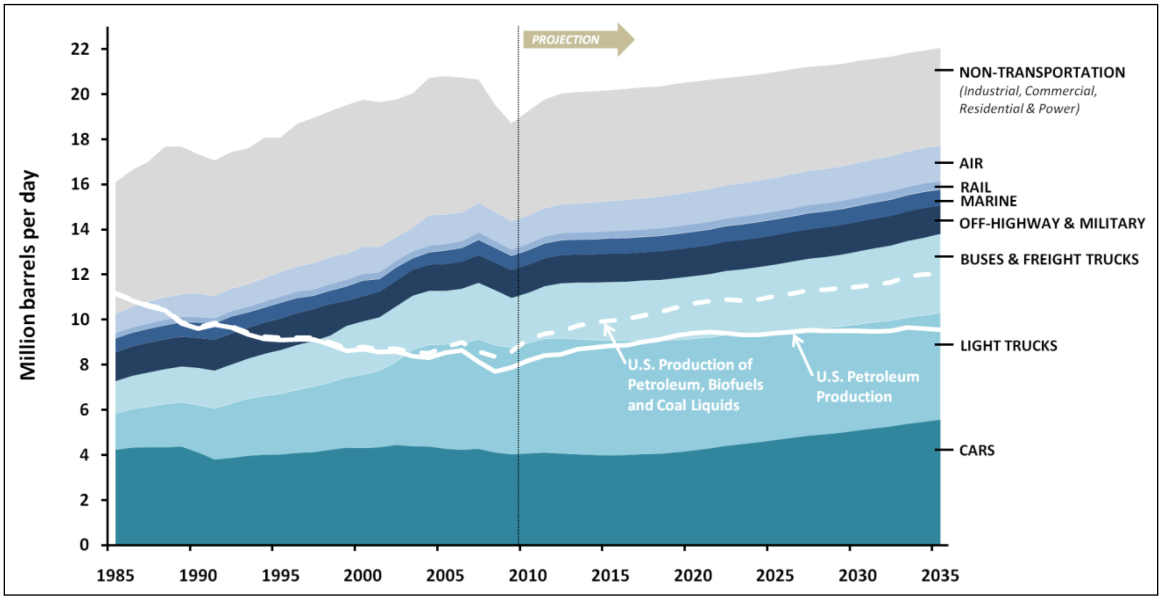


Figure 1.1. America's Widening "Oil Gap." *America's reliance on imported oil is the key challenge to our energy security. While oil is used in all sectors and for a wide variety of uses, the large majority is used for transportation—and a majority of that is used in light-duty passenger vehicles (cars and light trucks).*[8]

Environmental Quality

The combustion of fossil fuels accounts for the majority of anthropogenic greenhouse gas emissions (chiefly carbon dioxide, CO_2) released into the atmosphere. The largest sources of CO_2 emissions are the electric utility and transportation sectors. Should strong constraints on carbon emissions be required, hydrogen will play an important role in a low-carbon global economy. Distributed hydrogen production from natural gas and central hydrogen production from natural gas (with the potential for capture and sequestration of carbon) and coal (with the capture and sequestration of carbon) can provide the means for domestic fossil fuels to remain viable energy resources. In addition, fuel cells operating on hydrogen produced from renewable resources or nuclear energy result in near-zero carbon emissions.

Air quality is a major national concern. It has been estimated that about 50% of Americans live in areas where levels of one or more air pollutants are high enough to affect public health and/or the environment.[9] Personal vehicles and electric power plants are significant contributors to the nation's air quality problems. Most states are now developing strategies for achieving national ambient air

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[8] Sources: Oak Ridge National Laboratory, *Transportation Energy Data Book: Edition 29, ORNL-6985,* July 2010, http://info.ornl.gov/sites/publications/files/Pub24318.pdf; Energy Information Administration, *Annual Energy Outlook*, April 2010, www.eia.doe.gov/oiaf/aeo/pdf/0383(2010).pdf

[9] DOE Hydrogen Program Record 8013, available at: http://www.hydrogen.energy.gov/pdfs/8013_air_quality_population.pdf

quality goals and bringing their major metropolitan areas into compliance with the requirements of the Clean Air Act. For example, the introduction of commercial bus fleets using hydrogen is one of the approaches that local governments are taking to improve air quality. California, where 90% of the population breathes unhealthy levels of one or more air pollutants during some part of the year, has been one of the most aggressive states in its strategies and has launched a number of programs targeted at improving urban air quality. The Benefits section of this Plan describes the potential impact that fuel cells can have to improve air quality.

Economic Vitality

National economic security seems to be heavily dependent on our energy security. There is also evidence of growing worldwide interest in hydrogen and fuel cell technology, as reflected in the dramatic increase in public and private spending since the mid-1990s. Governments and industries in Canada, Europe, and Asia are investing heavily in hydrogen research, development, and demonstration. In 2001, the Japanese government nearly doubled its fuel cell RD&D budget to $220 million and launched a joint government/industry demonstration of hydrogen fuel cell vehicles, including the deployment of more than seven new hydrogen refueling stations. The Japanese fuel cell budget has continued to grow and is projected to total about $1 billion from 2008 through 2012. Japan announced plans for 2 million fuel cell vehicles and 1,000 fueling stations by 2025. As another example, Germany plans to invest $1 billion from 2007 through 2016 and plans up to 1,000 hydrogen fueling stations throughout the country. Korea is also significantly ramping up its efforts and plans to produce 20% of global fuel cell shipments and create 560,000 jobs in Korea.[10] The U.S. must be a leader in hydrogen and fuel cell technology development and commercialization in order to secure a competitive position for future energy technology innovations, new products, and service offerings.

Challenges for Hydrogen as an Energy Carrier

The transition from our current energy infrastructure to a clean and secure energy infrastructure based on hydrogen and other alternative fuels will take decades as the difficult challenges posed by technological, economic, and institutional barriers are addressed and overcome. For hydrogen, the "critical path" barriers are summarized in the following sections.

[10] Available at http://www1.eere.energy.gov/hydrogenandfuelcells/program_plans.html.

Technology Challenges

- Compact, lightweight, and low-cost storage systems must be developed. For vehicles, technologies must enable greater than 300-mile driving range across all vehicle platforms without reducing performance or interior space.
- The cost of producing and delivering hydrogen from zero or near-zero carbon sources must be reduced. Low-cost and environmentally sound CO_2 capture and sequestration technologies must be developed.
- The cost of fuel cells must be reduced and their durability improved, to be competitive with current technologies.

Economic and Institutional Challenges

- The risk of expanding the hydrogen delivery infrastructure is high, given technology status, but the infrastructure must keep pace with planned fuel cell roll outs in stationary and transportation applications.
- Uniform model codes and standards to ensure safety and insurability are needed.
- Local code officials, policy makers and the general public lack education on hydrogen benefits and on safe handling and use.
- A robust, domestic manufacturing and component supplier base for hydrogen and fuel cell technologies needs to be developed.

1.2 Program Vision and Mission

Today, after decades of dependence on imported petroleum, our nation has a new vision for our energy future: forms of domestically derived, clean energy to power not only our vehicles but our industries, buildings, and homes. In addition to clean coal (with carbon sequestration) and nuclear energy, the energy carriers of the future will include electricity from renewable sources, alternative liquid fuels (e.g., bio-based or renewable fuels), and hydrogen.

In the long-term vision, fuel cells will be available in all regions of the country and will serve all sectors of the economy. Diverse domestically available fuels, such as biogas and natural gas will be used in fuel cells with high efficiency and low emissions. Hydrogen will be produced from renewable resources and fossil fuels (with carbon capture and sequestration), as well as nuclear energy. It will be used in the transportation, electric power, and consumer sectors. Hydrogen will be produced in centralized facilities and in distributed facilities at fueling stations, rural areas, and community locations. Hydrogen production and storage costs will be competitive; the basic components of a national hydrogen delivery and distribution network will be in place; and hydrogen-powered fuel cells, engines, and turbines will have become mature technologies in mass production for diverse applications.

To succeed in achieving this vision, the Program's mission is to enable the widespread commercialization of a portfolio of hydrogen and fuel cell technologies through basic and applied research, technology development and demonstration, and diverse efforts to overcome institutional and market challenges.

1.3 Fuel Cell Technologies Program Key Activities

The FCT Program facilitates the applied research and technology development efforts needed for hydrogen and fuel cell technology readiness. The FCT Program is the lead for directing and integrating RD&D and deployment activities in hydrogen production, storage, delivery and end use for transportation, stationary, and portable applications. Table 1.1 lists the sub-programs of the FCT Program and their focus.

The FCT Program collaborates with industry, academia, and national laboratories, as well as closely coordinates activities with the Vehicle Technologies Program and other DOE programs to achieve EERE's strategic goals relevant to the FCT Program, as follows:

- Dramatically reduce dependence on foreign oil
- Promote the use of diverse, domestic and sustainable energy resources
- Reduce carbon emissions from energy production and consumption
- Increase the reliability and efficiency of electricity generation.

Table 1.1. Sub-Programs of the FCT Program	
Sub-Program	**Sub-Program Focus**
Production	Clean, cost-effective, and efficient production of hydrogen from renewable, fossil, and nuclear energy resources
Delivery	Low cost, safe distribution of hydrogen from centralized or distributed sites of production
Storage	Materials and systems RD&D for onboard vehicular hydrogen storage that will allow for a driving range of 300 miles or more and for storage for stationary and portable applications.
Fuel Cells	Materials, component, and system RD&D to reduce cost and improve durability of PEM fuel cells for transportation, stationary, and portable applications
Manufacturing	High-volume fabrication and assembly processes to reduce cost and develop a domestic supplier base
Technology Validation	Field tests and evaluation of hydrogen and fuel cell technologies and technical validation of integrated systems in real-world environments
Safety, Codes and Standards	Working to ensure safety in hydrogen production and use by applying lessons learned and best practices within the program and promulgating that experience outside the program. Working with Standards Development Organizations and Code Development Organizations to facilitate the development of hydrogen technology codes and standards. Also supports RD&D that provides a basis for the technical requirements needed for codes and standards.
Education	Educating key target audiences—state and local government stakeholders, early adopters and commercial end users, teachers and students, safety and code officials–about the use of hydrogen and fuel cell technologies in numerous applications.
Systems Analysis	Evaluating existing and emerging technologies through multiple pathways utilizing a fact-based analytical framework to guide the selection and evaluation of RD&D projects and to provide a basis for estimating the potential value of research efforts.
Systems Integration	Understanding the complex interactions between components, systems costs, environmental impacts, societal impacts, and system trade-offs. Identifying and analyzing these interactions will enable evaluation of alternative concepts and pathways and result in well-integrated and optimized hydrogen and fuel-cell systems.
Market Transformation	Stimulating the market and industry by providing financial assistance for demonstrating fuel cells in early-market applications.

These goals can be realized with a domestic hydrogen energy system, and are consistent with broader DOE policy goals. As illustrated in Figure 1.2, diverse fuels can be used in fuel cells, and hydrogen can be produced from a diverse set of domestic resources, including renewable, fossil, and nuclear resources, helping to attain the first three strategic goals. High efficiency and low emissions through the use of fuel cells in both transportation and distributed electric power generation support achieving the third and fourth strategic goals.

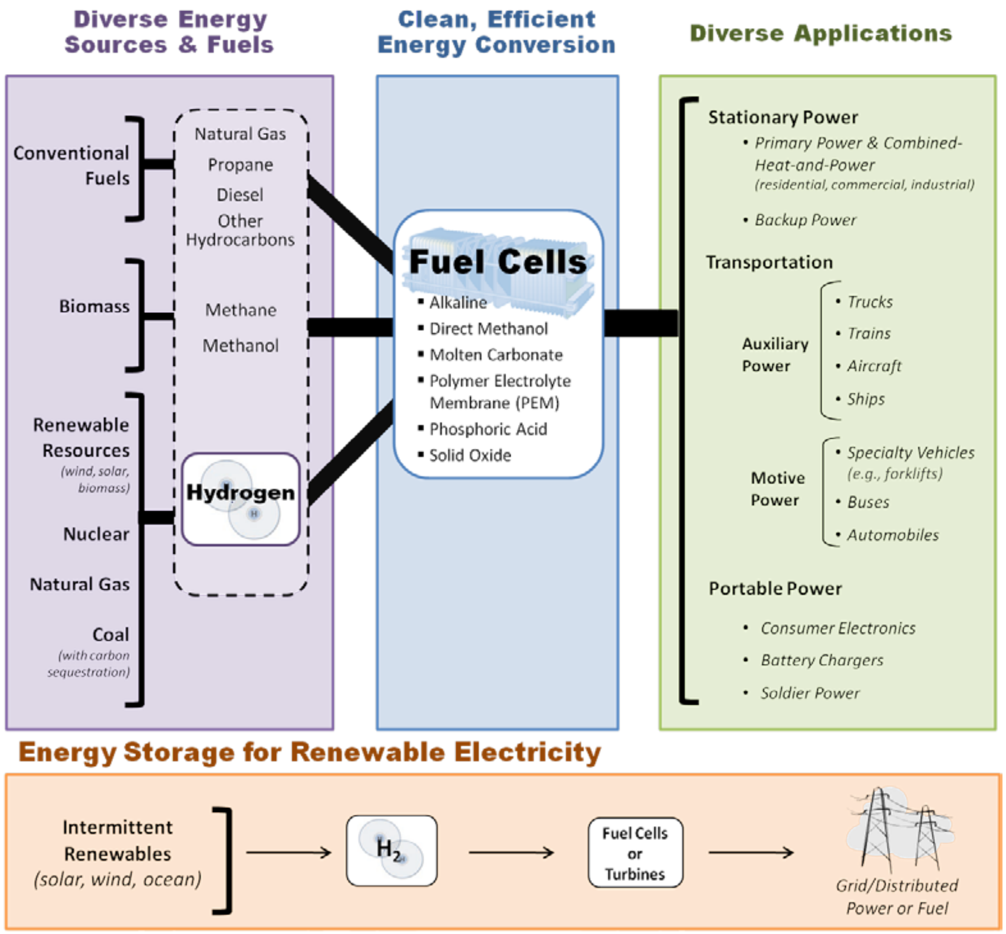

Figure 1.2 Fuel cells and hydrogen can be used for diverse applications.

The FCT Program supports research, development and demonstration activities linked to public-private partnerships. As activities progress through the stages of research and development to validating technical targets, the government's cost share will diminish. The government's role as co-funder will promote technology maturation, allowing the private sector to make informed decisions on feasibility and methods of commercializing the technology.

1.4 Program Planning

The FCT Program's Multi-Year RD&D plan is built upon several predecessor planning documents and is integrated with other DOE office plans (Figure 1.3). The Plan also describes the details of research and technology development, requirements, and schedule in support of the *Energy Policy Act of 2005*, the *Energy Independence and Security Act of 2007*, the *National Hydrogen Energy Vision and Roadmap*, *DOE Strategic Plans*, *DOE Hydrogen and Fuel Cells Program Plan*, *DOE Fuel Cell Report to Congress*, and the *U.S. DRIVE Partnership Plan.*

National Hydrogen Energy Vision and Roadmap

In response to recommendations within the *National Energy Policy*, DOE organized a November 2001 meeting of 50 visionary business leaders and policymakers to formulate a National Hydrogen Vision. ***A National Vision of America's Transition to a Hydrogen Economy – to 2030 and Beyond*** was published in February 2002 as a result of the Hydrogen Vision Meeting. This document summarizes the potential role for hydrogen systems in America's energy future, outlining the shared vision of the market transformation.

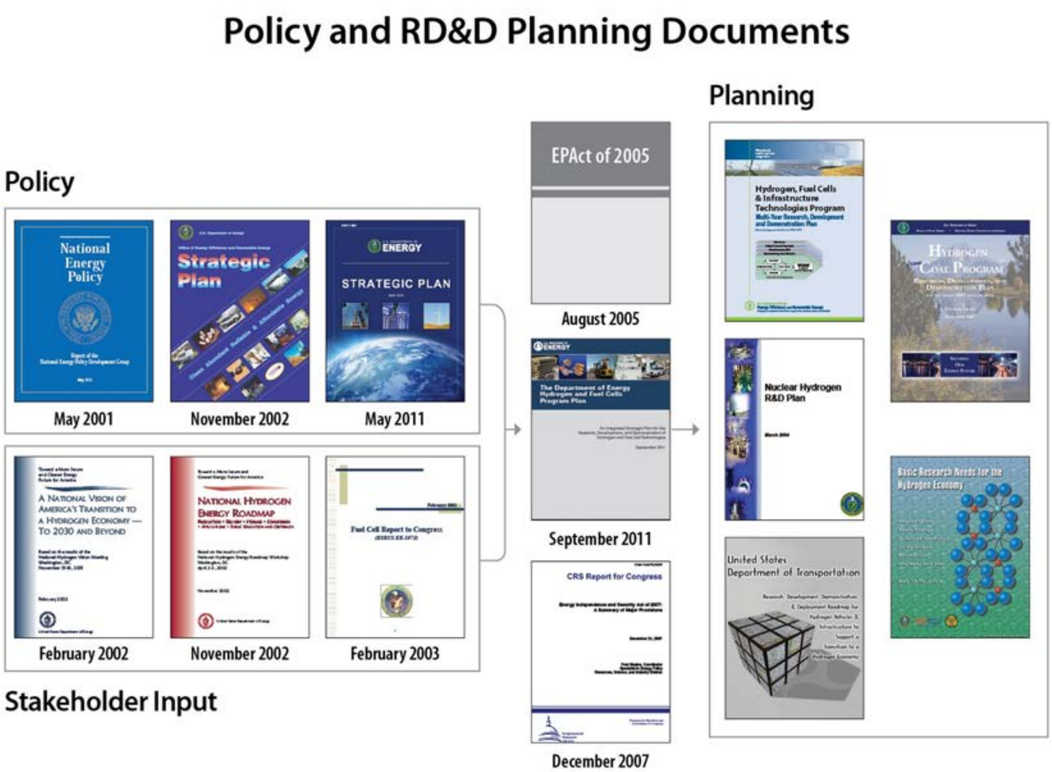

Figure 1.3 Policy and RD&D planning documents

In April 2002, DOE followed up with a larger group of over 200 technical experts from industry, academia, and the national laboratories to develop a ***National Hydrogen Energy Roadmap***. This roadmap, released in November 2002, describes the principal challenges to be overcome and recommends paths forward to achieve the vision.

DOE Strategic Planning

Building on the recommendations of the *National Hydrogen Energy Vision and Roadmap*, DOE's and EERE's strategic plans provide the broad direction under which the Multi-Year RD&D Plan was formulated.

A central goal in the ***Department of Energy's Strategic Plan*** (May 2011) is to protect our national and economic security by promoting a diverse supply and delivery of reliable, affordable and environmentally sound energy. The Program supports DOE's mission as described in the DOE Strategic Plan, and it addresses three of the Department's four key goals:

> Goal 1: Catalyze the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in clean energy technologies
>
> Goal 2: Maintain a vibrant U.S. effort in science and engineering as a cornerstone of our economic prosperity with clear leadership in strategic areas
>
> Goal 4: Establish an operational and adaptable framework that combines the best wisdom of all Department stakeholders to maximize mission success

Hydrogen and Fuel Cells Program Plan

In February 2004, DOE published its ***Hydrogen Posture Plan***, which describes DOE's "plan for successfully integrating and implementing technology research, development and demonstration activities needed to cost-effectively produce, store and distribute hydrogen for use in fuel cell vehicles and electricity generation." Research, development, and demonstration efforts across the DOE Offices of EERE, Nuclear Energy, Fossil Energy, and Science, and the Department of Transportation are described and are consistent with the recommendations in the *National Hydrogen Energy Roadmap*. The *Hydrogen Posture Plan* is the key supporting document underpinning the DOE Hydrogen and Fuel Cells Program. It was updated in fiscal year 2007 to reflect progress and to address the implications of EPACT 2005 and updated and renamed to the ***Hydrogen and Fuel Cells Program* Plan** in fiscal year 2011 to reflect progress and to address the implication of EISA 2007 and the Recovery Act of 2009. The revised plan was posted online in 2010 for public comment, and feedback was incorporated both in the plan and in this document

DOE Fuel Cell Report to Congress

Another document that provides a framework for the Multi-Year RD&D Plan is *DOE's Fuel Cell Report to Congress* (February 2003). This report summarizes the technical and economic barriers to the use of fuel cells in transportation, portable power, stationary, and distributed power generation applications, and also provides a preliminary assessment of the need for public-private cooperative programs to demonstrate the use of fuel cells in commercial-scale applications by 2015. Specifically, the report recommends federally sponsored programs to do the following:

- Focus on advanced materials, manufacturing techniques and other advancements that will lower costs, increase longevity, and improve reliability of fuel cell systems

- Increase emphasis on hydrogen production and delivery infrastructure, storage, codes and standards development, and education
- Develop public-private learning demonstrations, namely, a transportation and infrastructure partnership, as an integrated means of addressing commercialization barriers through collaboration between energy and auto industries.

U.S. DRIVE Partnership

In January 2002, the FreedomCAR Partnership was established as a research and development collaboration between the Department of Energy and the U.S. Council for Automotive Research (USCAR), a partnership formed by Ford Motor Company, Chrysler Corporation, and General Motors Corporation. In September 2003, the Partnership was expanded to the FreedomCAR and Fuel Partnership by bringing the major energy companies (BP America, Chevron Corporation, ConocoPhillips, ExxonMobil Corporation and Shell Hydrogen) to the group. In June 2008, the Partnership was expanded to include two utilities, DTE Energy and Southern California Edison. In May 2011, the Partnership was expanded once again to include the Electric Power Research Institute and Tesla Motors and was renamed U.S. DRIVE Partnership (U.S. DRIVE) where DRIVE represents Driving Research and Innovation in Vehicle efficiency and Energy sustainability.

U.S. DRIVE facilitates frequent and detailed pre-competitive technical information exchange on a broad portfolio of technologies, including hydrogen and fuel cells. By providing a framework for discussing RD&D needs, developing technology roadmaps, and evaluating RD&D progress, U.S. DRIVE helps accelerate RD&D progress, avoid duplication of efforts, and ensure that DOE RD&D targets support industry commercialization needs. These technologies will reduce the dependence of the nation's personal transportation system on imported oil and minimize harmful vehicle emissions, without sacrificing mobility and vehicle choice.

Energy Policy Act of 2005 and Energy Independence and Security Act of 2007

The Multi-Year RD&D Plan also directly supports the *Energy Policy Act of 2005* and the *Energy Independence and Security Act of 2007*. The Plan serves not only to establish the milestones and tasks of the programs, but also reports goals, challenges, and progress to the Secretary of Energy, Congress, and stakeholders. These historic pieces of legislation support many of the principles outlined in the *National Energy Policy* to strengthen our nation's electricity infrastructure, reduce dependence on foreign oil, increase conservation, and expand the use of clean, renewable energy.

Title VIII of EPACT 2005 focuses on hydrogen and Title I of EISA 2007 focuses on improved vehicle fuel economy including fuel cells and reflects strong Congressional support for research and development of hydrogen and fuel cell technologies. These two Acts make the long-term commitment necessary for a market transformation by authorizing the Hydrogen and Fuel Cell Technologies Program through 2020 and by requiring coordinated plans and documentation of the Program's activities.

1.5 Scope of Multi-Year RD&D Plan

Implementation of the FCT Program will be governed by its Multi-Year RD&D Plan, which covers the period 2004 through 2020 and describes the activities of the FCT Program. The Plan addresses technologies for hydrogen production, delivery, storage and infrastructure, as well as fuel cells for transportation, stationary, and portable power applications. Government resources for these RD&D activities will be fully leveraged through partnerships with industry as the nation moves toward hydrogen as an energy carrier. The Plan's aim is to bring technologies to the point where early adopters can begin implementation and manufacturers can invest in plant and capital equipment with confidence that markets are emerging.

Planned activities are focused on technologies for hydrogen production, delivery, and storage; fuel cells for transportation, portable, and stationary applications; technology validation; codes and standards; safety; education; systems analysis; systems integration; manufacturing and market transformation. Goals, objectives, and technical targets are identified through 2020 for each of the sub-programs, and milestones and schedules are identified through 2020. While the government's role is essential to advancing hydrogen and fuel cell technologies in the early stages of development, once the technical targets are validated in a systems context, the government's role will diminish and industry will complete commercialization. The government will help by promoting market transformation through policy and incentives and support of early adopter activities. Funding for RD&D in each sub-program will be scaled according to measurable progress and determined needs—as technical and cost targets are met or missed, funding for particular technological approaches will be adjusted. When performance, safety, and cost targets are met, a sub-program's RD&D funding will be redirected as appropriate. If specific performance issues remain at that time, RD&D could be extended if the risk of the continued effort is justified by the potential benefit. To continue moving efficiently toward the goal of technology readiness, the Plan will be updated periodically to reflect technological advances, system changes, and policy decisions.

1.6 Program Evaluation

The Department of Energy commissioned the National Academies to review the June 2003 draft RD&D Plan. Almost all of the resulting report's recommendations have been incorporated into the FCT Program. Some of the significant points in the report were as follows:

- Establish a comprehensive systems analysis capability to drive technology development decisions relevant to energy, environmental and economic criteria
- Establish an independent systems integration effort to ensure that the various sub-programs (such as Production, Delivery, and Storage) fit together seamlessly
- Increase emphasis on hydrogen safety to understand how hydrogen systems must be designed, built, and operated differently from today's vehicles and infrastructure
- Engage universities to play a much bigger role in the research program.

The actions taken in response to these recommendations include the enhancement of the FCT Program's systems analysis capabilities, establishment of a Systems Integration Office, creation of a hydrogen safety experts panel to help DOE audit safety plans and practices within the FCT Program; and the competitive selection of numerous universities to carry out hydrogen and fuel cell technologies research.

In addition, DOE created the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) in 2006. The Committee's responsibility, as required by EPACT, is to provide technical and programmatic advice to the Energy Secretary on hydrogen research, development, and demonstration efforts. The Program's Annual Merit Review and Peer Evaluation provides an additional means of assessment. At this annual meeting, projects within the Program are reviewed by experts. These reviews may be used to make changes in the scope and direction of the projects.

1.7 Program Coordination

The DOE Hydrogen and Fuel Cells Program coordinates its activities with other Federal agencies, with States and regional entities by participating in organizations such as the California Fuel Cell Partnership, and with other countries through the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) and the International Energy Agency and its relevant implementing agreements.

In November 2003, the United States hosted the inaugural Ministerial meeting of IPHE, which brought together 16 countries and the European Union and helped launch international cooperation on vital hydrogen-related research activities. Additional meetings, including ministerial meetings, have enabled the IPHE to provide a mechanism to organize, evaluate, and coordinate multinational research, development, and deployment programs that advance the transition to a global market transformation. The IPHE leverages resources; identifies promising directions for RD&D and commercial use; provides technical assessments for policy decisions; prioritizes, identifies gaps, and develops common recommendations for international codes and standards and safety protocols. Additionally, the IPHE maintains communications with the key stakeholders to foster public-private collaboration that addresses the technological, financial, and institutional barriers to a cost-competitive, standardized, widely accessible, safe, and environmentally benign market transformation.

In accordance with the *Energy Policy Act of 2005*, the Interagency Hydrogen and Fuel Cell Technical Task Force was formed to work toward safe, economical, and environmentally sound hydrogen and fuel cell technologies by coordinating the efforts of the Office of Science and Technology Policy; the Departments of Energy, Transportation, Defense, Commerce, and Agriculture; the Office of Management and Budget; National Science Foundation; Environmental Protection Agency; National Aeronautics and Space Administration; and other agencies as appropriate. The Task Force created a website at www.hydrogen.gov to provide information on all Federal hydrogen and fuel cell activities. An interagency working group under the Task Force meets monthly to coordinate efforts among Federal agencies.

2.0 Program Benefits

Fuel cells provide power and heat cleanly and efficiently, using diverse domestic fuels, including hydrogen produced from renewable resources and biomass-based fuels. Fuel cells can be used in a wide range of stationary, transportation, and portable-power applications. Hydrogen can also function as an energy storage medium for renewable electricity.

Hydrogen and fuel cell technologies are being developed by the U.S. Department of Energy's (DOE) Hydrogen and Fuel Cells Program, which includes the Office of Energy Efficiency and Renewable Energy's Fuel Cell Technologies (FCT) Program, the Office of Fossil Energy, the Office of Nuclear Energy, and the Office of Science. The FCT Program's sponsored research and development (R&D) are capable of providing benefits in three main areas: 1) ***energy security*** – through the production of a fuel that can be produced domestically from a diversity of feedstocks, 2) ***environmental benefits*** – through the reduction of the environmental impact (local criteria pollutants and regional/global greenhouse gases) of transportation applications and stationary markets, and 3) ***economic competitiveness*** – advantages ensuing from the markets that these technologies serve.

Achieving FCT sub-program objectives enable hydrogen and fuel cell technologies that are not just competitive with conventional technologies in both performance and cost, but also provide additional energy and environmental benefits and make market acceptance feasible.

2.1 National Benefits

Fuel cells offer a broad range of benefits for the environment, for our nation's energy security, and for our domestic economy. These benefits include:

1. reduced greenhouse gas emissions;
2. reduced oil consumption;
3. expanded use of renewable power (through use of hydrogen for energy storage and transmission);
4. highly efficient energy conversion;
5. fuel flexibility (use of diverse, domestic fuels, including clean and renewable fuels);
6. reduced air pollution; and
7. highly reliable grid-support.

Fuel cells also have numerous advantages that make them appealing for end-users, including: quiet operation, rapid recharging, low maintenance needs, and high reliability. In addition to using hydrogen, fuel cells can provide power from a variety of other fuels, including natural gas and renewable fuels such as methanol or biogas.

Fuel cells provide these benefits and address critical challenges in all energy sectors—commercial, residential, industrial, and transportation. They are used in a variety of applications, including: distributed energy and combined heat and power (CHP) systems; backup power systems; systems for storing and transmitting renewable energy; portable power; auxiliary power for trucks, aircraft, rail, and ships; specialty vehicles, such as forklifts; and passenger and freight vehicles, including cars, light trucks, buses, and short-haul trucks.

Widespread use of hydrogen and fuel cells would play a substantial role in overcoming our nation's key energy challenges, including significant reductions in greenhouse gas emissions and oil consumption as well as improvements in air quality. A study by the National Academies[1] has shown that by 2050, fuel cell electric vehicles (FCEVs) could provide the largest reduction in emissions and oil consumption of any advanced vehicles. In addition, hydrogen and fuel cells provide a significant economic opportunity for the United States, with various studies projecting up to 900,000 new jobs in the U.S. by 2030–2035.[2] Growing interest and investment among leading world economies such as Germany, Japan, and South Korea, underscore the global market potential for these technologies and the need for continued investment for industry to remain competitive.

2.1.1 Energy Security Benefits

A significant challenge to the nation's energy security is our increasing use of petroleum (See Figure 2.1.1.1). Because more than 70% of our petroleum consumption occurs in the transportation sector[3] (with most of the remainder being used in various industrial processes), this will be where fuel cells will have the most substantial energy security benefits.

The National Academies' 2008 study *Transitions to Alternative Transportation Technologies – A Focus on Hydrogen* projects that the use of fuel cell vehicles could reduce gasoline consumption by 24% (or 34 billion gallons per year) in 2035 and 69% (or 109 billion gallons per year) in 2050.[4] If a portfolio of technologies was employed, gasoline consumption could be reduced nearly 60% by 2035 and 100% by 2050. As with their carbon dioxide (CO_2) reduction estimates, the National Academy of Sciences (NAS) found that fuel cell vehicles would provide the largest reductions in gasoline use by 2050, and that no single technology approach could achieve total elimination of gasoline consumption alone (Figure 2.1.1.1).

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[1] *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen*, National Research Council of the National Academies, 2008, www.nap.edu/catalog.php?record_id=12222

[2] "Defining, Estimating, and Forecasting the Renewable Energy and Energy Efficiency Industries in the U.S. and in Colorado," American Solar Energy Society, December 2008, http://www.cleanenergycongress.org/system/medias/33/original/CO_Jobs_Final_Report_December2008.pdf; "Effects of a Transition to a Hydrogen Economy on Employment in the United States—Report to Congress." U.S. Department of Energy, July 2008, www.hydrogen.energy.gov/pdfs/epact1820_employment_study.pdf; "A Compendium of Job Estimates in the Fuel Cell Industry," Fuel Cells 2000, February 2011, http://fuelcells.org/Fuel_Cell_Industry_Job_Estimates.pdf; "Fuel Cell Industry Could Create 700,000 Green Manufacturing Jobs by 2020," Fuel Cell Today, January 14, 2010, http://www.fuelcelltoday.com/news-events/news-archive/2010/january/fuel-cell-industry-could-create-700,000-green-manufacturing-jobs-by-2020

[3] *Annual Energy Review 2010*, Energy Information Administration, Figure 5.13a Petroleum Consumption Estimates by Sector, August 2011, http://www.eia.gov/totalenergy/data/annual/pdf/sec5_3031.pdf

[4] *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen*, National Research Council of the National Academies, 2008, www.nap.edu/catalog.php?record_id=12222

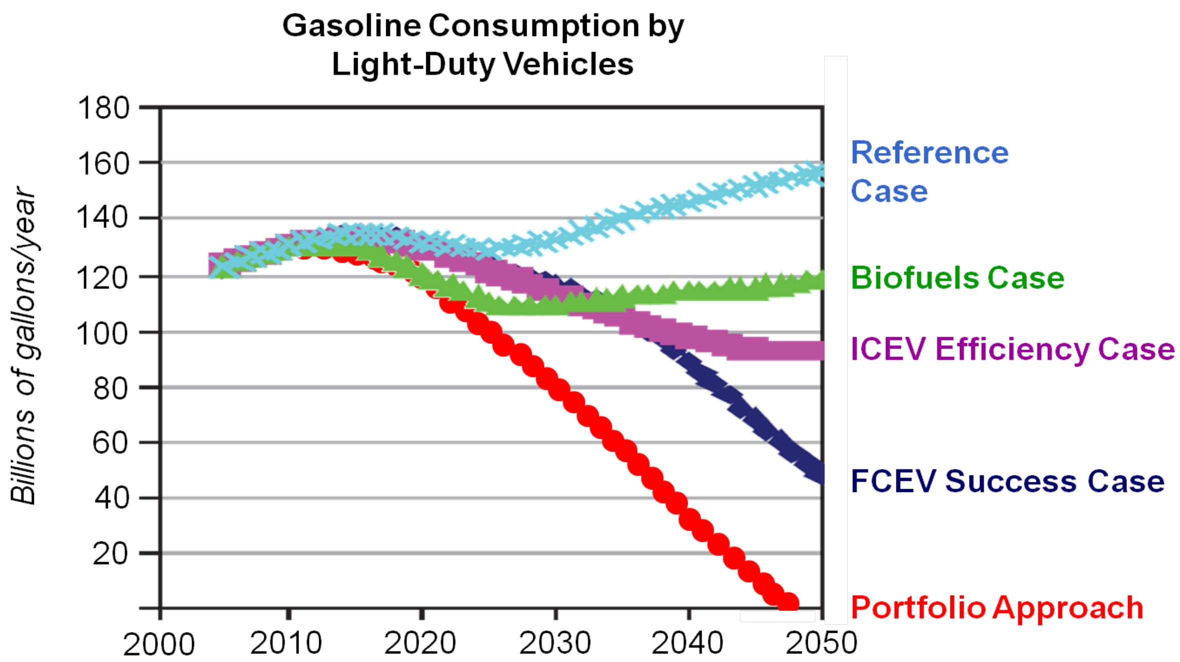

Figure 2.1.1.1. Reduced Oil Consumption. Significant reductions in the nation's consumption of oil could be achieved through the use of fuel cells—making substantial gains toward the long-term goal of independence from imported oil. The portfolio approach shown here assumes a significant introduction of fuel cell electric vehicles (FCEVs) to the market, the maximum practical rate of improvements in internal combustion engine vehicle (ICEV) efficiency (including hybrid electric vehicles - HEVs), and large-scale use of biofuels. Graph adapted from the National Academies report, "Transitions to Alternative Transportation Technologies—A Focus on Hydrogen."[5]

[5] Adapted from: *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen*, National Research Council of the National Academies, 2008, www.nap.edu/catalog.php?record_id=12222; **Reference Case is** based on the Energy Information Administration's 2008 Annual Energy Outlook high-oil-price scenario; fuel cell electric vehicles **(FCEV) Success Case** ("Hydrogen Success Case" in the NAS report) assumes that development programs are successful and policies are implemented to ensure commercial deployment; internal combustion engine vehicle (**ICEV) Efficiency Case** assumes maximum practical rate of efficiency improvement for ICEVs [including hybrid electric vehicles (HEVs)], resulting in more than doubling in fuel economy by 2050; **Biofuels Case** assumes large-scale use of biofuels from crop and cellulosic feedstocks, at a maximum practical production rate; **Portfolio Approach** assumes that all of these advances are pursued simultaneously.

2.1.2 Environmental Benefits (Climate Change and Air Quality)

While addressing the energy security issue, we must also address our environmental viability. Air quality is a major national concern. As shown in Figure 2.1.2.1, personal vehicles and electric power plants are significant contributors to the Nation's air quality problems. Most states are now developing strategies for reaching national ambient air quality goals and bringing their major metropolitan areas into attainment with the requirements of the Clean Air Act. The state of California has been one of the most aggressive in its strategies and has launched a number of programs targeted at improving urban air quality.

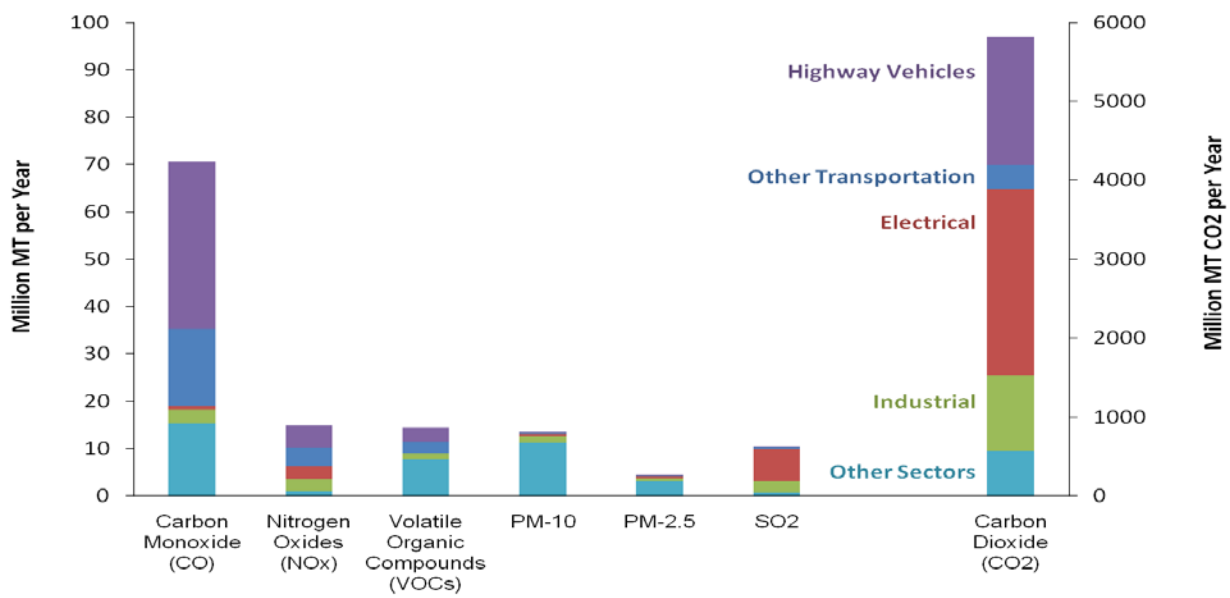

Figure 2.1.2.1 Emissions from Fossil Fuels in the United States. Fossil fuels are major contributors to air pollution and greenhouse gas emissions.[6] Fuel cells can convert conventional fossil fuels and low- to zero-carbon renewable fuels into usable energy with significantly reduced emissions.

Substantial environmental benefits from fuel cells will come from their use in the stationary power and transportation sectors, where the markets are very large and a significant amount of energy is consumed.

In the stationary power sector, the use of fuel cells in distributed applications can provide reductions in emissions over both distributed and central generation technologies. The high electrical efficiency of fuel cells will enable lower emissions when compared with conventional distributed power

[6] Sources: U.S. Environmental Protection Agency, *National Emissions Inventory Air Pollutant Emissions Trends Data*, 2008, www.epa.gov/ttnchie1/trends/; Energy Information Administration, *Annual Energy Outlook 2010*, Table 18: Carbon Dioxide Emissions by Sector and Source, www.eia.doe.gov/oiaf/aeo/aeoref_tab.html; Energy Information Administration, *Emissions of Greenhouse Gases in the United States 2008*, December 2009, www.eia.doe.gov/oiaf/1605/ggrpt/pdf/0573%282008%29.pdf

technologies such as internal combustion engines (ICEs) or turbines. Emissions reductions can be even more substantial through the use of CHP for distributed energy—which can be greatly expanded by fuel cells, due to their clean and quiet operation. Fuel cells, like other distributed energy technologies, can achieve very high efficiencies when used in CHP systems, far surpassing those of even the most advanced centralized generation facilities. Even greater emissions reductions are possible when fuel cells use biogas, which has near-zero life-cycle emissions.

In addition, hydrogen has the potential to contribute to reducing emissions by functioning as an energy storage medium that helps enable the expansion of power generation from intermittent renewable resources, such as wind, solar, and ocean energy. Hydrogen can be produced through electrolysis, using surplus electricity (when generation exceeds demand), and later converted back into electricity, using fuel cells or turbines, when demand exceeds generation. In addition to helping balance generation and load, energy storage at the regional level can also increase network stability and power quality and improve frequency regulation. In addition, hydrogen produced by surplus renewable power may also improve the economics of renewable power installations, as these facilities may gain a valuable revenue stream by selling their surplus hydrogen for use in fuel cell vehicles, stationary fuel cells, and other applications.

For transportation applications, the greatest impact will come from the use of fuel cells in light-duty vehicles, which suffer from the least efficient use of energy by any major sector of our economy. The National Academies' 2008 "Transitions" study found that FCEVs could reduce CO_2 emissions from the light-duty vehicle fleet by 19% in 2035 and 60% (or more than one billion metric tons per year) in 2050. Furthermore, the same study found that CO_2 emissions from light duty vehicles could be reduced by nearly 50% in 2035 and nearly 90% in 2050 using a portfolio of technologies including fuel cells, improved vehicle efficiency (for ICEs and hybrid systems), and biofuels (Figure 2.1.2.2). Although plug-in hybrid-electric vehicles (PHEVs) and biofuels have the potential to achieve impacts sooner than fuel cell vehicles, the NAS has concluded that fuel cells would provide the largest reductions in emissions by 2050, and that no single technology approach could achieve an 80% reduction in CO_2 emissions[7] alone.

[7] The Obama-Biden Plan, available at http://change.gov/agenda/energy_and_environment_agenda/.

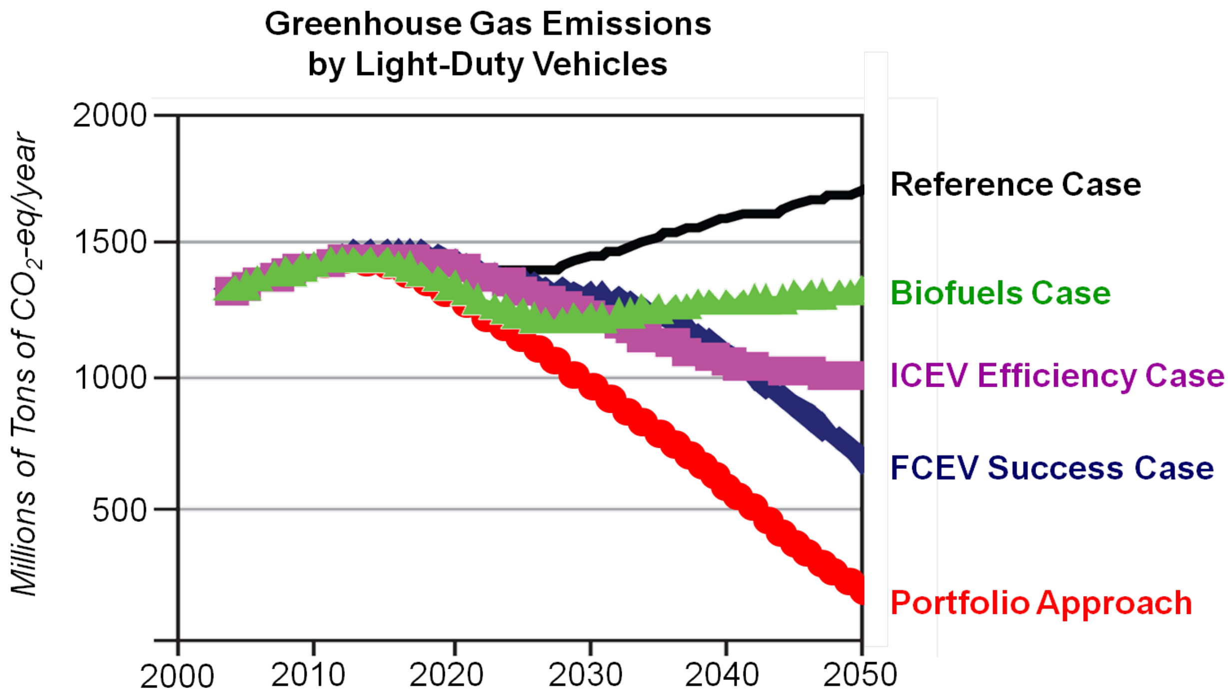

Figure 2.1.2.2. Reduced Greenhouse Gas Emissions. Significant reductions in greenhouse gas emissions could be achieved through the use of fuel cells—making substantial gains toward the goal of 80% reduction in CO_2 emissions[8] by 2050. The portfolio approach shown here assumes a significant introduction of FCEVs to the market, the maximum practical rate of improvements in ICEV efficiency (including hydrid electric vehicle (HEVs)), and large-scale use of biofuels. Graph adapted from the National Academies report, Transitions to Alternative Transportation Technologies—A Focus on Hydrogen.[9]

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[8] The Obama-Biden Plan, available at http://change.gov/agenda/energy_and_environment_agenda/.

[9] *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen*, National Research Council of the National Academies, 2008, www.nap.edu/catalog.php?record_id=12222; **Reference Case is** based on the Energy Information Administration's 2008 Annual Energy Outlook high-oil-price scenario; **FCEV Success Case** ("Hydrogen Success Case" in the NAS report) assumes that development programs are successful and policies are implemented to ensure commercial deployment; **ICEV Efficiency Case** assumes maximum practical rate of efficiency improvement for ICEVs [including hybrid electric vehicles (HEVs)], resulting in more than doubling in fuel economy by 2050; **Biofuels Case** assumes large-scale use of biofuels from crop and cellulosic feedstocks, at a maximum practical production rate; **Portfolio Approach** assumes that all of these advances are pursued simultaneously.

2.1.3 Economic Competitiveness Benefits

The potential for long-term employment growth from the widespread use of fuel cells in the United States is substantial. A study commissioned by DOE found that successful widespread market penetration by fuel cells could help to revitalize the manufacturing sector and could add more than 180,000 net new jobs to the U.S. economy by 2020, and more than 675,000 net new jobs by 2035 (Figure 2.1.3.1).[10] A separate study, conducted by the American Solar Energy Society to quantify the economic benefits of renewable energy and energy efficiency technologies, found that gross revenues in the U.S. fuel cell and hydrogen industries could reach up to $81 billion/year by 2030, with total employment (direct and indirect) reaching more than 900,000 (Figure 2.1.3.2)—this is based on the most aggressive scenario, which represents what is "technologically and economically feasible." The base-case or "business as usual" case of this study shows these industries achieving about $9 billion/year in gross revenues by 2030, with more than 110,000 new jobs created.

Analyses of the near- to mid-term market for fuel cells also indicate substantial potential growth. The latest estimate of current fuel cell industry employment by Fuel Cells 2000 indicates more than 13,000 total direct fuel cell industry jobs worldwide, with more than 25,000 associated supply-chain jobs.[11] Fuel Cell Today's 2010 Industry Review predicts that by 2020 the global fuel cell industry could create over 700,000 new jobs in manufacturing, and as many as 300,000 additional jobs in installation, service, and maintenance.[12] In addition, a study conducted by the Connecticut Center for Advanced Technology[13] estimates that the global fuel cell/hydrogen market could reach maturity over the next 10 to 20 years; within this timeframe, the report estimated that global revenues for the hydrogen and fuel cell markets would reach $43 – $139 billion annually, including the following key market sectors:

- **$14 – $31 billion/year for stationary power**
- **$11 billion/year for portable power**
- **$18 – $97 billion/year for transportation**

To achieve such growth and enable U.S. competitiveness, sustained funding is required for research, development, and demonstration (RD&D) to build and strengthen core competencies in areas such as catalysis, advanced materials, and manufacturing technologies. Investments will also be needed at the university level for developing human capital and in industry for stimulating early markets to enhance manufacturing capabilities and help achieve economies of scale.

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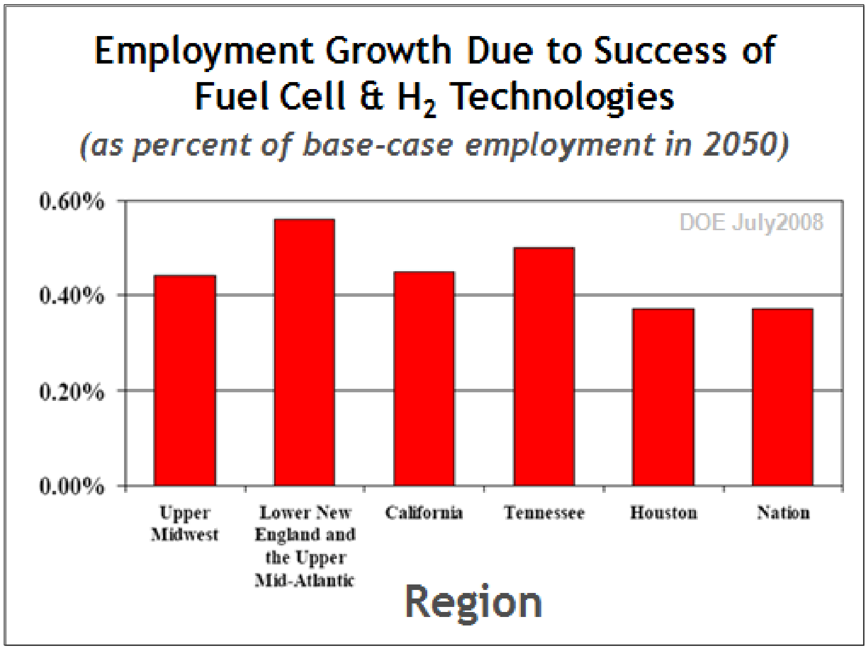
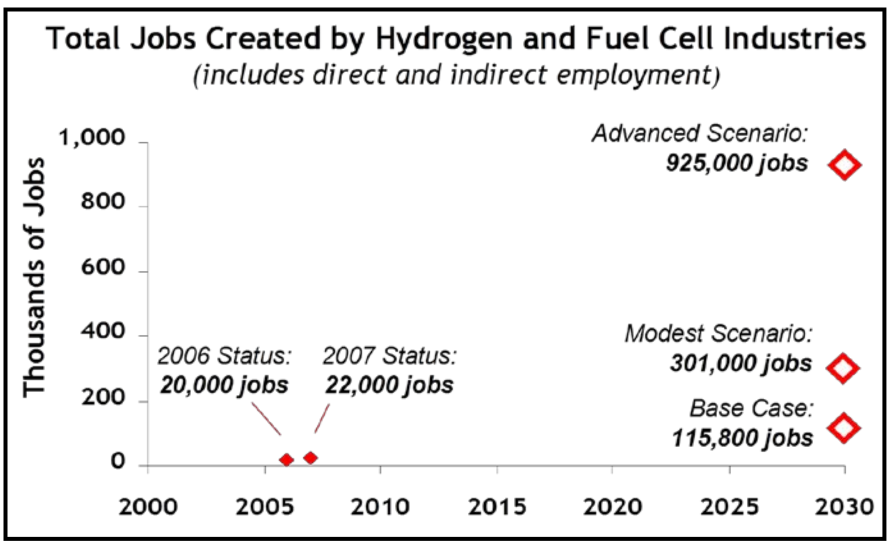
[10] "Effects of a Transition to a Hydrogen Economy on Employment in the United States—Report to Congress." U.S. Department of Energy, July 2008, www.hydrogen.energy.gov/pdfs/epact1820_employment_study.pdf. Key assumptions include: By 2035, fuel cell electric vehicles ramp up to 89% of light-duty vehicle (LDV) sales (60% of stock) and 20% of LDV (7% of stock), for the aggressive and less aggressive scenarios, respectively. By 2035, stationary fuel cells ramp up to 5% and 2% of new electricity demand, for the aggressive and less aggressive scenarios, respectively.

[11] A Compendium of Job Estimates in the Fuel Cell Industry," Fuel Cells 2000, February 2011, http://fuelcells.org/Fuel_Cell_Industry_Job_Estimates.pdf.

[12] "Fuel Cell Industry Could Create 700,000 Green Manufacturing Jobs by 2020," Fuel Cell Today, January 14, 2010, http://www.fuelcelltoday.com/news-events/news-archive/2010/january/fuel-cell-industry-could-create-700,000-green-manufacturing-jobs-by-2020.

[13] *Fuel Cell Economic Development Plan*, Connecticut Center for Advanced Technology, Inc. (produced for the Connecticut Department of Economic and Community Development), January 2008, http://energy.ccat.us/uploads/documents/energy/Fuel_Cell_Plan_1-31-08_DECD.pdf.





Figures 2.1.3.1 and 2.1.3.2: Employment Growth Due to Hydrogen and Fuel Cell Technologies. Studies by DOE (upper chart) and the American Solar Energy Society (ASES) (bottom chart) show the potential for substantial growth in employment due to the successful widespread commercialization of hydrogen and fuel cells. The DOE study projects up to 675,000 net new jobs by 2035 and the ASES study projects up to 925,000 jobs created by 2030.[14, 15]

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[14] "Defining, Estimating, and Forecasting the Renewable Energy and Energy Efficiency Industries in the U.S. and in Colorado," American Solar Energy Society and Management Information Services, Inc., December 2008, http://www.cleanenergycongress.org/system/medias/33/original/CO_Jobs_Final_Report_December2008.pdf

[15] "Effects of a Transition to a Hydrogen Economy on Employment in the United States: Report to Congress," U.S. Department of Energy, July 2008, www.hydrogen.energy.gov/pdfs/epact1820_employment_study.pdf.

2.2 Benefits of Specific Fuel Cell Applications

Power Generation

Stationary fuel cell systems can power a broad range of commercial, industrial, and residential applications. These systems have the potential to supplement or replace any application presently served by the electrical grid. Fuel cell systems can meet the change requirements of critical backup and remote power applications.

Commercial power generation includes telecommunications sites, remote communications facilities, office buildings, industrial plants, laboratories, hospitals, computer centers, and small businesses, among many others.

Fuel cell systems can be used as backup power generators, primary power generators, or in combination with the electrical grid and can provide high reliability. These systems can power all or part of the electrical requirements, serving the total power demand, or that of selected critical circuits such as those for computer rooms, telecommunications, emergency response, life support, national defense, and homeland security. Commercial fuel cell systems can provide intermittent power during periods of high demand and high grid power cost. This "peak shaving" has the ability to save money to commercial customers.

Large coal-based SECA (Solid State Energy Conversion Alliance) solid oxide fuel cell systems facilitate CO_2 sequestration, allowing very low CO_2 emissions, even from coal. Researchers are working on projects that will achieve these results at a cost of electricity no higher than today.

Distributed Energy (Including Combined Heat and Power)

The advantages of fuel cells for distributed power generation include: elimination of transmission and distribution losses, low emissions, increased reliability, and reduction in bottlenecks and peak demand on the electric grid. They can also provide the very large efficiency improvements inherent in CHP installations, with the potential to use more than 80% of the fuel energy, compared to the 45% to 50% overall efficiency of using electricity from coal or natural gas plants. The thermal energy from on-site natural-gas combustion (Figure 2.2.1)[16] is an added bonus. The lack of criteria pollutant emissions makes fuel cells one of the best options for use in non-attainment zones and residential and commercial areas (Figure 2.2.2). Other benefits include nearly silent and vibration-free operation, ability to use the existing natural gas fuel supply as well as biogas from sources such as wastewater treatment plants and landfill gas facilities, low operation and maintenance requirements, and excellent transient response and load following performance.

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[16] *Catalog of CHP Technologies*, U.S. Environmental Protection Agency, December 2008, www.epa.gov/chp/basic/catalog.html.

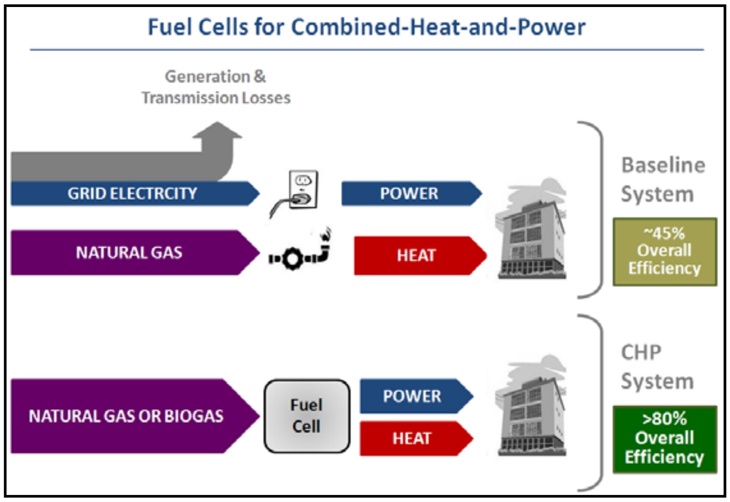


Figure 2.2.1. Fuel Cells for CHP Systems. Fuel cells in CHP installations can provide dramatic improvements in efficiency over conventional grid power and on-site natural gas heat.

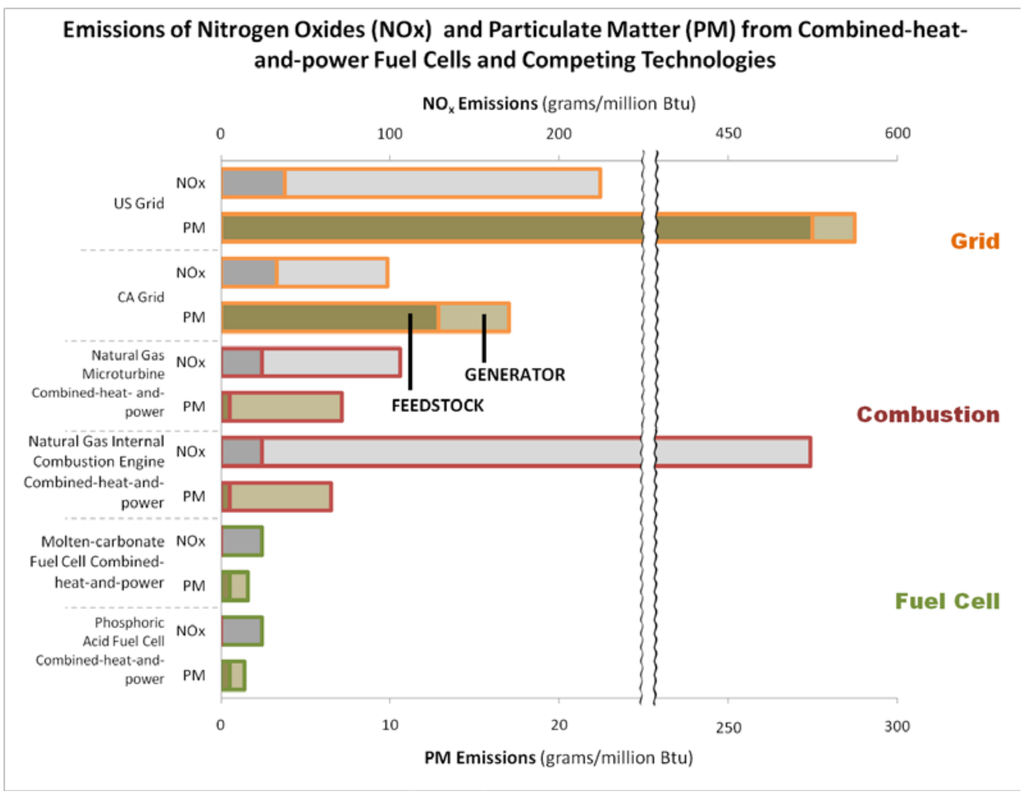
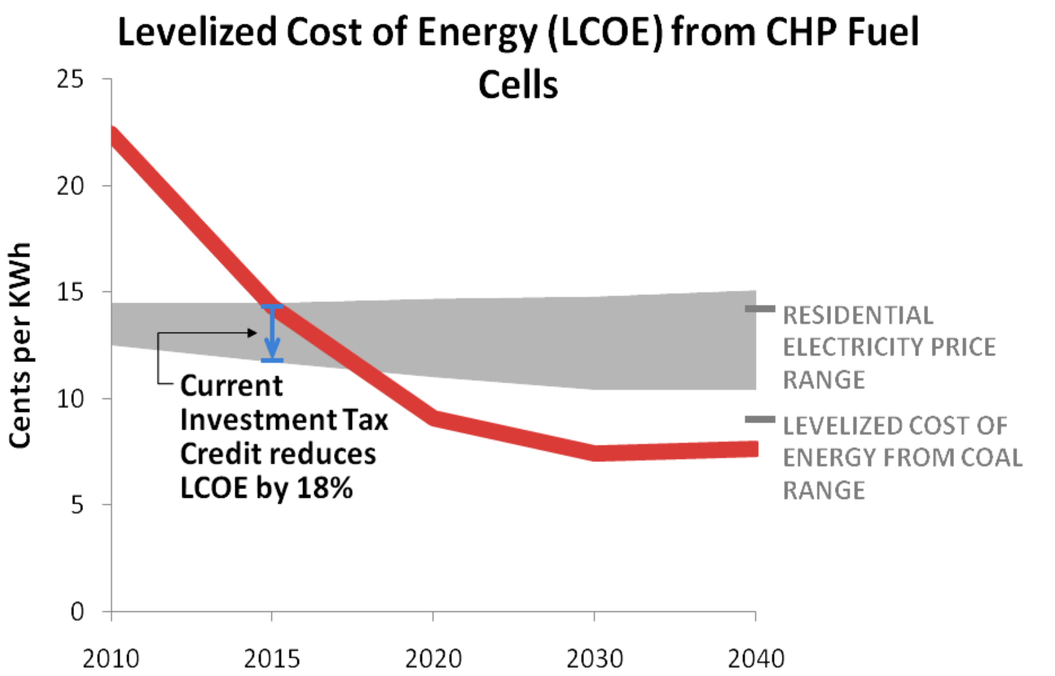


Figure 2.2.2. Criteria Pollutant Emissions from Generating Heat and Power. Fuel cells emit about 75 – 90% less NOx and about 75 – 80% less PM than other CHP technologies, on a life-cycle basis. In addition, similar to other CHP technologies, fuel cells can provide more than 50% reduction in CO_2 emissions, when compared with the national grid.[17]

[17] Wang, MQ; Elgowainy, A; and Han, J. "Life-Cycle Analysis of Criteria Pollutant Emissions from Stationary Fuel Cell Systems," 2010 DOE Annual Merit Review Proceedings

Expected advances in CHP fuel cell systems would make them a cost-competitive option for providing light commercial and residential heat and power. While the levelized cost of energy (LCOE) depends on a number of assumptions, Figure 2.2.3 provides an example of the potentially significant reductions in overall LCOE that can be achieved through technology advancements that achieve cost reductions and efficiency improvements in fuel cell CHP systems.



Note: no carbon costs assumed

ASSUMPTIONS	2010	2015	2020	2030	2040	2050
Total Efficiency (HHV)	72.7%	74.8%	78.0%	84.0%	85.2%	86.4%
CHP Electrical Efficiency (HHV)	39.7%	42.4%	45.1%	46.9%	48.7%	48.7%
Capital costs w/o stack replacement ($/kWe)	7,200	4,600	2,000	1,000	960	960
Fixed O&M Costs ($/kWe-yr)	302	204	108	68	67	67
Variable O&M Costs ($/MWh)	13.7	8.8	3.8	1.9	1.8	1.8

Figure 2.2.3. Example of Levelized Cost of Energy from Fuel Cell CHP.[18] (Note: no carbon costs assumed.)

[18] Based on analysis conducted by National Renewable Energy Laboratory (NREL); and *Annual Energy Outlook 2009*, Energy Information Administration.

Backup Power

Fuel cells are emerging as an economically viable option for providing backup power, particularly for telecommunications towers, data centers, hospitals, and communications facilities for emergency services. Compared with batteries, fuel cells offer longer continuous run-times (two- to ten-times longer) and greater durability in harsh outdoor environments under a wide range of temperature conditions. Compared with conventional internal combustion generators, fuel cells are quieter and have low to zero emissions (depending on fuel source). Because fuel cells are modular, backup power systems that use them can be more readily sized to fit a wider variety of sites than those using conventional generators. They also require less maintenance than both generators and batteries.

In a study for DOE, Battelle Memorial Institute found that fuel cells can provide more than 25% savings (when compared with batteries) in the life-cycle costs of specific backup power installations for emergency response radio towers (excluding additional savings due to existing tax incentives for fuel cells). In the United States, there were about 200,000 backup power systems for wireless communications towers a few years ago, and this number has been rapidly increasing.[19] If potential new regulations—requiring longer run-times for these systems—are put in place, fuel cells might be a competitive option for all of these sites. In addition, many developing countries are experiencing explosive growth in new installations of cell phone towers. For example, the number of towers in India is expected to grow from a current base of 240,000 to 450,000 in just three years.[20] As the world's leading supplier of backup-power fuel cells, the United States stands to benefit greatly from growing worldwide demand.

Auxiliary Power

Fuel cells can provide clean, efficient auxiliary power for trucks (Figure 2.2.4), recreational vehicles, marine vessels (yachts, commercial ships), airplanes, locomotives, and similar applications that have significant auxiliary power demands. In many of these applications, the primary motive-power engines are often kept running solely for auxiliary loads resulting in significant additional fuel consumption and emissions.

For the approximately 500,000 long-haul Class 7 and Class 8 trucks in the United States, emissions during overnight idling have been estimated to be 10.9 million tons of CO_2 and 190,000 tons of nitrogen oxides (NOx) annually.[21] The use of auxiliary power units (APUs) for Class 7–8 heavy trucks to avoid overnight idling of diesel engines could save up to 280 million gallons of fuel per year and avoid more than 92,000 tons of NOx emissions.[22]

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[19] "Fuel Cells in Distributed Telecomm Backup," Citigroup Global Markets, August 24, 2005; *Identification and Characterization of Near-Term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets*, Battelle Memorial Institute, April 2007. http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pemfc_econ_2006_report_final_0407.pdf

[20] T. Worthington, "India Telecom Towers, Build 'em High," Reuters, September 1, 2009, http://in.reuters.com/article/2009/09/01/idINIndia-42120920090901.

[21] Nicholas Lutsey, Christie-Joy Brodrick & Timothy Lipman, "Analysis of Potential Fuel Consumption and Emissions Reduction from Fuel Cell Auxiliary Power Units (APUs) in Long Haul Trucks," Elsevier Science Direct, Energy 32, September 2005.

[22] Estimate for 475 thousand trucks using fuel consumption and NOx emissions reported in L. Gaines and C. Hartman, "Energy Use and Emissions Comparison of Idling Reduction Options for Heavy-Duty Diesel Trucks," Center for Transportation Research, Argonne National Laboratory, November 2008; and using the reported 28 hours per week for night idling from *Idle Reduction Technology: Fleet Preferences Survey*, American Transportation Research Institute (prepared for New York State Energy Research and Development Authority), February 2006

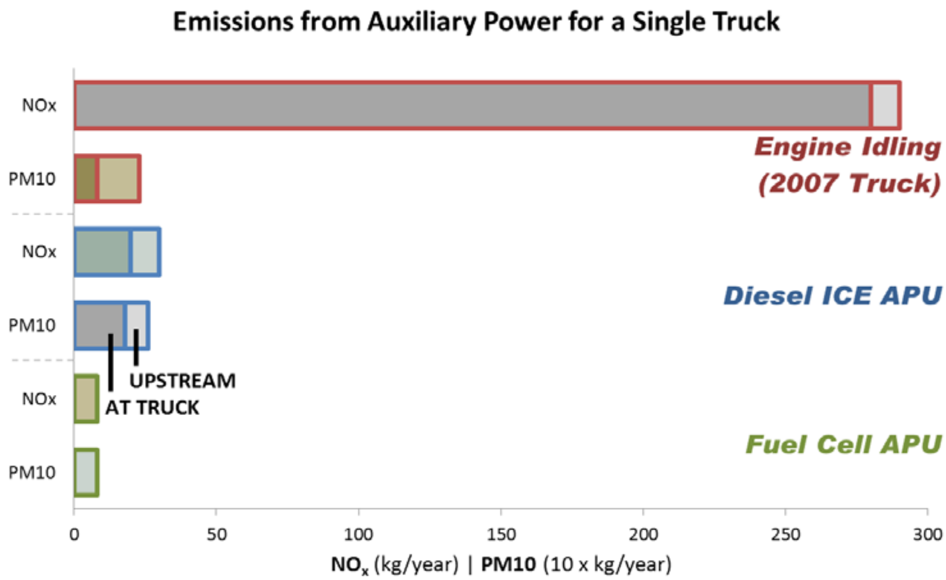

Figure 2.2.4. Emissions of Criteria Pollutants from Auxiliary Power for Trucks. Fuel cell auxiliary power units (APUs) can achieve significant reductions in criteria pollutant emissions over diesel internal combustion engine APUs and truck engine idling, while still using the truck's existing supply of diesel fuel. A key benefit of fuel cells is that they only emit negligible NOx and particulate matter at the point of use (at the truck) which can have substantial benefits for local air quality. In addition, fuel cell APUs can achieve more than 60% reduction in CO_2 emissions over truck engine idling.[23]

Pollution from commercial cargo ships has also become a matter of concern, as these vessels rely almost exclusively on diesel generators for their power while in port. According to the U.S. Environmental Protection Agency (EPA), commercial ships are responsible for more than 15% of the ozone concentration and particulate matter in some port areas. In addition, EPA has stated that marine diesel engines "are significant contributors to air pollution in many of our nation's cities and coastal areas," emitting substantial amounts of NOx and particulate matter.[24] Idling of commercial aircraft engines is also responsible for excessive emissions, as the use of these engines at low power settings results in incomplete combustion, which produces carbon monoxide and unburned hydrocarbons. [25]

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[23] L. Gaines and C. Hartman, "Energy Use and Emissions Comparison of Idling Reduction Options for Heavy-Duty Diesel Trucks," Center for Transportation Research, Argonne National Laboratory, November 2008; fuel cell APUs on freight trucks are expected to emit an insignificant amount of criteria pollutants at the truck, even when diesel is assumed to be the input feed to the on-board reformer. The upstream emissions (from activities preceding the use in APU or truck engine—i.e., crude oil extraction, transportation and refining, diesel transportation, etc.) of diesel are the same for each unit volume used by the fuel cell or by the conventional APU. Furthermore, it was conservatively estimated that a fuel cell APU would consume a similar amount of diesel as an ICE APU, resulting in comparable overall CO_2 emissions. Actual CO_2 emissions by fuel cell APUs are likely to be lower, and improvements in the efficiency of diesel reformers and fuel cells will result in further reductions.

[24] "Diesel Boats and Ships," U.S. Environmental Protection Agency Web site, http://www.epa.gov/otaq/marine.htm

[25] "Safeguarding Our Atmosphere," National Aeronautics and Space Administration Glenn Research Center Web site, accessed October 7, 2010, www.nasa.gov/centers/glenn/about/fs10grc.html.

While aircraft that have APUs rely less on main engine idling, the gas turbine APUs that are used operate at low efficiency and emit criteria pollutants, contributing significantly to local pollution at airports. Additionally, the high auxiliary power loads required during flight operations—up to 500 kW on larger commercial aircraft—are responsible for a significant portion of in-flight emissions. APU fuel cells installed on aircraft can reduce emissions during flight as well as gate and taxiing operations. Analysis of Air Force cargo planes found that the use of fuel cell APUs could result in a 2% to 5% reduction in the total amount of aircraft fuel used by the Air Force,[26] saving 1 million to 3 million barrels of jet fuel and avoiding 900 to 2,200 tons of NOx emissions per year.[27] Fuel cells also produce usable water, which could reduce the amount of water an aircraft needs to carry, reducing overall weight and resulting in further fuel savings.

For providing auxiliary power, fuel cells may be a more attractive alternative to internal combustion engine generators, because they are more efficient and significantly quieter, but they are still able to use the vehicle's existing supply of diesel or jet fuel (in addition to other fuel options that include hydrogen, biofuels, propane, and natural gas). Also, because fuel cells produce no NOx or particulate emissions, they can help improve air quality in areas where there is a high concentration of auxiliary power use—such as airports, truck stops, and ports, and they can be used in EPA-designated nonattainment areas, where emissions restrictions limit the use of internal combustion engine generators. Fuel cells may also offer an attractive alternative to batteries, because they are lighter and do not require long recharge times.

Emissions from idling and auxiliary power are likely to be the subject of increasing regulations in the future. Idling restrictions for heavy-duty highway vehicles have already been enacted in 30 states;[28] in 2008 the EPA adopted new requirements for limiting idling emissions from locomotives;[29] also in 2008, the EPA finalized a three-part program to reduce emissions from marine diesel engines, with rules phasing in from 2008 through 2014; [30]and regulations could also emerge to limit emissions from aircraft while they are on the ground. Fuel cells have the potential to play an important role in all of these applications.

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[26] Sigler, D., "Several Groups Now Testing Electric Taxiing," CAFE: Comparative Aircraft Flight Efficiency Web Site, accessed March 13, 2012, http://blog.cafefoundation.org/?p=5207

[27] *DESC Fact book 2009*, U.S. Defense Logistics Agency, http://www.desc.dla.mil/DCM/Files/FY09%20Fact%20Book%20%288-10-10%29.pdf

[28] Nguyen, T., U.S. Department of Energy, "Market for Fuel Cells as Auxiliary Power Units on Heavy Trucks," *2009 NHA Hydrogen Conference Proceedings*, National Hydrogen Association.

[29] Control of Emissions from Idling Locomotives," U.S. Environmental Protection Agency Web site, accessed October 7, 2010, www.epa.gov/otaq/regs/nonroad/locomotv/420f08014.htm .

[30] "Diesel Boats and Ships," U.S. Environmental Protection Agency Web site, accessed October 7, 2010, www.epa.gov/otaq/marine.htm.

Portable Power

Portable fuel cells are beginning to enter the consumer marketplace, and they are being developed for a range of applications including cell phones, cameras, personal digital assistants (PDAs), MP3 players, laptop computers, as well as portable generators and battery chargers, which are of particular interest for military applications. Fuel cells can have significant advantages over batteries, including rapid recharging and higher energy density—allowing up to twice the run-time of lithium ion batteries of the same weight and volume. An independent market research firm has estimated that the worldwide market for portable fuel cells could exceed $38 billion by 2017.[31]

Motive Power — Specialty Vehicles, Light-duty Vehicles, Transit Buses, Etc.

Fuel cells powered by hydrogen and methanol have become a cost-competitive option for some transportation applications. The specialty vehicle market—which includes lift trucks, airport tugs, etc.—has emerged as an area of early commercial success for fuel cells. Specialty vehicles usually require power in the 5- to 20-kW range, and they often operate in indoor facilities where air quality is important and internal combustion engines cannot be used. Lift trucks (including forklifts and pallet trucks) powered by fuel cells are currently in use in commercial applications by several major U.S. companies.

Fuel cells offer advantages over batteries for specialty vehicles. While both can be used indoors, without emitting any criteria pollutants, fuel cells can increase operational efficiency—and raise productivity—because refueling takes much less time than changing batteries. While changing forklift batteries can take from 15 to 30 minutes, refueling a fuel cell–powered forklift with hydrogen takes less than three minutes, and fuel cell forklifts using methanol can be refueled even faster. This makes fuel cells a particularly appealing option for continuously used lift trucks running two or three shifts per day, which require multiple battery change-outs and incur significant labor costs.

Furthermore, the voltage delivered by a fuel cell is constant as long as fuel is supplied, unlike battery-powered forklifts, which lose power as the batteries are discharged, significantly reducing overall performance and productivity. Also, since fuel cells do not require storage space, battery change-out equipment, chargers, or a dedicated area for changing batteries, less space is required. The Battelle study mentioned previously found that fuel cells used in lift trucks can provide up to 50% savings in lifecycle costs over batteries. These results will be updated as more information becomes available, such as that from the Recovery Act lift truck deployments.

These applications have broader environmental and economic benefits as well. Using fuel cells (powered by hydrogen from natural gas) could reduce the energy consumption of lift trucks by up to 29% and their greenhouse gas emissions by up to 38% (Figure 2.2.5), when compared with lift trucks using conventional internal combustion engines. When compared with using batteries charged by grid power (average grid mix), the use of fuel cells could reduce the energy consumption of lift trucks by up to 14% and their greenhouse gas emissions by up to 33% (Figure 2.2.5).[32] The lift truck market in the United States involves sales of approximately 170,000 units per year and annual revenues of more than $3 billion; it is expected to grow 5% per year through 2013;[33] and it is

[31] "Fuel Cells for Portable Power Applications," Pike Research, 2011, www.pikeresearch.com.
[32] ANL, Full Fuel-Cycle Comparison of Forklift Propulsion Systems, http://www.transportation.anl.gov/pdfs/TA/537.pdf
[33] "Identification and Characterization of Near Term Direct Hydrogen PEM Fuel Cell Markets" Battelle April 2007

estimated that more than 20,000 U.S. manufacturing jobs would be created if U.S. fuel cell manufacturers could capture 50% of the current global market for battery-powered lift trucks.[34] Ongoing improvements in transportation fuel cell technologies will enable industry to further capitalize on the early success in these and other markets for specialty vehicles.

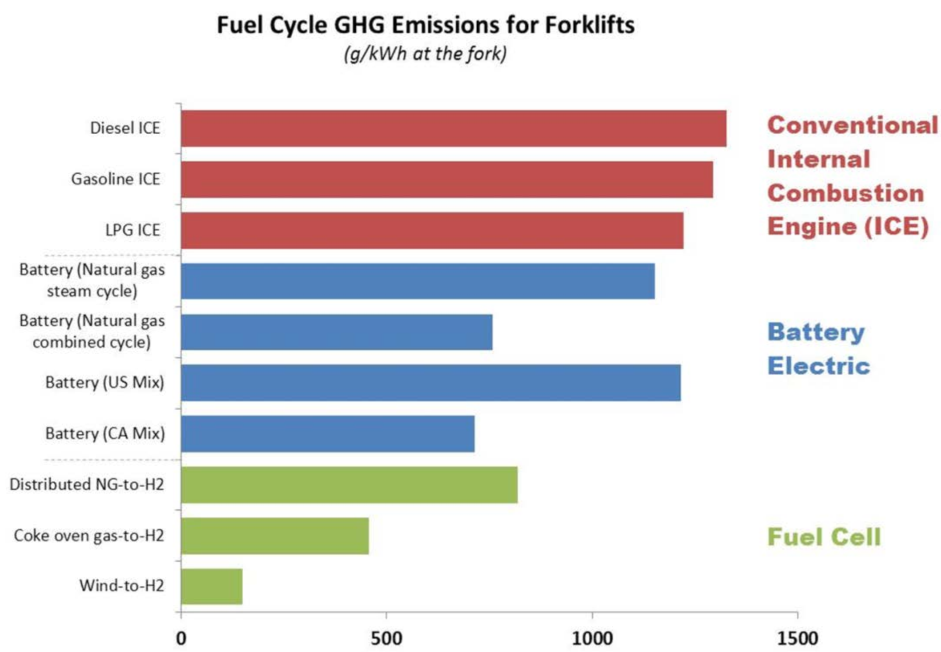

Figure 2.2.5. Greenhouse Gas Emissions from Forklifts. Specialty vehicles (including forklifts, lift trucks, and others) have become a key early market for fuel cells, where hydrogen and fuel cells can offer substantial reductions in emissions and significant benefits to the end-user in terms of economics and performance.[35]

Fuel cells are also being developed for mainstream transportation, where they can be used in a number of applications, including personal vehicles, fleet vehicles (for municipal and commercial use), transit buses, short-haul trucks (such as delivery trucks and drayage trucks for port facilities), and others. Thus, fuel cells play a central role in the diverse portfolio of vehicle technologies required to meet the full range of driving and duty cycles (Figure 2.2.6). Many automobile manufacturers around the world, and several transit bus manufacturers, are developing and demonstrating FCEVs today. The timeline for market readiness varies, but several companies—including Daimler, Toyota, Honda, General Motors, Hyundai, and Proterra—have announced plans to commercialize before 2015.

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[34] Jobs estimate based on preliminary analysis using Argonne National Laboratory's jobs estimation tool and the following: Assuming that battery-powered lift trucks comprise 2/3 of total sales, 50% of the worldwide market would be approximately 247,000 lift trucks per year (based on total worldwide lift-truck shipments of about 740,000 in 2010--source: "Lifts Trucks: Top 20 Lift Truck Suppliers, 2011," Modern Materials Handling, August 1, 2011, www.mmh.com/article/lift_trucks_top_20_lift_truck_suppliers_2011/

[35] ANL, Full Fuel-Cycle Comparison of Forklift Propulsion Systems, http://www.transportation.anl.gov/pdfs/TA/537.pdf

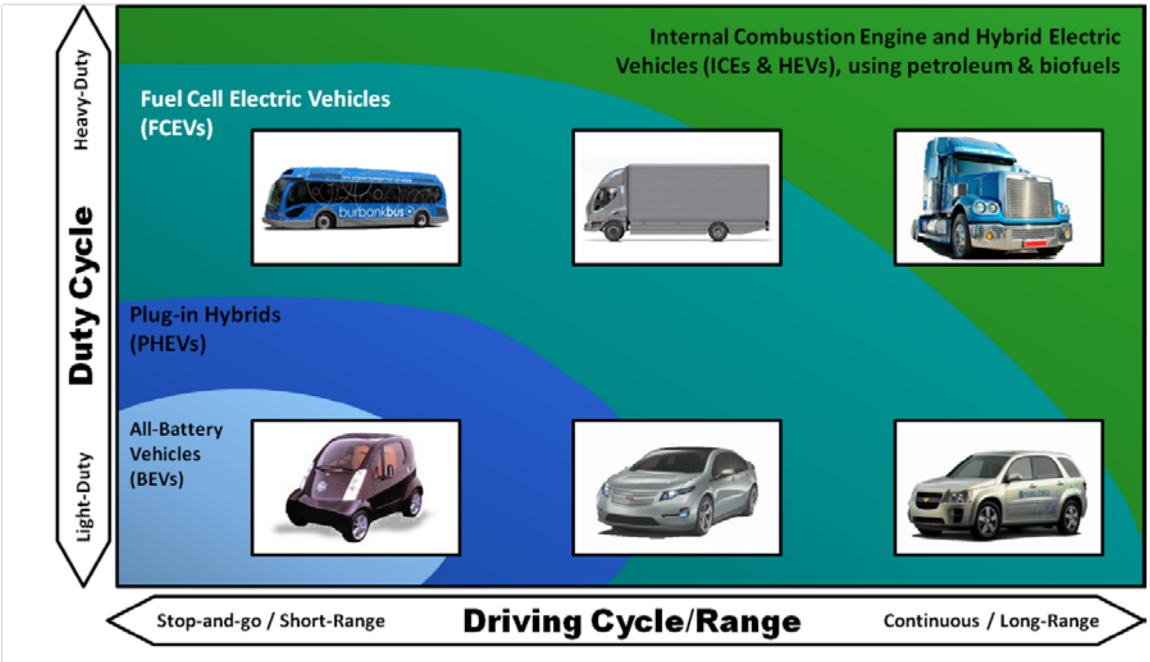

Figure 2.2.6. Diverse Technologies for Transportation Needs. A diverse portfolio of vehicle technologies will be required to meet the full range of driving cycles and duty cycles in the nation's vehicle fleet. Fuel cells play a central role, enabling longer driving ranges and heavier duty cycles for certain vehicle types (graphic adapted from General Motors).

Fuel cell vehicles enable longer driving ranges. Assuming DOE targets are met for both FCEVs and battery electric vehicles (BEVs), battery system mass is preferable for short driving ranges (<100 miles), but FCEVs have much lower system mass (including the fuel cell and hydrogen storage systems) at longer driving ranges (Figure 2.2.7).

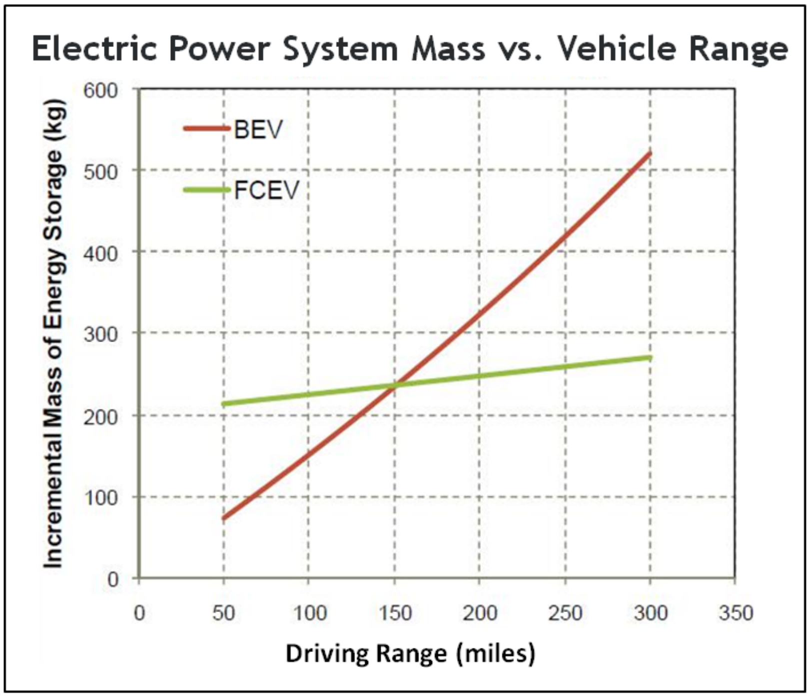

Figure 2.2.7.Range and Mass of Energy Storage Systems for Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs)[36] Battery system mass is preferable for short driving ranges (<150 miles), but FCEVs have much lower system mass (including the fuel cell and hydrogen storage systems) at longer driving ranges.

Due to the unique characteristics (including size, weight, and performance, fast start-up time, and quick response to transients) required for motive-power systems, the type of fuel cell used in vehicles is the polymer electrolyte membrane (PEM) variety, operating on pure hydrogen. In light-duty vehicles, these fuel cells have demonstrated system efficiencies of 53% to 59%—more than twice the efficiency that can be expected from gasoline ICEs, and substantially higher than even hybrid electric power systems. In transit buses, fuel cells have demonstrated more than 40% higher fuel economy than diesel ICE buses and more than double the fuel economy of natural gas ICE buses.[37] Fuel cell electric vehicles operate quietly and with all the performance characteristics that are expected of today's vehicles. Most significantly, there are no direct emissions of CO_2 or criteria pollutants at the point of use.

Analysis of complete life-cycle emissions (or "well-to-wheels emissions") conducted using models developed by Argonne National Laboratory (Figure 2.2.8) indicate that the use of hydrogen FCEVs will produce among the lowest quantities of greenhouse gases per mile of all conventional and

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[36] Mathias, M. (General Motors, Inc.), "Electrification Technology and the Future of the Automobile," 2010 Advanced Energy Conference, November 2010, http://www.aertc.org/conference2010/speakers/AEC%202010%20Session%201/1F%20ESO%20for%20Trans.%20App/Mark%20Mathias/mathias%20presSECURED.pdf.
[37] "Technology Validation: Fuel Cell Bus Evaluations," DOE Hydrogen Program 2010 Annual Progress Report, http://hydrogen.energy.gov/pdfs/progress10/viii_7_eudy.pdf.

alternative vehicle and fuel pathways being developed.[38] Even in the case where hydrogen is produced from natural gas (which is likely to be the primary mode of production for the initial introduction of FCEVs), the resulting life-cycle emissions per mile traveled will be about 40% less than those from advanced gasoline internal combustion vehicles, 15% less than those from advanced gasoline hybrid electric vehicles, and about 25% less than those from gasoline powered plug-in hybrids.

When hydrogen is produced from renewable resources (such as biomass, wind, or solar power), nuclear energy, or coal (with carbon sequestration), overall emissions of greenhouse gases and criteria pollutants are minimal. There are some emissions associated with the delivery of hydrogen to the point of use, but these are relatively minor.

In addition, substantial reductions in petroleum consumption are possible through the use of a variety of advanced transportation technologies and fuels, including FCEVs using hydrogen from a variety of sources (Figure 2.2.9).

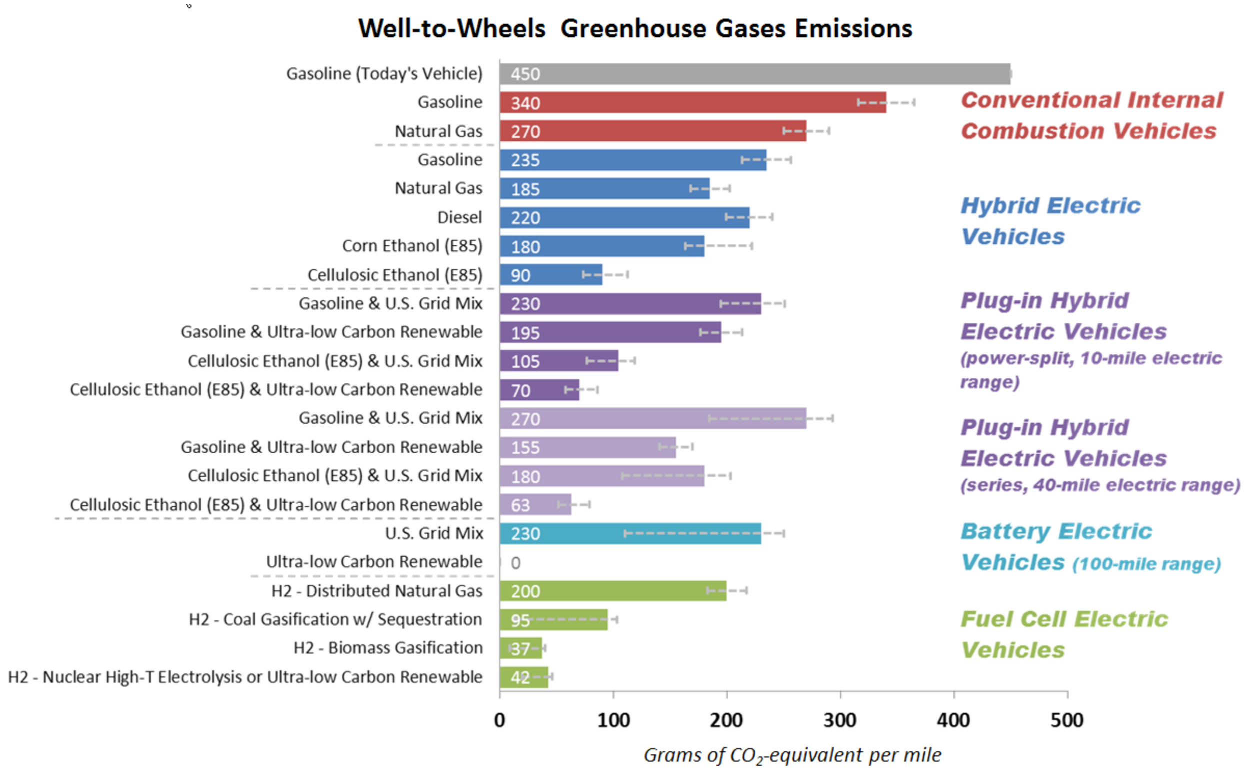

Figure 2.2.8. Well-to-Wheels Analysis of Greenhouse Gas Emissions. Substantial reductions in greenhouse gas emissions are possible through the use of a variety of advanced transportation technologies and fuels, including FCEVs using hydrogen from a variety of sources. Notes: (1) analysis based on a mid-sized car; (2) assumes the state of the technologies expected in 2035–2045; (3) ultra-low carbon renewable electricity includes wind, solar, etc.; (4) there is no accounting for the life-cycle effects of vehicle manufacturing and infrastructure construction/decommissioning.[39]

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[38] DOE Hydrogen Program Record #10001, http://hydrogen.energy.gov/pdfs/10001_well_to_wheels_gge_petroleum_use.pdf.
[39] DOE Hydrogen Program Record #10001, http://hydrogen.energy.gov/pdfs/10001_well_to_wheels_gge_petroleum_use.pdf

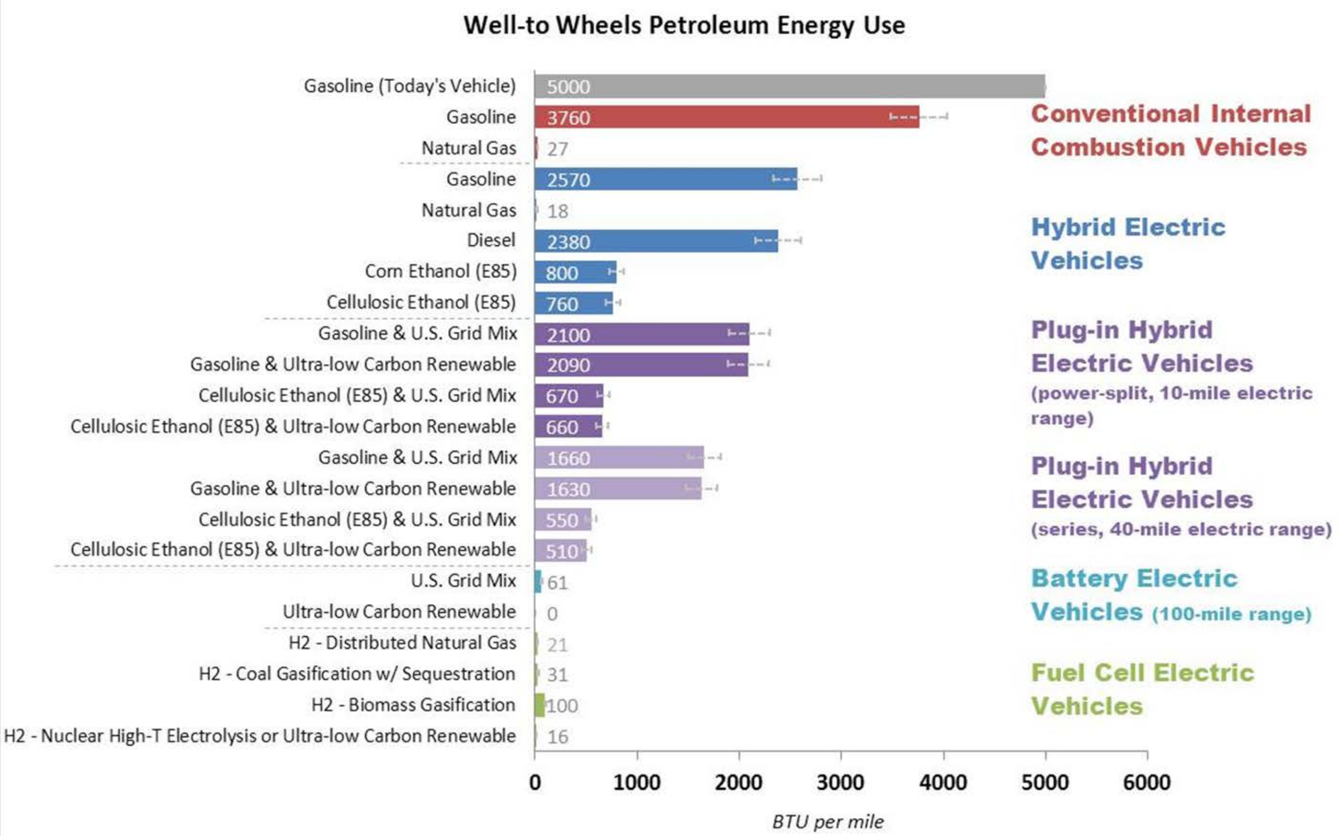

Figure 2.2.9. Well-to-Wheels Analysis of Petroleum Use. Notes: (1) analysis based on a mid-sized car; (2) assumes the state of the technologies expected in 2035–2045; (3) ultra-low carbon renewable electricity includes wind, solar, etc.; (4) the life-cycle effects of vehicle manufacturing and infrastructure construction/decommissioning are not accounted for.[40]

[40] DOE Hydrogen Program Record #10001, http://hydrogen.energy.gov/pdfs/10001_well_to_wheels_gge_petroleum_use.pdf

2.3 Domestic Resources for Hydrogen Production

One of the principal energy security advantages of using hydrogen as an energy carrier is diversity—it can be produced from a variety of low-carbon domestic energy resources, including renewable resources (such as biomass, wind, and solar energy), nuclear power, and coal (with carbon sequestration). Producing a significant amount of hydrogen—for example, to support widespread use of FCEVs—would add relatively little additional demand to some resources such as natural gas, coal, biomass, and nuclear power. In other cases, such as wind energy, solar energy, and other under-utilized resources, while significant production of hydrogen would require relatively larger expansion of capacity, it would make minimal impact on the overall availability of the resource.

The following scenario provides examples of how domestic resources could be utilized to provide a large amount of hydrogen. For illustration purposes, it is assumed that there are 100 million FCEVs on the road and each resource is examined as if it were relied upon to provide 20% of this future hydrogen demand (4 million metric tons, enough for 20 million FCEVs[41]). It is important to note, however, that what is shown here does not represent all the potential production pathways—there are a number of other promising pathways under development, including direct conversion of solar energy through photoelectochemical, biological, and high-temperature thermo chemical systems. As technologies and efficiencies improve, these analyses are periodically updated. The latest updates can be found on the FCT Program records page (http://www.hydrogen.energy.gov/program_records.html).

Technologies and resources to individually produce 10 million metric tons of hydrogen include:

- **Gasification and Reforming:**
  - **Biomass:** Depending on the type of biomass used for hydrogen production, approximately 50 million dry metric tons annually would be required. Current biomass resources available are between 384 million[42] and 1.2 billion dry metric tons annually.[43, 44]
  - **Coal (with Carbon Sequestration):** 54 million metric tons would be required annually. The current estimated recoverable coal reserves are 239 billion metric tons. [45]
  - **Natural Gas:** 634 billion cubic feet would be required annually. The current proven reserves of natural gas are 260 trillion cubic feet.[46]

[41] This assumes FCEVs travel an average of 13,000 miles per year with an average fuel economy of 67 mpgge. For the annual number of miles and fuel economy, see: U.S. Department of Energy program records, "Record No. 11002, Number of Cars Equivalent to 100 Metric Tons of Avoided Greenhouse Gases per Year" and "Record No. 10001, Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles," http://www.hydrogen.energy.gov/program_records.html.

[42] Milbrandt, A., A Geographic Perspective on the Current Biomass Resource Availability in the United States, National Renewable Energy Laboratory (NREL) Report No. TP-560-39181, 2005, http://www.nrel.gov/docs/fy06osti/39181.pdf.

[43] Includes only biomass not currently used for food, feed or fiber products.

[44] Perlack, R. D. et al., *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*, (April 2005), performed by Oak Ridge National Laboratory for the U.S. Department of Agriculture and U.S. Department of Energy, ORNL/TM-2005/66, DOE/GO-102995-2135, http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf.

[45] U.S. Department of Energy, Energy Information Administration, *Annual Coal Report – 2007*, Table 15: "Recoverable Coal Reserves at Producing Mines, Estimated Recoverable Reserves, and Demonstrated Reserve Base by Mining Method, 2006," retrieved January 20, 2009, from http://www.eia.doe.gov/cneaf/coal/page/acr/table15.html.

- **Water Electrolysis:**
  - **Wind:** 121 GW_e of installed wind would be needed. The estimated wind capacity in the United States is around 3,500 GW_e (nameplate capacity, not power output).[47]
  - **Solar (Photovoltaic and Concentrated Solar Thermal):** 230 GW_e would be required. The estimated solar capacity is 5,400 GW_e [48].
  - **Nuclear Energy:** Nuclear power can also provide electricity to produce hydrogen via electrolysis of water. Around 64 GW_e would be required. The current net nuclear generation capacity is approximately 101 GW_e. Current nuclear resource availability is 67 million metric tons at $66/lb and 385 million metric tons at $110/kg.[49]
- **Thermo chemical Production:**
  - **Nuclear:** 85 GW_{th} would be required. The current net nuclear generation capacity is approximately 101 GWe. Current nuclear resource availability is 67 million metric tons at $66/lb and 385 million metric tons at $110/kg.[50]

The following provides a brief description of the key attributes of some of the various resources from which hydrogen can be produced.

Natural Gas. Reforming of natural gas makes up nearly 50% of the world's hydrogen production and is the source of 95% of the hydrogen produced in the United States.[51] Steam reforming is a thermal process, typically carried out over a nickel-based catalyst that involves reacting natural gas or other light hydrocarbons with steam. Large-scale commercial units capable of producing hydrogen are available as standard "turn-key" packages.

Coal. Currently, more than 140 gasification plants are operating throughout the world using coal or petroleum coke as a feedstock. [52] Hydrogen can be produced from coal by gasification followed by processing the resulting synthesis gas using currently available technologies. Advanced systems including carbon capture and storage and membrane separation technologies are the subject of RD&D activities that will provide the pathways to produce affordable hydrogen from coal in an environmentally clean manner.

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46 Natural gas proved reserves estimate from Annual Energy Review 2009, Table 4.2 (http://www.eia.doe.gov/aer).
47 Black & Veatch, 2007, 20% Wind Energy Penetration in the United States: A Technical Analysis of the Energy Resource. Walnut Creek, CA, retrieved January 20, 2009, from link available at http://www.20percentwind.org/Black_Veatch_20_Percent_Report.pdf. Table 6-3 indicates 3,484 GW of wind potential from onshore and shallow offshore wind resources, classes 4-7.
48 U.S. Department of Energy (Hydrogen Program), "Record 5006: Solar Resources in the U.S." (in development) http:// http://www.hydrogen.energy.gov/program_records.html.
49 U.S. Department of Energy, Energy Information Administration, U.S. Uranium Reserves Estimates by State, 2004, retrieved June 24, 2008 from http://www.eia.doe.gov/cneaf/nuclear/page/reserves/uresst.html.
50 *Ibid.*
51 National Academies' National Research Council and National Academy of Engineering, The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs, National Academies Press, Washington (2004)
52 National Energy Technology Laboratory, 2010 Worldwide Gasification database, available at http://www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/index.html.

Biomass. Renewable feedstocks can be used to produce hydrogen, either directly or through intermediate carriers (e.g., ethanol). Some biological organisms can produce hydrogen through fermentation. Alternatively, fermentation could be used to produce methane or sugar alcohols that can be reformed to hydrogen. Thermal processing (pyrolysis or gasification) can also be used and the techniques for biomass and fossil fuels (reforming, water gas shift, gas separation) are similar. Approximately 12-14 kg of biomass is required to produce 1 kg of hydrogen. [53]

Wind. Wind turbines have been connected to electrolysis systems that can operate with high efficiency (~70%) to produce hydrogen. Over the last 20 years, the cost of electricity from utility-scale wind systems has dropped by more than 80% and current wind power plants can generate electricity for less than 5 cents/kWh with the Production Tax Credit in many parts of the U.S., a price that is competitive with new coal- or gas-fired power plants.[54]

Solar Energy. Sunlight can provide the necessary energy to split water into hydrogen and oxygen. Photovoltaic arrays can be used to generate electricity that can then be used by an electrolyzer to produce hydrogen. Some semiconductor materials can also be used to directly split water in a single device, eliminating the need for separate electricity-generation and hydrogen-production steps. Similarly, a number of biological organisms have the ability to directly produce hydrogen as a product of metabolic activity. Finally, solar concentrators can be used to drive high-temperature chemical cycles that split water. There are abundant solar resources in the United States, especially in the southwestern portion of the Nation.

Nuclear Energy. Current nuclear technology generates electricity that can be used to produce hydrogen via electrolysis of water. Advanced nuclear reactor concepts (Gen IV) are also being developed that will be more efficient in the production of hydrogen. These technologies provide heat at a temperature that permits high-temperature electrolysis (where heat energy replaces a portion of the electrical energy needed to split water) or thermo chemical cycles that use heat and a chemical process to split water. The thermodynamic efficiencies of thermo chemical cycles for the direct production of hydrogen with Gen IV reactors may be as high as 45%. This contrasts with the 33% efficiency of the existing reactors for electric power production.[55] By bypassing the inefficiencies of electric power production and electrolysis losses, the overall efficiency of converting heat energy to hydrogen energy is increased significantly.

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[53] The National Renewable Energy Laboratory *H2A Production Model*, available at: http://www.hydrogen.energy.gov/h2a_analysis.html.

[54] American Wind Energy Association (AWEA), Wind Web Tutorial, available at: http://archive.awea.org/faq/wwt_costs.html.

[55] Supercritical-Water-Cooled Reactor (SCWR), Idaho National Laboratory, http://inl.gov/featurestories/2002-12-15.shtml.

2.4 Conclusion

Hydrogen and fuel cells offer a broad range of benefits for the environment, for our nation's energy security, and for our domestic economy, including: reduced greenhouse gas emissions; reduced oil consumption; expanded use of renewable power (through use of hydrogen for energy storage and transmission); highly efficient energy conversion; fuel flexibility (use of diverse, domestic fuels, including clean and renewable fuels); reduced air pollution; and highly reliable grid-support. Fuel cells also have numerous advantages that make them appealing for end-users, including quiet and more productive operation, low maintenance needs, and high reliability. In addition to using hydrogen, fuel cells can provide power from a variety of other fuels, including natural gas and renewable fuels such as methanol or biogas.

Hydrogen and fuel cells can provide these benefits and address critical challenges in all energy sectors—commercial, residential, industrial, and transportation—through their use in a variety of applications, including distributed energy and CHP systems; backup power systems; systems for storing and transmitting renewable energy; portable power; auxiliary power for trucks, aircraft, rail, and ships; specialty vehicles, such as forklifts; and passenger and freight vehicles, including cars, light trucks, buses, and short-haul trucks.

The widespread use of hydrogen and fuel cells will play an increasingly more substantial role in overcoming our nation's key energy challenges, including significant reductions in greenhouse gas emissions and oil consumption as well as improvements in air quality. In addition, hydrogen and fuel cells provide a significant economic opportunity for the United States, with various studies projecting up to 900,000 new jobs in the United States by 2030–2035. Growing interest and investment among leading world economies such as Germany, Japan, and South Korea, underscores the global market potential for these technologies and the need for continued investment for industry to remain competitive.

The sales volumes of commercial fuel cell systems continue to grow. Worldwide, nearly 16,000 fuel cell systems were shipped in 2010, or more than double the total number of units shipped in 2008.[56] Both North America and Japan have experienced major increases in sales, despite the global financial crisis that began in 2008. The number of fuel cell units shipped from North America quadrupled between 2008 and 2010.[57] U.S. fuel cell companies shipped about 40 MW of fuel cell systems in 2010, or about one-half of the worldwide totals in terms of MW shipped.[58]

While fuel cells are becoming competitive in several markets, these markets can be greatly expanded with improvements in durability and performance and reductions in manufacturing cost, as well as advances in technologies for producing, delivering, and storing hydrogen. Successful entry into new markets will also require overcoming certain institutional and economic barriers, such as the need for codes and standards, the lack of public understanding and acceptance of the technologies, and the high initial installation costs and lack of a supply base that many new technologies face in their critical early commercialization stages.

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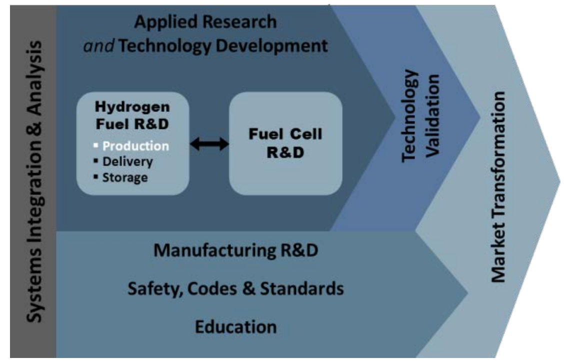
[56] 2010 Fuel Cell Technologies Market Report. Breakthrough Technologies Institute, Inc, Lisa Callaghan-Jerram of Pike Research, Rachel Gelman of the National Renewable Energy Laboratory: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/2010_market_report.pdf
[57] *Ibid.*
[58] *Ibid.*

3.1 Hydrogen Production



Hydrogen can be produced from diverse energy resources, using a variety of process technologies. Energy resource options include fossil, nuclear, and renewables. Examples of process technologies include thermochemical, biological, electrolytic, and photolytic.

3.1.1 Technical Goal and Objectives

Goal

Research and develop technologies for low-cost, highly efficient hydrogen production from diverse renewable sources.

Objectives

Reduce the cost of hydrogen production to <$2.00/gge[1] (<4.00/gge delivered and dispensed[2, 3]). This cost is independent of the technology pathway and takes into consideration a range of assumptions for fuel cell electric vehicles (FCEVs) to be competitive with hybrid electric vehicles (HEVs). Those considerations include a range of gasoline prices and fuel economies. Technologies are being researched to achieve this goal in timeframes appropriate to their current states of development.

- By 2020, reduce the cost of distributed production of hydrogen from biomass-derived renewable liquids to <$2.30/gge (≤$4.00 delivered and dispensed).
- By 2020, reduce the cost of distributed production of hydrogen from water electrolysis to <$2.30/gge (≤$4.00 delivered and dispensed).
- By 2015, reduce the cost of central production of hydrogen from water electrolysis using renewable power to $3.00/gge at plant gate. By 2020, reduce the cost of central production of hydrogen from water electrolysis using renewable power to ≤$2.00/gge at plant gate.
- By 2020, reduce the cost of hydrogen produced from biomass gasification to ≤$2.00/gge at the plant gate.
- By 2015, verify the potential for solar thermochemical (STCH) cycles for hydrogen production to be competitive in the long term and by 2020, develop this technology to produce hydrogen with a projected cost of $3.00/gge at the plant gate.
- By 2020, develop advanced renewable photoelectrochemical hydrogen generation technologies to produce hydrogen with a projected cost of $4.00/gge at the plant gate.

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[1] The energy content of a gallon of gasoline and a kilogram of hydrogen are approximately equal on a lower heating value basis; a kilogram of hydrogen is approximately equal to a gallon of gasoline equivalent (gge) on an energy content basis.

[2] This cost results in equivalent fuel cost per mile for a hydrogen fuel cell vehicle compared to gasoline hybrid vehicles in 2020. The full explanation and basis can be found in U.S. Department of Energy (DOE) Record 11007 (see www.hydrogen.energy.gov/program_records.html).

[3] All costs in this plan are in 2007 dollars to be consistent with EERE planning which uses the energy costs from the 2009 Annual Energy Outlook.

- By 2020, develop advanced biological generation technologies to produce hydrogen with a projected cost of $10.00/gge at the plant gate.
- By 2017, develop technologies for direct solar-to-hydrogen (STH) production at centralized facilities for ≤$5.00/gge at the plant gate.
- By 2020, demonstrate plant-scale-compatible photoelectrochemical water-splitting systems to produce hydrogen at solar-to-hydrogen energy conversion efficiencies ≥15%, and plant-scale-compatible photobiological water-splitting systems to produce hydrogen at solar-to-hydrogen energy conversion efficiencies ≥5%.

3.1.2 Technical Approach

Hydrogen production research is focused on meeting the objectives outlined in Section 3.1.1 by conducting Research and Development (R&D) through industry, national laboratory, and university projects. The Hydrogen Production sub-program will continue to develop the technologies to produce hydrogen for transportation and stationary applications. Integrated systems will be validated in the field by the Technology Validation sub-program to obtain real-world data (refer to the Technology Validation section of the Multi Year Research, Development, and Demonstration Plan). Results of validation projects will guide continued Research, Development, and Demonstration (RD&D) efforts.

A portfolio of feedstocks and technologies for hydrogen production will be necessary to address energy security and environmental needs and the geographic variability in feedstock availability and cost. This sub-program addresses multiple feedstock and technology options for hydrogen production for the short and long term. The research focus for the near term is on distributed reforming of renewable liquid fuels and on electrolysis to meet initial lower volume hydrogen needs with the lowest capital equipment cost. An example of a near term distributed hydrogen production and delivery station is shown in Figure 3.1.1. Both short and long-term research is focused on hydrogen production from renewable feedstocks and energy sources, with an emphasis on centralized options to take advantage of economies of scale when an adequate hydrogen delivery infrastructure is in place. There is collaboration with the U.S. Department of Energy's (DOE's) Office of Fossil Energy (http://fossil.energy.gov/programs/fuels/index.html) to develop centralized production from coal with carbon sequestration, and with DOE's Office of Nuclear Energy (http://www.nuclear.energy.gov/HTGCR/overview.html) to develop centralized production from advanced nuclear energy-driven high temperature electrolysis. DOE's Office of Science (http://science.energy.gov) is a collaborator on longer-term technologies such as biological and photoelectrochemical hydrogen production.

Figure: 3.1.1 Distributed Hydrogen Reforming Station

The development of a national hydrogen production infrastructure will likely take multiple pathways. Some of these pathways and their roles within the strategy of the Hydrogen Production sub-program are described below.

Distributed Production Pathway

Distributed hydrogen production (i.e., production of hydrogen at the point of use) may be the most viable approach for introducing hydrogen as an energy carrier because it does not require a substantial transport and delivery infrastructure or large capital investments as high as those needed for large central production plants.

Two distributed hydrogen production technologies that have good potential for development are (1) reforming of natural gas or liquid fuels, including bio-derived liquids, such as ethanol and pyrolysis oil; and (2) small-scale water electrolysis. Distributed steam methane reforming technologies exist today for hydrogen to be cost-competitive with gasoline.[4] Projections based on high-volume production indicate that reforming natural gas at the fueling station can produce hydrogen for a cost close to $2/gge (See Tables 3.1.1 and 3.1.1.A). As a result, the Department of Energy is no longer funding R&D in natural gas reforming for FCEV fueling, although it is anticipated that industry will continue to make incremental improvements to this technology. Using a renewable resource, high temperature and aqueous phase bio-derived liquids reforming are two possible pathways to produce hydrogen with dramatically lower net greenhouse gas emissions. Reforming of bio-derived liquids is applicable to distributed, semi-central, and central production.

The second focus area is on small-scale electrolyzers for splitting water. Electrolyzers present the opportunity for non-carbon-emitting hydrogen production when a renewable electricity source such as wind or hydropower is used. To be cost competitive, R&D is necessary to reduce electrolysis capital and operating costs and the cost of electricity needs to be less than or equal to half the current average grid price of electricity.

Table 3.1.1 Distributed Forecourt Natural Gas Reforming [a, b, c]

Characteristics	Units	2011 Status [d]	2015 Estimate [e]
Hydrogen Levelized Cost (Production Only) [f]	$/kg H_2	2.00	2.10
Production Equipment Total Capital Investment	$M	1.5	1.2
Production Energy Efficiency [g]	%	71.4	74
Production Equipment Availability [c]	%	97	97
Industrial Natural Gas Price [h]	$/MMBtu	from Annual Energy Outlook (AEO) 2009	from AEO 2009

[4] *Distributed Hydrogen Production from Natural Gas—Independent Review*, National Renewable Energy Laboratory, October 2006, http://www.hydrogen.energy.gov/pdfs/40382.pdf.

Table 3.1.1.A Distributed Natural Gas H2A Example Cost Contributions [a, b, c]			
Characteristics	**Units**	**2011 Status [d]**	**2015 Estimate [e]**
Production Unit Capital Cost Contribution	$/kg	0.60	0.40
Feedstock Cost Contribution	$/kg	1.10	1.30
Production Fixed Operations and Maintenance (O&M) Cost Contribution	$/kg	0.20	0.20
Production Other Variable Cost Contribution	$/kg	0.10	0.20
Hydrogen Levelized Cost (Production)	$/kg	2.00	2.10
Compression, Storage, and Dispensing (CSD) Levelized Cost [i]	$/kg	2.50	1.70
Total Hydrogen Levelized Cost (Dispensed)	$/kg	4.50	3.80

a The H2A Distributed Production Model 3.0 (www.hydrogen.energy.gov/h2a_production.html) was used to generate the values in the table with the exceptions described in the notes below.

b The H2A Distributed Production Model 3.0 was used with the standard economic assumptions: All values are in 2007 dollars (2007$), 1.9% inflation rate, 10% After Tax Real Internal Rate of Return, 100% equity financing, 20-year analysis period, 38.9% overall tax rate, and 15% working capital. A MACRS (Modified Accelerated Cost Recovery System) 7-year depreciation schedule was used. The plant design capacity is 1,500 kg/day of hydrogen. It is assumed that Design for Manufacture and Assembly (DFMA) would be employed and that production would have realized economies of scale.

c The plant production equipment availability is 97% including both planned and unplanned outages; ten unplanned outages of 14h duration per year; 1 planned outage of 5 days duration per year. The plant usage factor (defined as the actual yearly production/equipment design production capacity) is 86% based on over sizing of the production equipment to accommodate a summer surge in demand of 10% above the yearly average demand.

d Current technology status based on 01D_Current_Forecourt_Hydrogen_Production_from_Natural_Gas_(1,500_kg_per_day)_version_3.0 http://www.hydrogen.energy.gov/h2a_prod_studies.html

e 2015 Technology projections based on 02D_Future_Forecourt_Hydrogen_Production_from_Natural_Gas_(1,500_kg_per_day)_version_3.0 http://www.hydrogen.energy.gov/h2a_prod_studies.html

f The levelized cost is equivalent to the minimum required selling price to achieve a 10% annual rate of return over the life of the plant.

g Energy efficiency is defined as the energy of the hydrogen out of the production process (lower heating value [LHV]) divided by the sum of the energy into the process from the feedstock (LHV) and all other energy needed for production. Energy used for compression, storage and dispensing (CSD) is not included in the calculation of production energy efficiency.

h Industrial natural gas prices are taken from the U.S. Energy Information Administration (EIA) 2009 AEO reference case projection, in 2007$. The average price over the modeled life of the plant is $7.87/MMBtu (LHV) for the current technology case, and $9.35/MMBtu for the 2015 case. Prices are in $/MMBtu on a LHV basis, as utilized in the H2A models. Conversion of EIA natural gas price data on a HHV basis to a LHV basis is done with heat content values of 52.2 MJ/kg (HHV) and 47.1 MJ/kg (LHV).

i Costs for the forecourt station compression and storage are consistent with the status and targets in the Delivery Multi Year Research, Development and Demonstration (MYRD&D) section. Storage capacity for 1540 kg of hydrogen at the forecourt is included. It is assumed that the hydrogen refueling fill pressure is 5000 psi for 2010/11 and that in 2015 and 2020, the hydrogen refueling fill pressure is 10,000 psi.

Centralized Production Pathway

Large hydrogen production facilities that can take advantage of economies of scale will be needed in the long term to meet increases in hydrogen fuel demand. Central hydrogen production allows management of greenhouse gas emissions through strategies like carbon sequestration. In parallel with the distributed production effort, DOE is pursuing central production of hydrogen from a variety of resources - fossil, nuclear, and renewable.

- Coal and natural gas are possibly the least expensive feedstocks, and carbon sequestration is required to reduce or eliminate greenhouse gas emissions. Centralized natural gas reforming is not being pursued because it is already an established commercial technology.
- Biomass gasification offers the potential of a renewable option and near-zero greenhouse gas emissions.
- Water electrolysis based on renewable power may be a viable approach - as the cost of capital equipment is reduced through advanced development providing the cost of electricity is less than or half of the current average grid price.
- DOE's Office of Nuclear Energy has been investigating the feasibility of hydrogen production through high-temperature electrolysis as a potential end-user application under the Next Generation Nuclear Plant project.
- High-temperature thermochemical hydrogen production that uses concentrated solar energy may be viable with the development of efficient water-splitting chemical process cycles and materials.
- Photoelectrochemical and biological hydrogen production are early development technologies to produce hydrogen using sunlight and need long-term research and development to produce hydrogen economically.
  - In photoelectrochemical production, hydrogen is produced directly from water using sunlight and a special class of semiconductor materials. These highly specialized semiconductors absorb sunlight and use the light energy to separate water molecules into hydrogen and oxygen.
  - In biological production, specialized microorganisms produce hydrogen using different feedstock materials and conditions: sunlight drives photolytic production from water and photosynthetic production using organic matter, dark fermentation releases hydrogen from biomass without requiring light, and microbial electrolysis cells use bacterial metabolism to generate a low voltage that, supplemented with a small amount of energy, produces hydrogen gas at a submerged cathode.

Other feedstocks and technologies for hydrogen production that show promise may also be considered. Central production of hydrogen includes a wide diversity of feedstocks, but to be viable, it would require development of a distribution and delivery infrastructure. DOE is pursuing projects to identify a cost-effective, energy-efficient, safe infrastructure for the delivery of hydrogen or hydrogen carriers from centrally located production facilities to the point of use (refer to the Delivery MYRD&D section).

Semi-Central/City-Gate Production Pathway

Another option for hydrogen production is semi-central facilities that could be located, for example, on the edge of urban areas. These would be intermediate in production capacity. They would have limited economies of scale while being located only a short distance from refueling sites and thus reduce the cost and infrastructure needed for hydrogen delivery. Several technologies may be well suited to this scale of production including wind or solar driven electrolysis, reforming of renewable bio-derived liquids, natural gas reforming and photoelectrochemical and biological hydrogen production. Although many of the technologies currently under development are applicable to the semi-central concept, it is not a major focus of the program to emphasize development at the semi-central scale.

Co-Production Pathways

Other production pathways being explored combine production of hydrogen fuel, heat, and electric power. In these scenarios, hydrogen fuel could be produced for use: (1) in stationary fuel cells to produce electricity and heat and (2) as a transportation fuel in fuel cell vehicles or hydrogen internal combustion engine vehicles. This process allows two markets for the hydrogen that could help to initiate the use of hydrogen when hydrogen demand is small. As the demand grows, more of the hydrogen could be produced for vehicle fuel rather than used for power production.

Hydrogen Purification and Enrichment

Hydrogen purification and enrichment are key technology needs that cross-cut hydrogen production options. The quality of the hydrogen produced must meet the hydrogen quality requirements as described in Appendix C. Additional performance requirements for cost, flux rates, hydrogen recovery, and hydrogen purification will be functions of actual system configurations and operation. Going forward, innovations in purification and enrichment of hydrogen will be addressed in pathway specific RD&D.

The DOE Office of Fossil Energy (FE) is developing coal to hydrogen membrane separation systems that will operate in large-scale integrated gasification combined cycle plants to separate hydrogen and to capture and sequester carbon dioxide.

In addition to hydrogen separation membranes, FE is developing oxygen separation membranes. These could be used to replace expensive oxygen cryogenic separation technologies, reducing the cost of hydrogen production from processes that use oxygen such as coal gasification, potentially biomass gasification, or even auto-thermal distributed reforming.

3.1.3 Programmatic Status

Current Activities

Major hydrogen production sub-program activities are listed in Table 3.1.2.

Table 3.1.2 FY 2012 Current Hydrogen Production Program Activities

Technology Pathway	Approach	FY 2012 Activities
Distributed reforming of renewable liquid feedstocks	• Improve reforming and separation efficiencies and yields • Identify more durable, low cost, reforming catalysts • Incorporate breakthrough separations technology • Reduce space needed • Optimize system operation • Intensify and consolidate the number of process steps, unit operations	• National Renewable Energy Laboratory (NREL): Catalytic steam reforming of biomass pyrolysis-derived bio-oils • Pacific Northwest National Laboratory (PNNL): Aqueous phase reforming of biomass liquids such as sugar alcohols and pyrolysis oils
Electrolysis	• Reduce electricity costs of hydrogen production by developing new materials and systems to improve efficiency • Reduce capital costs of electrolysis system through new designs with lower cost materials and advanced manufacturing methods • Develop low-cost hydrogen production from electrolysis using wind and other renewable electricity sources • Develop stacks with integral electrochemical compression schemes to produce hydrogen at higher pressures	• Proton Energy Systems: PEM electrolysis system for reduced cost, improved subsystem/component performance, and increased durability • Giner Electrochemical Systems: Lower cost, higher pressure PEM electrolyzer stacks and electrolysis system • NREL: Integrated electrolysis with the renewable power source, including power electronics development • Avalence: High-efficiency, ultra high-pressure alkaline electrolysis
Biomass Gasification	• Develop advanced, lower-cost reforming technologies for hydrogen production from biomass gasification • Reduce capital costs of gasification • Demonstrate feasibility at pilot scale	• Gas Technology Institute (GTI), National Energy Technology Laboratory, Schott North America , Wah Chang (An Allegheny Company): One step shift separation Membrane reactor for biomass gas reforming for hydrogen production

Table 3.1.2 FY 2012 Current Hydrogen Production Program Activities (continued)		
Technology Pathway	**Approach**	**FY 2012 Activities**
Solar Thermochemical [5]	• Utilize the high-temperature energy from concentrated solar power to produce hydrogen through thermochemical cycles • Demonstrate feasibility of reaction cycles • Demonstrate durability of cycle reaction materials • Develop durable materials of construction. • Improve solar to hydrogen efficiencies.	• Science Applications International Corporation: High-temperature water splitting using the sulfur-ammonia reaction cycle for large scale production of hydrogen using solar energy. • Sandia National Laboratories, University of Colorado, Boulder: Solar hydrogen production with a metal oxide based thermochemical cycle. • Argonne National Laboratory, GTI, Pennsylvania State University, Orion Consulting Group, University of Illinois-Chicago: Membrane/electrolyzer development in the Cu-Cl thermochemical cycle
Photoelectrochemical (PEC) [6]	• Establish standards in theory, synthesis, characterization, and certification for PEC materials, interfaces, devices, and systems • Develop durable forms of known PEC materials and devices with limited-lifetime high efficiencies • Develop high-efficiency forms of known PEC materials devices with stabilized moderate efficiencies • Discover and develop new generation of high-efficiency, high-durability photocatalytic materials and devices • Develop cost-effective solar water-splitting reactors based on the best available PEC photoelectrode or photocatalyst materials and devices	• NREL: III-V crystalline material and device development; Improving stability/durability of the III-V materials; Study corrosion mechanism and validate surface of III-V semiconductors; Theoretical discovery of new PEC materials; Standardization of PEC characterizations and certifications • University of Nevada, Las Vegas; Advanced spectroscopic characterizations of PEC materials and interfaces synthesized by PEC Working Group researchers • Stanford University: Development of new generation MoS_2 nano-particle photocatalysts with electronic support scaffolds for device integration • Lawrence Livermore National Laboratory: Advanced ab initio theoretical modeling of water-splitting and corrosion reactions at the semiconductor/electrolyte interface ▪ MV Systems / University of Hawaii at Manoa: development of thin film PEC materials and monolithic integrated devices based on low cost metal oxides, silicon alloys, and copper chalcopyrites Midwest Optoelectronics: Develop combinations of solar cell and catalyst materials for PEC immersion-type devices and systems

[5] In collaboration with DOE Office of Nuclear Energy.
[6] In collaboration with DOE's Office of Science (http://science.energy.gov).

Table 3.1.2 FY 2012 Current Hydrogen Production Program Activities (continued)

Technology Pathway	Approach	FY 2012 Activities
Biological [7]	• Develop modifications to green algae, cyanobacteria, dark fermentative microorganisms, and microbial electrolysis systems that will facilitate efficient production of hydrogen • Develop biochemical process methods	• NREL: Develop photobiological and integrated biological systems for large-scale H_2 production using green algae • University of California Berkeley: Minimize the chlorophyll antenna size of photosynthesis to maximize solar conversion efficiency in green algae. • J. Craig Venter Institute and NREL: Develop an O_2-tolerant cyanobacterial system for continuous light-driven H_2 production from water • NREL and Penn State University: Develop direct fermentation technologies to convert renewable lignocellulosic biomass resources to H_2 by bioreactor optimization, improving molar yield, and developing a microbial electrolysis cell system
Separation and purification systems (cross-cutting research) [8] (ended in 2011)	• Develop separation technology for distributed and central hydrogen production	• Media and Process Technologies: Carbon molecular sieve membrane in a single-step water-gas shift reactor • University of Cincinnati: Zeolite membrane reactor for single-step water-gas shift reaction

3.1.4 Technical Challenges

The overarching technical challenge to providing hydrogen that is cost competitive with other fuels is reducing cost. The production cost component for hydrogen from central natural gas reforming is unlikely to decrease significantly from current projected costs (See http://hydrogen.energy.gov/h2a_prod_studies.html). As a result, achieving the threshold cost of <$4.00/gge will depend primarily on technical improvements leading to cost reductions in station compression, storage, and dispensing (CSD).

The capital cost of current water electrolysis systems, along with the high cost of electricity in many regions, limits widespread adoption of electrolysis technology for low cost hydrogen production. Water electrolyzer capital cost reductions and efficiency improvements are required along with the design of utility-scale electrolyzers capable of grid integration and compatible with low-cost, near-zero emission electricity sources. Electrolytic production of hydrogen, where coal is the primary

[7] In collaboration with DOE's Office of Science (http://science.energy.gov).
[8] In collaboration with DOE Office of Fossil Energy (http://fossil.energy.gov/programs/fuels/index.html,).

energy resource, will not lead to carbon emission reduction without carbon sequestration technologies.

Hydrogen can be produced from biomass either by reforming of bio-derived liquids or through gasification or pyrolysis of biomass feedstocks. The costs of currently available bio-derived liquids such as ethanol or sugar alcohols (e.g., sorbitol) need to be reduced. Significant improvements in reforming and associated technologies need to be developed for bio-derived liquids to reduce the capital and operating costs for this distributed production option to become competitive. As is the case for electricity, biomass feedstocks costs and availability may vary significantly from region to region. The efficiencies of biomass gasification, pyrolysis, and reforming need to be increased and the capital costs need to be reduced by developing improved technologies and approaches.

High-temperature, solar-driven, thermochemical hydrogen production using water-splitting chemical cycles is in an early stage of research. Research is also needed to cost-effectively couple the thermochemical cycles with advanced concentrated solar energy technology. If these efforts are successful, high-temperature thermochemical processes may provide a clean, efficient, and sustainable route for producing hydrogen from water.

Photoelectrochemical (PEC) hydrogen production based on semiconductor photoelectrodes or photocatalysts is in an early stage of development and requires significant advancements in materials, material systems, and reactor concept development. The primary materials-based research in this area is progressing on three fronts: (1) the study of costly high-efficiency materials to establish performance benchmarks, and to attain a fundamental understanding of PEC hydrogen generation versus corrosion mechanisms; (2) the study of durable lower-quality/lower-cost material systems to improve efficiency by mitigating loss mechanisms; and (3) the development of sophisticated multi-component devices and systems with the potential to achieve efficient PEC water splitting through the effective combination of functionalized materials specifically optimized for light-absorption, charge transport and interfacial catalysis.

Biological hydrogen production is in early- to mid-stage of research and presents many technical challenges, beginning with bioengineering of microorganisms that can efficiently produce hydrogen at high rates. Some of the challenges are related to the need for increased light utilization efficiency, increased rate of hydrogen production, improved continuity of photoproduction, and increased hydrogen molar yield. The advantages of biological hydrogen production are that high-purity water is not required and toxic or polluting by-products are not generated.

Technical Targets

A variety of feedstocks and processes are being researched and developed for producing hydrogen fuel. Each technology is in a different stage of development, and each offers unique opportunities, benefits, and challenges. Economics favor certain technologies more than others in the near term, and other technologies are expected to become economically viable as the technologies mature and market drivers shift.

Tables 3.1.3 through 3.1.12 list the DOE technical targets for hydrogen production from a variety of feedstocks. The targets and timeline for each technology reflect a number of factors, including the expected size/capacity of a production unit, the current stage of technology development, and the costs and characteristics of the feedstock. The current case values in the tables are based on the status of technologies which have been demonstrated in the laboratory, not on currently available commercial systems. Current cost estimates (2007$) are based on the projected high volume production of these technologies. Where appropriate, target tables are accompanied by another table that details the estimated cost breakdown as determined using the H2A hydrogen production cost models. The accompanying table is provided as an example only. The cost breakdowns are not targets. For many of the production pathways, achievement of the cost targets will depend on technical breakthroughs (e.g., feedstock processing, heliostat development) beyond the scope of the Hydrogen and Fuel Cells Program. Feedstock costs (including electricity costs) and availability may limit deployments of some pathway technologies.

Out-year targets are RD&D milestones for measuring progress. For hydrogen to become a major energy carrier, the combination of its cost and that of the power system it is used in, must be competitive with the alternatives available in the marketplace. For light duty vehicles, this means that the combination of the hydrogen cost, and its use in a hydrogen fuel cell vehicle, must be competitive with conventional fuels used in advanced vehicles on a cost per mile basis to the consumer. The estimated cost of hydrogen needed to be competitive (with HEVs) is <$4.00/gge (untaxed) at the dispenser. This estimate will be periodically re-evaluated to reflect projected fuel costs and vehicle power system energy efficiencies on a cost-per-mile basis. The ultimate target for all of the production technologies being researched is a hydrogen cost that will be competitive for transportation on a well-to-wheels basis, regardless of the production method.

The threshold cost goal of <$4.00/gge was apportioned between the production and delivery components of the total cost in order for targets, goals, and R&D priorities to be set. A split of the target based on central natural gas reforming as the dominant incumbent technology was used to identify separate threshold targets of <$2.00/gge by 2020 for both production and delivery.[9] Somewhat higher costs can be allowed for distributed production since the 2020 targets for CSD result in a levelized cost projection of forecourt costs of ~ $1.70/gge.

Although not listed in each table, it is understood that the quality of the hydrogen produced by each of these production technologies must meet the hydrogen quality requirements as described in Appendix C. All costs in the following tables are in 2007 dollars to be consistent with DOE Office of Energy Efficiency and Renewable Energy (EERE) planning which uses the energy costs from the 2009 Annual Energy Outlook.

[9] Record 12001

Table 3.1.3 Technical Targets: Distributed Forecourt Production of Hydrogen from Bio-Derived Renewable Liquids – High Temperature Ethanol Reforming [a, b, c, j]				
Characteristics	**Units**	**2011 Status [d]**	**2015 Target [d]**	**2020 Target [e]**
Hydrogen Levelized Cost (Production Only) [f]	$/kg	6.60	5.90	2.30
Production Equipment Total Capital Investment [c]	$	1.9M	1.4M [e]	1.2M [e]
Production Energy Efficiency [g]	%	68	70 [e]	75 [e, h]
Production Equipment Availability [c]	%	97	97	97
Ethanol Price [d,e]	average $/gal	2.47	2.41	0.85

Table 3.1.3.A Distributed Bio-Derived Renewable Liquids H2A – High Temperature Ethanol Reforming Example Cost Contributions [a, b, c, j]				
Characteristics	**Units**	**2011 Status [d]**	**2015 [d]**	**2020 [e]**
Production Unit Capital Cost Contribution [b]	$/kg	0.80	0.70	0.50
Feedstock Cost Contribution [d,e]	$/kg	5.50	5.10	1.60
Production Fixed O&M Cost Contribution	$/kg	0.20	0.10	0.10
Production Other Variable O&M Cost Contribution [d]	$/kg	0.10	0.10	0.10
Hydrogen Levelized Cost (Production)	$/kg	6.60	5.90	2.30
CSD Cost Contribution [i]	$/kg	2.50	1.70	1.70
Total Hydrogen Levelized Cost (Dispensed)	$/kg	9.10	7.70	4.00

Note: numbers may not sum due to rounding.

[a] The H2A Distributed Production Model 3.0 (www.hydrogen.energy.gov/h2a_production.html) was used to generate the values in the table with the exceptions described in the notes below. Results are documented in the H2A v3 Current and Future Case studies for Forecourt Hydrogen Production from Ethanol (http://www.hydrogen.energy.gov/h2a_prod_studies.html).

[b] The H2A Distributed Production Model 3.0 was used with the following standard economic assumptions: All values are in 2007 dollars, 1.9% inflation rate, 10% After Tax Real Internal Rate of Return, 100% Equity Financing, 20-year analysis period, 38.9% overall tax rate, and 15% working capital. The plant design capacity is 1,500 kg/day of hydrogen. It is assumed that Design for Manufacture and Assembly (DFMA) would be employed and that production would have realized economies of scale.

[c] The plant production equipment availability is 97% including both planned and unplanned outages; ten unplanned outages of 14h duration per year; 1 planned outage of 5 days duration per year. The plant usage factor (defined as

the actual yearly production/equipment design production capacity) is 86% based on over sizing of the production equipment to accommodate a summer surge in demand of 10% above the yearly average demand.

[d] Ethanol prices for the 2011 status and 2015 target cases are derived from Table B-6: Unit Operation Cost Contribution Estimates (2007 Dollars) and Technical Projections for Thermochemical Conversion to Ethanol Baseline Process Concept. Biomass Multi-Year Program Plan, DOE April 2011. Minimum ethanol price ($/gal) = 2.77 (2010), 2.15 (2012) for ethanol from corn stover feedstock. An additional cost of $0.25/gal was added for delivery. The 2012 target price was assumed throughout the remainder of the analysis period. The average delivered ethanol prices shown in Table 3.1.3 were calculated assuming a 20 year facility life starting in 2010 and 2015, respectively. The electricity cost utilized is the EIA AEO 2009 reference case commercial rate.

[e] The capital cost and energy efficiency of the production unit are based on preliminary analyses and projections for what could be achieved with successful development of this technology (i.e., 2020 target values for conversion process efficiency and equipment cost are assumed to be the same as the 2015 projection for distributed steam methane reforming. The threshold cost goal of <$4.00/gge dispensed hydrogen cost could be achieved with ethanol reforming if the equipment cost and efficiency targets are met and the cost of ethanol is reduced to <$.85/gal (40% of the value projected by the Bioenergy Technologies Office).

[f] The levelized cost is equivalent to the minimum required selling price to achieve a 10% annual rate of return over the life of the plant.

[g] Energy efficiency is defined as the energy of the hydrogen out of the production process (LHV) divided by the sum of the energy into the process from the feedstock (LHV) and all other energy needed for production. Energy used for CSD is not included in the calculation of production energy efficiency.

[h] Production unit energy efficiency may vary (as low as 65%) if the capital cost, feedstock costs and other costs associated with alternative process options such as aqueous phase reforming are low enough to still achieve the target of <$4.00/gge dispensed hydrogen cost.

[i] Costs for the forecourt station compression and storage are consistent with the status and targets in the Delivery MYRD&D Section. Storage capacity for 1540 kg of hydrogen at the forecourt is included. It is assumed that the hydrogen refueling fill pressure is 5000 psi for 2010 and it assumed that in 2015 and 2020, the hydrogen refueling fill pressure is 10,000 psi.

[j] Details in this target table are being revised to match recent changes in the high level cost target.

Table 3.1.4 Technical Targets: Distributed Forecourt Water Electrolysis Hydrogen Production [a, b, c, l]				
Characteristics	**Units**	**2011 Status**	**2015 Target**	**2020 Target**
Hydrogen Levelized Cost [d] (Production Only)	\$/kg	4.20 [d]	3.90 [d]	2.30 [d]
Electrolyzer System Capital Cost	\$/kg \$/kW	0.70 430 [e, f]	0.50 300 [f]	0.50 300 [f]
System Energy Efficiency [g]	% (LHV)	67	72	75
	kWh/kg	50	46	44
Stack Energy Efficiency [h]	% (LHV)	74	76	77
	kWh/kg	45	44	43
Electricity Price	\$/kWh	From AEO 2009 [i]	From AEO 2009 [i]	0.037 [j]

Table 3.1.4.A Distributed Electrolysis H2A Example Cost Contributions [a, b, c, l]					
Characteristics		**Units**	**2011 Status**	**2015**	**2020**
Electrolysis System	Cost Contribution [a, b, e]	\$/kg H_2	0.70	0.50	0.50
	Production Equipment Availability [c]	%	98	98	98
Electricity	Cost Contribution	\$/kg H_2	3.00 [i]	3.10 [i]	1.60 [j]
Production Fixed O&M	Cost Contribution	\$/kg H_2	0.30	0.20	0.20
Production Other Variable Costs	Cost Contribution	\$/kg H_2	0.10	0.10	<0.10
Hydrogen Production	Cost Contribution	\$/kg H_2	4.10	3.90	2.30
Compression, Storage, and Dispensing [k]	Cost Contribution	\$/kg H_2	2.50	1.70	1.70
Total Hydrogen Levelized Cost (Dispensed)		\$/kg H_2	6.60	5.60	4.00

[a] The H2A Distributed Production Model 3.0 (www.hydrogen.energy.gov/h2a_production.html) used alkaline electrolysis parameters to generate the values in the table with the exceptions described in the notes below. Results are documented in the Current and Future H2A v3 case studies for Forecourt Hydrogen Production from Grid Electrolysis which can be found at http://www.hydrogen.energy.gov/h2a_prod_studies.html.

[b] The H2A Distributed Production Model 3.0 was used with the standard economic assumptions: All values are in 2007 dollars, 1.9% inflation rate, 10% After Tax Real Internal Rate of Return, 100% Equity Financing, 20-year analysis period, 38.9% overall tax rate, and 1% working capital (based on independent review input). A MACRS 7-year depreciation schedule was used. The plant design capacity is 1,500 kg/day of hydrogen. It is assumed that

Design for Manufacture and Assembly (DFMA) would be employed and that production would have realized economies of scale.

[c] The plant production equipment availability is 98% including both planned and unplanned outages; four unplanned outages of 14h duration per year; 1 planned outage of 5 days duration per year. The plant usage factor (defined as the actual yearly production/equipment design production capacity) is 90% based on over sizing of the production equipment to accommodate a summer surge in demand of 10% above the yearly average demand.

[d] The levelized cost is equivalent to the minimum required selling price to achieve a 10% annual rate of return over the life of the plant.

[e] Electrolyzer uninstalled capital costs based on independent review panel results [DOE 2009, Current (2009)] State-of-the-Art Hydrogen Production Cost Estimate using Water Electrolysis, Independent Review, NREL/BK-6A1-46676, September 2009 (http://www.hydrogen.energy.gov/pdfs/46676.pdf). "Electrolyzer capital costs are expected to fall to $380/kW for forecourt production." Escalated to 2007 dollars = $430/kW (purchased equipment cost).

[f] Electrolyzer cells capital replacement = 25% of total purchased capital every 7 years (DOE, 2009).

[g] System energy efficiency is defined as the energy in the hydrogen produced by the system (on a LHV basis) divided by the sum of the feedstock energy (LHV) plus all other energy used in the process.

[h] Stack energy efficiency is defined as the energy in the hydrogen produced by the stack (on a LHV basis) divided by the electricity entering the stack. Additional electricity use for the balance of plant is not included in this calculation. Stack energy efficiency is a guideline and the targets do not need to be met as long as the system energy efficiency meets the targets.

[i] Hydrogen cost is calculated assuming purchase of industrial grid electricity. Electricity prices are taken from the 2009 AEO Reference Case price projections to 2030. Prices beyond 2030 are not available in the 2009 AEO case so they are projected based on the PNNL MiniCAM model output http://www.globalchange.umd.edu/models/gcam/). The average electricity price is $0.063/kWh ($0.061/kWh effective) over the modeled life of the plant for the current (2011) case and $0.070/kWh ($0.069/kWh effective) for the 2015 case.

[j] Electricity cost is assumed to be 3.7¢/kWh throughout the analysis period to meet the $4.00/gge target for dispensed hydrogen.

[k] Costs for the forecourt station compression and storage are consistent with the status and targets in the Delivery MYRD&D section. Storage capacity for 1579 kg of hydrogen at the forecourt is included. It is assumed that the hydrogen refueling fill pressure is 5000 psi for 2010 and it assumed that in 2015 and 2020, the hydrogen refueling fill pressure is 10,000 psi.

[l] Details in this target table are being revised to match recent changes in the high level cost target.

Table 3.1.5 Technical Targets: Central Water Electrolysis [a, b, j]				
Characteristics	**Units**	**2011 Status [c]**	**2015 Target [d]**	**2020 Target [e]**
Hydrogen Levelized Cost (Plant Gate) [f]	$/kg H_2	4.10	3.00	2.00
Total Capital Investment [b]	$M	68	51	40
System Energy Efficiency [g]	%	67	73	75
	kWh/kg H_2	50	46	44.7
Stack Energy Efficiency [h]	%	74	76	78
	kWh/kg H_2	45	44	43
Electricity Price [i]	$/kWh	From AEO '09	$0.049	$0.031

Table 3.1.5.A Central Water Electrolysis H2A Example Cost Contributions [a, b, j]				
Characteristics	**Units**	**2011 Status [c]**	**2015 [d]**	**2020 [e]**
Capital Cost Contribution	$/kg	0.60	0.50	0.40
Feedstock Cost Contribution	$/kg	3.20	2.30	1.40
Fixed O&M Cost Contribution	$/kg	0.20	0.10	0.10
Other Variable Cost Contribution	$/kg	0.10	0.10	0.10
Total Hydrogen Levelized Cost (Plant Gate)	$/kg	4.10	3.20	2.00

[a] The H2A Central Production Model 3.0 (www.hydrogen.energy.gov/h2a_production.html) assumed alkaline electrolysis was used to generate the values in the table with the exceptions described in the notes below. Results are documented in the Current and Future H2A v3 case studies for Central Hydrogen Production from Grid Electrolysis which can be found at http://www.hydrogen.energy.gov/h2a_prod_studies.html.

[b] The H2A Central Production Model 3.0 was used with the standard economic assumptions: All values are in 2007 dollars, 1.9% inflation rate, 10% After Tax Real Internal Rate of Return, 100% Equity Financing, 40-year analysis period, and a 38.9% overall tax rate. A MACRS 20-year depreciation schedule was used. The working capital was set at 5% instead of the standard 15% based on input from the 2009 independent review of the "Current State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis" (http://www.hydrogen.energy.gov/pdfs/46676.pdf). The plant design capacity is 52,300 kg/day of hydrogen. The cell stacks for central electrolyzers are assumed to be replaced regularly at a cost of 25% of the initial capital cost. The replacement period is every 7 years in the 2011 case and every 10 years in the 2020 target case. Power availability of 100% is assumed so the electrolysis capacity factor is 98%. The staffing requirement is 10 full time equivalents (FTE) in the 2011 case and 4 FTE in the target cases. The plant gate hydrogen pressure is 300 psi.

[c] The 2011 status is based on the H2A v3 case study on Current Central Hydrogen Production from Grid Electrolysis (http://www.hydrogen.energy.gov/h2a_prod_studies.html) with modifications as outlined in the other footnotes. The uninstalled equipment cost of the electrolyzer system is $368/kW (2007$ - equivalent to $327/kW in 2005$). They were calculated from the independent review panel's report (http://www.hydrogen.energy.gov/pdfs/46676.pdf). The panel reported a Total Depreciable Capital Cost of $50M (2005$) in table 4 (p 22). Using the H2A v2 default indirect costs of 1% for site preparation, 5% for Engineering and Design, 10% for Project Contingency, and 1% for up-front permitting (all percentages of the total direct capital cost), the calculated total direct capital cost is $43,000,000. Removing the installation factor of 1.2, results in a purchased cost of $35,700,000. At the panel's design capacity of 52,300 kg/day and electricity usage of 50kWh/kg, the resulting purchased cost is $327/kW. The estimated system operation is 50 kWh/kg hydrogen resulting in an efficiency of 67%. The startup year is 2010 and the electricity prices over the plant's life are from the 2009 AEO's reference case projections (extrapolated for dates beyond 2030).

[d] The 2015 targets are intermediate targets between the 2011 status and 2020 targets. Uninstalled cost of the electrolyzer was set at $300/kW (2007$ - equivalent to $267/kW in 2005$), system electricity requirement set at 46 kWh/kg (73% efficiency), and staffing set at 4 FTE. The startup year is 2015 and the electricity price is held constant at $0.049/kWh.

[e] The 2020 target is based on the capital cost and performance (energy efficiency) required to approach the production portion of the <$4/gge overall delivered hydrogen production cost consistent with the threshold cost and the 2020 delivery cost target of $2.00/gge. The startup year is set to 2025. Uninstalled cost of the electrolyzer is $242/kW (2007$ - equivalent to $215/kW in 2005$) based on a 50% reduction in the stack cost from the 2010 status and a 20% reduction in the cost of power electronics resulting in an overall reduction of 34% from the 2010 status. Electricity requirement is reduced to 44.7 kWh/kg (75% efficiency). Electricity price was set to $0.031/kWh (constant over the analysis period) and staffing level was reduced to 4 FTE to achieve the targeted levelized cost of $2.00/kg.

[f] The H2A Central Production Model 3.0 (www.hydrogen.energy.gov/h2a_production.html) was used to generate these values at the total invested capital and process energy efficiency indicated in the table.

[g] System energy efficiency is defined as the energy in the hydrogen produced by the system (on a LHV basis) divided by the sum of the feedstock energy (LHV) plus all other energy used in the process.

[h] Stack energy efficiency is defined as the energy in the hydrogen produced by the stack (on a LHV basis) divided by the electricity entering the stack. Additional electricity use for the balance of plant is not included in this calculation. Stack energy efficiency is a guideline and the targets do not need to be met as long as the system energy efficiency meets the targets.

[i] Hydrogen cost is calculated assuming purchase of industrial grid electricity. Electricity prices are taken from the 2009 AEO Reference Case price projections to 2030. Prices beyond 2030 are not available in the 2009 AEO case so they are projected based on the PNNL MiniCAM model output (http://www.globalchange.umd.edu/models/gcam/). The average electricity price is $0.067/kWh ($0.063/kWh effective) for the modeled life of the plant for the 2011 case. The electricity price for the 2015 target case is held constant over the plant's life at $0.049/kWh. The electricity price for the 2020 target case is held constant over the plant's life at $0.031/kWh.

[j] Details in this target table are being revised to match recent changes in the high level cost target.

Table 3.1.6 Technical Targets: Biomass Gasification/Pyrolysis Hydrogen Production [a, b, k]				
Characteristics	**Units**	**2011 Status [c,d]**	**2015 Target [e]**	**2020 Target [f,g]**
Hydrogen Levelized Cost [h] (Plant Gate)	$/kg	2.20	2.10	2.00
Total Capital Investment [b,i]	$M	180	180	170
Energy Efficiency [j]	%	46	46	48

Table 3.1.6.A Biomass Gasification H2A Example Cost Contributions [a, b, k]				
Characteristics	**Units**	**2011 Status[c]**	**2015**	**2020 [d]**
Capital Cost Contribution	$/kg	0.60	0.60	0.60
Feedstock Cost Contribution	$/kg	1.00	1.00	0.90
Fixed O&M Cost Contribution	$/kg	0.20	0.20	0.20
Other Variable Cost Contribution	$/kg	0.40	0.30	0.30
Total Hydrogen Levelized Cost (Plant Gate)	$/kg	2.20	2.10	2.00

[a] These costs are based on modeling the cost of hydrogen production utilizing the H2A Central Production Model 3.0. Results are documented in the Current and Future H2Av3 case studies for Central Hydrogen Production via Biomass Gasification (http://www.hydrogen.energy.gov/h2a_prod_studies.html).

[b] The H2A Central Production Model 3.0 was used with the standard economic assumptions: All values are in 2007 dollars, 1.9% inflation rate, 10% After Tax Return on Investment, 100% Equity Financing, 20-year MACRS straight line depreciation, 40-year analysis period, and 38.9% overall tax rate, 90% capacity factor, and 15% working capital. The plant gate hydrogen pressure is 300 psi. The nominal processing capacity is 2070 and 2000 dry metric tons of biomass per day in the current and 2020 cases, respectively. The specific hydrogen design capacity is 155 metric tons per day for both cases. The current case has a startup year of 2010 and the 2020 case has a startup year of 2020. All feedstock and utility costs are based on their projected costs over the 40-year plant life consistent with the approach used to determine the overall delivered hydrogen threshold cost of <$4/gge. The biomass feedstock cost varies over time and is $75/dry short ton in 2010 and $63/dry short ton in 2017 and following. It is consistent with the EERE Bioenergy Technologies Office estimate for 2012 for woody biomass. The utility costs are based on the 2009 U.S. Energy Information Administration AEO reference projection consistent with the standard H2A methodology.

[c] The current status is based on the H2A v3 Hydrogen Production via Biomass Gasification Current Case (http://www.hydrogen.energy.gov/h2a_prod_studies.html). No one has actually operated an integrated biomass gasification process designed specifically for hydrogen production at any scale. The H2A analysis is based on pilot-scale results of biomass gasification for power generation combined with available information from similar processes for the other components. Performance parameters (e.g., efficiencies) are on individual unit operations hypothetically linked together because integrated performance data are unavailable. Startup year is 2010.

[d] An independent review panel found the current status of a first-of-a-kind plant to be $5.40/kg (2009$) based on a nominal capacity of 500 dry short ton/day with a total capital investment of $214,000,000 (2009$). They used a different methodology for estimating capital costs than this analysis as well as different feedstock costs ($60/dry short ton). Their results are reported at http://www.hydrogen.energy.gov/pdfs/51726.pdf.

[e] The 2015 Targets are intermediate targets between the current status and 2020 targets. The capital cost, biomass yield, and natural gas requirement in the current case were used, the startup year was set to 2015, and all other factors are set to the same as the 2020 target case.

[f] The 2020 Targets are based on the capital cost and performance (energy efficiency) required to approach the production portion of the <$4/gge overall delivered hydrogen production cost consistent with the threshold cost and the 2020 delivery cost target of $2.00/gge. The startup year is set to 2025. Capital cost reductions are based on development of a gasification system with internal reforming that produces hydrogen thus making a stand-alone tar reforming system unnecessary. The capital improvements fall within the sensitivity analysis of the H2A Biomass Gasification Future case (2020 technology-readiness, 2025 startup).

[g] An independent review panel (http://www.hydrogen.energy.gov/pdfs/51726.pdf) projected a levelized cost of $2.80/kg for an n^{th} plant based on a nominal capacity of 2000 dry ton/day with a total capital investment of $344,000,000 (2009$). They used a different methodology for estimating capital costs than this analysis and different feedstock costs ($80/dry ton).

[h] The H2A Central Production Model 3.0 (www.hydrogen.energy.gov/h2a_production.html) was used to generate these values at the total invested capital and process energy efficiency indicated in the table. See Record #14005 for more details (www.hydrogen.energy.gov/program_records.html).

[i] All cases assume capital replacement at 0.5%/yr. of total depreciable capital investment.

[j] Energy efficiency is defined as the energy in the hydrogen produced (on a LHV basis) divided by the sum of the feedstock energy (LHV) plus all other energy used in the process.

[k] Details in this target table are being revised to match recent changes in the high level cost target.

Table 3.1.7 Technical Targets: Solar-Driven High-Temperature Thermochemical Hydrogen Production [a, h]					
Characteristics	**Units**	**2011 Status**	**2015 Target**	**2020 Target**	**Ultimate Target**
Solar-Driven High-Temperature Thermochemical Cycle Hydrogen Cost [b]	\$/kg	NA	14.80	3.70	2.00
Chemical Tower Capital Cost (installed cost) [c]	\$/TPD H_2	NA	4.1MM	2.3MM	1.1MM
Annual Reaction Material Cost per TPD H_2 [d]	\$/ yr.-TPD H_2	NA	1.47M	89K	11K
Solar to Hydrogen (STH) Energy Conversion Ratio [e,f]	%	NA	10	20	26
1-Sun Hydrogen Production Rate [g]	kg/s per m^2	NA	8.1E-7	1.6E-6	2.1E-6

[a] The targets in this table are for research tracking with the Ultimate Target values corresponding to market competitiveness. Targets are based on an initial analysis utilizing the H2A Central Production Model 3.0 with standard H2A economic parameters (http://www.hydrogen.energy.gov/h2a_production.html). Projections assume a ferrite high-temperature cycle with a central production capacity of 100,000 kg H_2/day. Further analysis assumptions may be found in "Support for Cost Analyses on Solar-Driven High Temperature Thermochemical Water-Splitting Cycles, TIAX LLC, Final Report to U.S. Department of Energy, 22 February 2011" (http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/solar_thermo_h2_cost.pdf).

[b] Hydrogen cost represents the complete system hydrogen production cost for purified, 300 psi compressed gas. System level losses such as heliostat collector area losses, replacement parts, operation, and maintenance are included in the cost calculations which are documented in the H2A v3 Future Case study for Solar-thermochemical Production of Hydrogen (http://www.hydrogen.energy.gov/h2a_prod_studies.html).

[c] The chemical tower capital cost is the projected total installed cost for the ferrite cycle conversion of water into hydrogen.

[d] Reaction material cost is defined as the effective annual cost of the active (ferrite) material within the thermochemical process per metric ton rated hydrogen capacity of the system. The value is calculated as the expected annual purchase price of the material in its usable form (e.g., ferrite coated on a substrate) divided by the material lifetime under expected use condition (i.e., nearly continuous usage during the sunlight hours with an annual capacity factor of 90%); divided by the net rated hydrogen production capacity of the system [in metric tons per day (TPD)] (For example, 100,000 kg H_2/day = 100 TPD). Material cost improvements are expected to result from a combination of decreased material usage, improved cycle time, and increased material lifetime.

[e] STH energy conversion ratio is defined as the energy of the net hydrogen produced (LHV) divided by full-spectrum solar energy consumed. For systems utilizing solar energy input only, the consumed energy is calculated based on the incident irradiance over the total area of the solar collector. For hybrid systems, all additional non-solar energy sources (e.g., electricity) must be included as equivalent solar energy inputs added to the denominator of the ratio.

[f] Due to the developmental nature of the technology, the STH energy conversion ratio has not yet been measured for the complete solar to hydrogen reaction. Consequently, STH targets are calculated based on partial laboratory measurements using artificial light sources with extrapolation to overall system performance.

[g] The hydrogen production rate in kg/s per total area of solar collection under full-spectrum 1-sun incident irradiance (1,000 W/m^2). Under ideal conditions, STH can be related to this rate as follows: STH = H_2 Production Rate (kg/s per m^2) * 1.23E8 (J/kg) / 1.00E3 (W/m^2). Measurements of the 1-sun hydrogen production rate can provide an invaluable diagnostic tool in the evaluation of loss mechanisms contributing to the STH ratio.

[h] Details in this target table are being revised to match recent changes in the high level cost target.

Table 3.1.7A contains the values of several cost and performance parameters which, when combined, achieve the DOE performance targets for each target year. The parameters may be traded-off against one another to achieve the overall cost targets (e.g. reaction material cost may be traded-off with replacement lifetime). Consequently, the parameter values are listed merely as examples as there are numerous numerical combinations that meet the DOE targets.

Table 3.1.7.A Example Parameter Values to Meet Cost Targets: Solar-Driven High-Temperature Thermochemical Hydrogen Production [b]

Characteristics	Units	2011 Status	2015 Target	2020	Ultimate
Solar to Hydrogen (STH) Energy Conversion Ratio	%	NA	10	20	26
Cycle Time	minutes/ cycle	NA	5	3	1
Reaction Material Cost	$/kg	270	270	270	270
Reaction Material Replacement Lifetime	years	NA	1	5	10
Heliostat Capital Cost (installed cost) [a]	$/m^2	200	140	75	75

[a] Heliostat capital costs encompass all capital costs, including installation, with the solar reflector system needed to focus solar energy onto the chemical tower reactor. Cost is stated per square meter of solar capture area. Heliostat capital cost status for 2010 and the capital cost targets for 2015 and 2020 are consistent with the current viewpoint of the EERE Solar Program as reflected in the "Power Tower Technology Roadmap and Cost Reduction Plan" SAND2011-2419, April 2011, (http://prod.sandia.gov/techlib/access-control.cgi/2011/112419.pdf) and the DOE SunShot Vision Study (http://www1.eere.energy.gov/solar/pdfs/47927_chapter5.pdf), respectively.

[b] Details in this target table are being revised to match recent changes in the high level cost target.

Table 3.1.8 Technical Targets: Photoelectrochemical Hydrogen Production: Photoelectrode System with Solar Concentration [a, h]					
Characteristics	**Units**	**2011 Status**	**2015 Target**	**2020 Target**	**Ultimate Target**
Photoelectrochemical Hydrogen Cost [b]	$/kg	NA	17.30	5.70	2.10
Capital cost of Concentrator & PEC Receiver (non-installed, no electrode) [c]	$\$/m^2$	NA	200	124	63
Annual Electrode Cost per TPD H_2 [d]	$/ yr-TPD$H_2$	NA	2.0M	255K	14K
Solar to Hydrogen (STH) Energy Conversion Ratio [e, f]	%	4 to 12%	15	20	25
1-Sun Hydrogen Production Rate [g]	kg/s per m^2	3.3E-7	1.2E-6	1.6E-6	2.0E-6

[a] The targets in this table are for research tracking with the Ultimate Target values corresponding to market competitiveness. Targets are based on an initial analysis utilizing the H2A Central Production Model 3.0 with the standard H2A economic parameters (www.hydrogen.energy.gov/h2a_production.html). Targets are based on photoelectrode-type PEC systems wherein a solar trough collector concentrates light onto a PEC receiver assembly. The PEC receiver consists of a flat panel PEC electrode (submerged in an electrolyte bath) and the collection housing and manifolds to collect and separate the evolved hydrogen and oxygen gases. Solar concentration is assumed to be 15:1 for the ultimate target case and 10:1 for all others. Further analysis assumptions may be found in "Technoeconomic Analysis of Photoelectrochemical (PEC) Hydrogen Production", Directed Technologies Inc., Final Report to the Department of Energy, December 2009 (http://www.hydrogen.energy.gov/pdfs/review09/pd_23_james.pdf). Plant assumed capacity is 50,000 kg H_2/day for all years. All targets are expressed in 2007 dollars.

[b] Hydrogen cost represents the complete system hydrogen production cost for purified, 300 psi compressed gas. System level losses and expenses due to solar collection/concentration, window transmittance/refraction, replacement parts, operation, and maintenance are included in the cost calculations which are documented in the H2A v3 Future Case study for Type 4 (Photoelectrode System with Concentration) Photoelectrochemical (PEC) Production of Hydrogen (http://www.hydrogen.energy.gov/h2a_prod_studies.html).

[c] Capital cost includes solar concentration and associated tracking (if any), the optical window, and the water/electrolyte/gas containment subsystem. The cost of the PEC electrode is not included. All areas refer to total solar capture area. While improvements beyond the current status are needed to meet these cost goals, this area is not presently a research focus of the Fuel Cell Technologies Program.

[d] Annual electrode cost refers to the annual replacement cost of the PEC photoelectrode panel normalized by the design capacity of the system (in metric tons H_2 per day). Electrode cost includes both the material and manufacturing cost of the PEC electrode used within the reactor.

[e] STH energy conversion ratio is defined as the energy of the net hydrogen produced (LHV) divided by full-spectrum solar energy consumed. For systems utilizing solar energy input only, the consumed energy is calculated based on the incident irradiance over the total area of the solar collector. For hybrid systems, all additional non-solar energy sources (e.g., electricity) must be included as equivalent solar energy inputs added to the denominator of the ratio.

[f] The 2011 Status of STH ratio is in the range of 4% and 12% for different semiconductor material systems exhibiting different levels of operational durability. Thin film material systems have been demonstrated with STH > 4% for hundreds of hours (A. Madan, Fuel Cell Technologies Program 2011 Annual Progress Report: http://www.hydrogen.energy.gov/pdfs/progress11/ii_g_5_madan_2011.pdf); Crystalline material systems have been demonstrated with STH > 12% for tens of hours. [O. Khaselev, J.A. Turner, Science 280, 425 (1998)].

[g] The hydrogen production rate in kg/s per total area of solar collection under full-spectrum 1-sun incident irradiance (1,000 W/m^2). Under ideal conditions, STH can be related to this rate as follows: STH = H_2 Production Rate (kg/s per m^2) * 1.23E8 (J/kg) / 1.00E3 (W/m^2). Measurements of the 1-sun hydrogen production rate can provide an invaluable diagnostic tool in the evaluation of loss mechanisms contributing to the STH ratio.

[h] Details in this target table are being revised to match recent changes in the high level cost target.

Table 3.1.8A contains the values of several cost and performance parameters which, when combined, achieve the DOE performance targets for each target year. The parameters may be traded-off against one another to achieve the overall cost targets (e.g., electrode cost may be traded-off with replacement lifetime). Consequently, the parameter values are listed merely as examples as there are numerous numerical combinations that meet the DOE targets.

Table 3.1.8.A Example Parameter Values to Meet Cost Targets: Photoelectrochemical Hydrogen Production (Photoelectrode System) [e]

Characteristics	Units	2011 Status	2015	2020	Ultimate
Solar to Hydrogen (STH) Energy Conversion Ratio	%	NA	15	20	25
PEC Electrode cost [a]	$\$/m^2$	NA	300	200	100
Electrode Cost per TPD H_2 [b]	$/ TPD	NA	1.0M	510K	135K
Electrode Replacement Lifetime [c]	Years	NA	0.5	2	10
Balance of Plant Cost per TPD H_2 [d]	$/ TPD	NA	420K	380K	310K

a PEC photoelectrode cost refers to the material and manufacturing cost of the PEC electrode. Area is based on the actual area of the electrode itself.

b This parameter is the PEC photoelectrode cost (as defined above) normalized by the metric tons per day of hydrogen design capacity of the electrode.

c Electrode replacement lifetime denotes the projected total duration of the electrode being immersed in electrolyte and under cyclic solar illumination until process energy efficiency drops to 80% of its original values. Thus, a 10 year electrode replacement lifetime refers to 10 years of operation under diurnal cycles and approximately 5 years of actual hydrogen production.

d This parameter denotes non-electrode, non-concentrator/PEC receiver, non-installation balance of plant costs normalized by the metric tons per day of hydrogen design capacity of the electrode.

e Details in this target table are being revised to match recent changes in the high level cost target.

Table 3.1.9 Technical Targets: Photoelectrochemical Hydrogen Production: Dual Bed Photocatalyst System [a, g]

Characteristics	Units	2011 Status	2015 Target	2020 Target	Ultimate Target
Photoelectrochemical Hydrogen Cost [b]	$/kg	NA	28.60	4.60	2.10
Annual Particle Cost per TPD H_2 [c]	$/ yr-TPD$H_2$	NA	1.4M	71K	4K
Solar to Hydrogen (STH) Energy Conversion Ratio [d,e]	%	NA	1	5	10
1-Sun Hydrogen Production Rate [f]	kg/s per m^2	NA	8.1E-8	4.1E-7	8.1E-7

[a] The targets in this table are for research tracking with the Ultimate Target values corresponding to market competitiveness. Targets are based on an initial analysis utilizing the H2A-Central Production Model 3.0 with standard H2A economic parameters (www.hydrogen.energy.gov/h2a_production.html). Targets are based on a dual-bed PEC nanoparticle slurry-type system wherein clear thin film polymer bag-style reactors are filled with water and photocatalytically active nanoparticles. The hydrogen evolution half-reaction occurs in one bag reactor section and the oxygen evolution half-reaction occurs in an adjacent reactor section. The reactor sections are connected by a porous ionic bridge which permits ion exchange to complete the electrochemical circuit but prevents gas mixing. Solar energy energizes both reactions. No solar concentration is used. Further analysis assumptions may be found in "Technoeconomic Analysis of Photoelectrochemical (PEC) Hydrogen Production," Directed Technologies Inc., Final Report to the Department of Energy, December 2009 (http://www.hydrogen.energy.gov/pdfs/review09/pd_23_james.pdf). Plant capacity is 50,000 kg H_2/day for all years. All targets are expressed in 2007 dollars.

[b] Hydrogen cost represents the complete system hydrogen production cost for purified, 300 psi compressed gas. System level losses and expenses due to solar window transmittance/refraction, replacement parts, operation, and maintenance are included in the cost calculations which are documented in the H2A v3 Future Case study for Type 2 (PEC Dual Bed Photocatalyst System) Photoelectrochemical Production of Hydrogen (http://www.hydrogen.energy.gov/h2a_prod_studies.html).

[c] PEC particle cost refers to the annual replacement cost of the PEC nanoparticles normalized by the design capacity of the system (metric tons H_2 per day). Particle cost includes both the material and manufacturing cost of the PEC nanoparticles used within the reactor. Although different chemical reactions occur in the two bed sections, particle cost is combined for purposes of cost reporting.

[d] STH energy conversion ratio is defined as the energy of the net hydrogen produced (LHV) divided by full-spectrum solar energy consumed. For systems utilizing solar energy input only, the consumed energy is calculated based on the incident irradiance over the total area of the solar collector. For hybrid systems, all additional non-solar energy sources (e.g., electricity) must be included as equivalent solar energy inputs added to the denominator of the ratio. In a dual bed system, this requires two material systems each with half reactions operating at twice the stated net STH energy conversion ratio.

[e] Dual bed systems are less mature than photoelectrode PEC systems. The current status STH energy conversion ratio is still under investigation.

[f] The hydrogen production rate in kg/s per total area of solar collection under full-spectrum 1-sun incident irradiance (1,000 W/m^2). Under ideal conditions, STH can be related to this rate as follows: STH = H_2 Production Rate (kg/s per m^2) * 1.23E8 (J/kg) / 1.00E3 (W/m^2). Measurements of the 1-sun hydrogen production rate can provide an invaluable diagnostic tool in the evaluation of loss mechanisms contributing to the STH ratio.

[g] Details in this target table are being revised to match recent changes in the high level cost target.

Table 3.1.9A contains the values of several cost and performance parameters which, when combined, achieve the DOE performance targets for each target year. The parameters may be traded-off against one another to achieve the overall cost targets (e.g., particle cost may be traded-off with replacement lifetime). Consequently, the parameter values are listed merely as examples as there are numerous numerical combinations that meet the DOE targets.

Table 3.1.9.A Example Parameter Values to Meet Cost Targets: Photoelectrochemical Hydrogen Production (Dual Bed Photocatalyst) [e]

Characteristics	Units	2011 Status	2015	2020	Ultimate
Solar to Hydrogen (STH) Energy Conversion Ratio	%	NA	1	5	10
PEC particle cost [a]	$/kg	NA	1000	500	300
Particle Replacement Lifetime [b]	Years	NA	0.5	1	5
Capital cost of reactor bed system (excluding installation and PEC particles) [c]	$/m^2	NA	7	7	5
Balance of Plant Cost per TPD H_2 [d]	$/ TPD	NA	6.4M	1.0M	0.6M

[a] PEC particle cost refers to the material and manufacturing cost of the PEC nanoparticles used within the reactor. While different chemical reactions occur in the two bed sections, the particle costs are combined for purposes of cost reporting. Particle mass is based on the total particle mass (including inert substrate if used).

[b] Particle replacement lifetime denotes the projected total duration of the nanoparticles being immersed in electrolyte and under cyclic solar illumination until process energy efficiency drops to 80% of its original values. Thus, a 5 year particle replacement lifetime refers to 5 years of operation under diurnal cycles and approximately 2.5 years of actual hydrogen production.

[c] Reactor system capital cost includes only the high density polyethylene clear plastic film reactor bed assembly and its associated ionic transfer bridges. Installation, fluid piping, and the photocatalytic nanoparticles are not included. All areas refer to total solar capture area.

[d] This parameter denotes the non-installed balance of plant costs exclusive of reactor beds and PEC particles. It includes piping, controls, sensors, pumps, and compressors and is normalized by the metric tons per day of hydrogen design capacity of the system.

[e] Details in this target table are being revised to match recent changes in the high level cost target.

Table 3.1.10 Technical Targets: Photolytic Biological Hydrogen Production [a, m]					
Characteristics	**Units**	**2011 Status**	**2015 Target [c]**	**2020 Target [d]**	**Ultimate Target [e]**
Hydrogen Cost [b]	\$/kg	NA	NA	9.20	2.00
Reactor Cost [f]	\$/m^2	NA	NA	14	11
Light utilization efficiency (% incident solar energy that is converted into photochemical energy) [g]	%	25 [h]	28	30	54
Duration of continuous H_2 production at full sunlight intensity [i]	Time Units	2 min [j]	30 min	4 h	8 h
Solar to H_2 (STH) Energy Conversion Ratio [k]	%	NA	2%	5%	17%
1-Sun Hydrogen Production Rate [l]	kg/s per m^2	NA	1.6E-7	4.1E-7	1.4E-6

[a] The targets in this table are for research tracking with the Ultimate Target values corresponding to market competitiveness. Targets are based on an initial analysis utilizing the H2A Central Production Model 3.0 with standard H2A economic parameters (www.hydrogen.energy.gov/h2a_production.html.)

[b] Hydrogen cost represents the complete system hydrogen production cost for purified, 300 psi compressed gas. Projections assume photolytic production of hydrogen gas by genetically engineered organisms (algal or bacterial) suspended in a water solution under solar illumination, modeled as algae, with an O_2-tolerant hydrogenase, grown in large, raceway-type, shallow bed reactors that are covered by a thin, optically transparent film, and provided with nutrients, CO_2, and sunlight. The evolved gas will be collected, purified to 99.999+ hydrogen purity by pressure swing adsorption (PSA), and compressed to 300 psi for hydrogen pipeline transport. Plant capacity is 50,000 kg H_2/day for all years. All targets are expressed in 2007 dollars. Cost calculations are documented in the H2A v3 Future Case Study for Photolytic Biological Production of Hydrogen (http://www.hydrogen.energy.gov/h2a_prod_studies.html). Further analysis assumptions may be found in "Technoeconomic Boundary Analysis of Biological Pathways to Hydrogen Production," Directed Technologies, Inc., Final Report to U.S. Department of Energy, 31 August 2009 (http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/46674.pdf).

[c] The 2015 target is based on analysis of the best technologies projected to be available in 2015 and assumes integration into a single, non-hybrid organism. Specifically, the 2015 target is based on a model of a *Chlamydomonas reinhardtii* strain with an O_2-tolerance hydrogenase system and a reduced chlorophyll antennae light harvesting complex (LHC), in which all the improvements listed in the table have been integrated.

[d] For 2020, all assumptions of the 2015 target system apply (such as reactor system design and organism type) except the organism is assumed to be further improved in the target parameters indicated in the table.

[e] For the 2015 and 2020 targets, the organism modeled is assumed to be an algal strain with a native photosynthesis system (i.e., with Photosystems I and II). For the Ultimate Target, previous assumptions (such as reactor system design) apply, but the modeled organism is both optimized and has a genetically modified hybrid photosynthetic system combining the native algal Photosystem II with a bacterial Reaction Center, achieving greater hydrogen production rates by extending the light spectrum that can be collected and improving the efficiency of other conversion steps. Fundamental genetic engineering advances are required to reach the hybrid organism's ultimate target efficiency values. If the hybrid organism was not successfully genetically engineered, performance would be limited to a light utilization efficiency of 34%, an STH ratio of 9.8%, and a cost of \$2.6/kg H_2.

[f] Installed cost per square meter of organism bed reactor equipment includes the containment structure, film covering, and any reactor interior flow control equipment. It does not include cost of complementary equipment

such as compressors, PSA, Control Room, etc. Square meters are defined as the solar capture area. Future designs for the reactors will need to address safety measures to deal with the co-production of hydrogen and oxygen (e.g., replacing PSA systems with Temperature Swing Apparatus systems), which may increase costs. Due to the early stage of development, photobioreactor designs and the required organismal characteristics will likely undergo modifications before widespread commercial use to address issues such as temperature, salinity, and pH control.

g The light utilization efficiency is the conversion efficiency of incident solar energy into photochemically available energy and is the product of two values: the light collection efficiency and the photon use efficiency at full sunlight intensity. The first value, light collection efficiency, is the fraction of solar incident light that is within the photosynthetically active radiation (PAR) wavelength band of the organism. For green algae, the light collection efficiency is estimated to be 45% ("Light and photosynthesis in aquatic ecosystems," Kirk, Cambridge University Press, 1994), and is considered fixed for the 2015 and 2020 targets; the hybrid organism modeled for the ultimate target is estimated to have a light collection efficiency of up to 64% ("Integrated biological hydrogen production," Melis and Melnicki, International Journal of Hydrogen Energy, September 2006) http://www.sciencedirect.com/science/article/pii/S0360319906002308). The second value, photon use efficiency, is the efficiency of converting the absorbed photon energy into chemical energy through photosynthesis at full sunlight intensity (2,500 micromol photons per square meter per second). At low-light conditions (i.e., with no light saturation), the average photon use efficiency for algae is 85% ("Absolute absorption cross sections for photosystem II and the minimum quantum requirement for photosynthesis in *Chlorella vulgaris*." Ley and Mauzerall, Biochim. Biophys. Acta 1982). Experimentally, photon use efficiency is determined by measuring the rate of photosynthesis (via oxygen evolution) per photon at different light intensities and comparing the rates at full sunlight and at sub-saturating light levels, with the maximum value set at the 85% efficiency level.

h "Maximizing Light Utilization Efficiency and Hydrogen Production in Microalgal Cultures," Melis, 2008 Annual Progress Report for DOE's Hydrogen Program (http://www.hydrogen.energy.gov/pdfs/progress08/ii_f_2_melis.pdf).

i For purposes of conversion efficiencies and duration reporting, full sunlight (2,500 micromol photons per square meter per second) conditions are assumed. Since in actual practice light intensity varies diurnally, only 8 hours of continuous duration is needed for a practical system. The duration values assume a system where the enzyme is regenerated at night with respiration scavenging oxygen.

j Brand et al., 1989, Biotechnol. Bioeng.

k STH energy conversion ratio is defined as the energy of the net hydrogen produced (LHV) divided by net full-spectrum solar energy consumed. For systems utilizing solar energy input only, the consumed energy is calculated based on the incident irradiance over the total area of the solar collector. For hybrid systems, all additional non-solar energy sources (e.g., electricity) must be included as equivalent solar energy inputs added to the denominator of the ratio. For photolytic biological hydrogen production, this can be thought of as the product of three components: $E_0*E_1*E_2$. The maximum potential value is calculated by determining the highest possible conversion efficiencies at three steps: E_0, the percent of solar energy (at sea level) that is absorbed by the organism; E_1, the percent of absorbed energy that is utilized for charge separation by the photosystems; and E_2, the energy for charge separation that is utilized for water splitting. The E_2 value is reduced by 20% to account for the fact that some photon energy will go to other processes, such as cellular maintenance, rather than hydrogen production. The hydrogen cost calculation takes into consideration reductions due to reactor light transmittance (10% loss) and the loss of production over a full production day due to durations less than 8 h. Cost calculations are documented in the H2A v3 Future Case Study for Photolytic Biological Production of Hydrogen (http://www.hydrogen.energy.gov/h2a_prod_studies.html).

l The hydrogen production rate in kg/s per total area of solar collection under full-spectrum 1-sun incident irradiance (1,000 W/m^2). Under ideal conditions, STH can be related to this rate as follows: STH = H_2 Production Rate (kg/s per m^2) * 1.23E8 (J/kg) / 1.00E3 (W/m^2). Measurements of the 1-sun hydrogen production rate can provide an invaluable diagnostic tool in the evaluation of loss mechanisms contributing to the STH ratio.

m Details in this target table are being revised to match recent changes in the high level cost target.

Table 3.1.11 Technical Targets: Photosynthetic Bacterial Hydrogen Production [a, f]				
Characteristics	Units	2011 Status	2015 Target	2020 Target [b]
Efficiency of Incident Solar Light Energy to H_2 (E0*E1*E2) [c] from organic acids	%	NA	3	4.5
Molar Yield of Carbon Conversion to H_2 (depends on nature of organic substrate) E3 [d]	% of maximum	NA	50	65
Duration of continuous photoproduction [e]	Time	NA	30 days	3 months

[a] The targets in this table are for research tracking. The final targets for this technology are costs that are market competitive. This table will be updated in a future version of this plan to incorporate hydrogen cost target and current technology assumptions.

[b] Technology readiness targets (beyond 2020) are 5.5% efficiency of incident solar light energy to H_2 (E0*E1*E2) from organic acids, 80% of maximum molar yield of carbon conversion to H_2 (depends on nature of organic substrate) E3, and 6 months duration of continuous photoproduction. See Figure 3.1.2 for a schematic representation of conversion steps and associated efficiencies.

[c] E0 reflects the light collection efficiency of the bacteria in the photoreactor and the fact that only a fraction of incident solar light is photosynthetically active (theoretical maximum is 68%, from 400 to 1000 nm). E1*E2 is equivalent to the efficiency of conversion of absorbed light to primary charge separation then to adenosine-5'-triphosphate; both are required for hydrogen production via the nitrogenase enzyme. E0*E1*E2 represents the efficiency of conversion of incident solar light to hydrogen through the nitrogenase enzyme (theoretical maximum is 10% for 4-5 electrons). This efficiency does not take into account the energy used to generate the carbon substrate.

[d] E3 represents the molar yield of H_2 per carbon substrate (the theoretical maximum is 7 moles per mole carbon in the substrate, based on the average yield of acetate and butyrate).

[e] Duration reflects continuous production in the light, not necessarily at peak efficiencies. It includes short periods during which ammonia is re-added to maintain the system active.

[f] Details in this target table are being revised to match recent changes in the high level cost target.

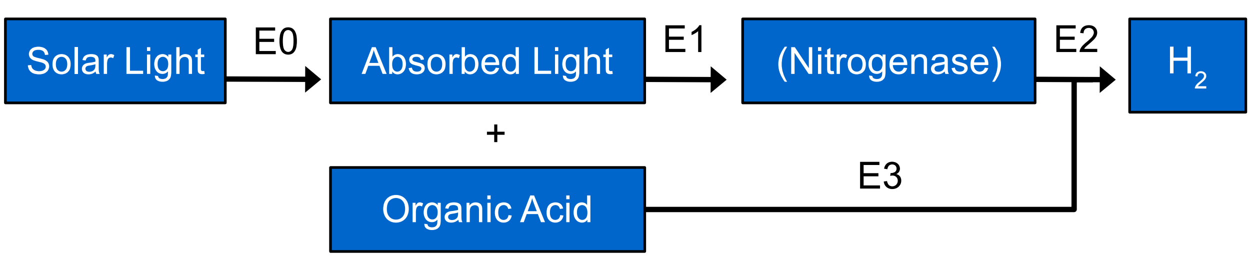


Figure: 3.1.2 Photosynthetic Bacterial System Overview Illustrating E0, E1, E2 and E3 Conversion Processes

Table 3.1.12 Technical Targets: Dark Fermentative Hydrogen Production and Microbial Electrolysis Cells (MECs) [a, i]

Characteristics	Units	2011 Status	2015 Target	2020 Target [b]
Feedstock Cost [c]	cents/lb. sugar	13.5	10	8
Yield of H_2 production from glucose by fermentation [d]	mol H_2 /mol glucose	3.2 [e]	4	6
Yield of H_2 production from glucose by integrated MEC – fermentation [f]	mol H_2 /mol glucose	-	6 [e]	9 [e]
Duration of continuous production (fermentation)	Time	17 days [g]	3 months	6 months
MEC cost of electrodes	$/m^2	2,400 [h]	300	50
MEC production rate	L-H_2 / L-reactor-day	-	1	4

[a] The targets in this table are for research tracking. The final targets for this technology are costs that are market competitive. This table will be updated in a future version of this plan to incorporate hydrogen cost targets and feedstock assumptions.

[b] Technology readiness targets (beyond 2020) are 10 molar yield of H_2 production from glucose, 6 cents/lb. sugar feedstock cost, and 12 months duration of continuous production.

[c] Targets are from the DOE Bioenergy Technologies Office Multi Year Program Plan 2007-2012, August, 2005, for sugar from lignocellulosic biomass. The targets have been shifted 2-5 years in Table 3.1.12 for purposes of FCT planning pending further analysis of this pathway.

[d] The theoretical maximum from known fermentative pathways is 4, although the H_2 content of 1 mole of glucose and the H_2O required for fermentation is 12. Clearly, in order to achieve molar yields greater than 4, the feasibility of developing new pathways or discovering new microbes needs to be assessed.

[e] In 2010, NREL reported a H_2 molar yield of 3.2 by supplying limited amounts of cellulose substrate during fermentation (2010 Annual Progress Report DOE Hydrogen Program; (http://www.hydrogen.energy.gov/pdfs/progress10/ii_h_3_maness.pdf).

[f] The yield assumes a system where the effluent from the glucose-fed fermentation system is used as feedstock for an MEC (e.g., in 2015 the target for fermentation is 4 mol H_2/mol glucose while that for MEC is 2 mol H_2/mol glucose, for a total combined target of 6 mol H_2/mol glucose). The goal is for continuous flow operation conditions.

[g] Van Ginkel, S., Sung, S. 2001. Environ. Sci. Technol. 35: 4726-4730.

[h] Estimated for replacing Pt with MoS_2, based on Tokash, J.C. and B.E. Logan. 2011. "Electrochemical evaluation of a molybdenum disulfide catalyst for the hydrogen evolution reaction under solution conditions applicable to microbial electrolysis cells." Int. J. Hydrogen Energy. 36(16): 9439-9445.

[i] Details in this target table are being revised to match recent changes in the high level cost target.

3.1.5 Technical Barriers

The following sections detail the technical and economic barriers that must be overcome to attain the Hydrogen Production goal and objectives. The barriers are divided into sections depending on the hydrogen production method.

Distributed Hydrogen Production from Renewable Liquid Feedstocks

Reforming of ethanol and other bio-derived liquids is similar to natural gas reforming but presents several unique issues, such as high feedstock costs and catalyst and water requirements. This technology is suitable for application in distributed and semi-central production.

A. Reformer Capital Costs and Efficiency. Current small-scale distributed renewable liquid feedstock reforming technologies have capital costs that are too high to achieve the targeted hydrogen production cost. Multiple-unit operations that entail many process steps in converting bio-derived liquids to hydrogen and low energy efficiencies are key contributors to the high capital cost. Improved reforming and water-gas shift catalysts are needed to increase yield and improve performance. Reforming and water-gas shift unit operations also generate considerable costs. Finally, the high purity of hydrogen required for fuel cells puts upward pressure on the capital costs.

B. Operations and Maintenance (O&M). O&M costs for distributed reforming hydrogen production from renewable feedstocks are too high. Robust systems that require little maintenance and that include remote monitoring capability need to be developed. The reliability of balance of plant (BOP) equipment (pumps, compressors, blowers, sensors, etc.) is often the limiting factor in overall system reliability. Increasing the reliability and service life of these components is critical, as is minimizing equipment complexity. For reformer systems, catalyst activity is also critical for reliable and efficient operation.

C. Biomass Feedstock Issues. Feedstock costs for bio-derived liquids are too high, and there is likely to be strong competition for the available resources from other end-use applications (e.g., bio-derived fuels). In addition to cost, biomass feedstock quality and availability may be limited in some areas, or the quality of the feedstock may change throughout the year. Feedstock-flexible reformers are needed to address location-specific feedstock supply issues. Effects of impurities on the system from multiple feedstocks as well as the effects of impurities from variations in single feedstocks need to be addressed in the reformer design.

D. Forecourt Footprint and Storage. To be economically feasible in urban settings, the physical footprint of stations needs to be reduced. Issues may arise regarding the storage of renewable feedstocks on site. Some feedstocks will be relatively benign (e.g., carbohydrates) and will likely require minimal regulation, while others may fit under the regulations now being developed for E85, E100, and bio-diesel. Regulations for still other types of feedstocks may need to be developed. Permitting will need to be addressed.

E. Control and Safety. Control and safety issues are associated with natural gas and renewable feedstock reforming, including on-off cycling. Effective operation control strategies are needed to minimize cost and emissions, maximize efficiency, and enhance safety. Hydrogen leakage is addressed within the Delivery and Safety, Codes & Standards sub-programs.

Hydrogen Generation by Water Electrolysis

F. Capital Cost. The capital costs of water electrolysis systems are prohibitive to widespread adoption of electrolysis technology for low cost hydrogen production. RD&D is needed to develop lower cost materials with improved manufacturing capability to lower capital cost requirements while improving the efficiency and durability of the system. Development of larger systems is also needed to take advantage of economies of scale. Technically viable systems for low-cost manufacturing need to be developed for this technology.

G. System Efficiency and Electricity Cost. Improvements in BOP efficiency and durability are necessary to the commercial viability of electrolysis. Mechanical high-pressure compression technology exhibits low energy efficiency and may introduce impurities while adding significantly to the capital and operating cost. Efficiency gains can be realized through minimized mechanical compression using electrochemical compression in the cell stack. Development is needed for low-cost cell stack optimization addressing efficiency, compression, and durability. Target costs cannot be met unless electricity price is < $0.04/kWh (see Tables 3.1.4 and 3.1.5).

H. Footprint. Station footprint is dependent on location and the needs of each specific locality. The footprint, in general, will have the same limitations that were described in the distributed hydrogen production from renewable liquid feedstocks section.

I. Grid Electricity Emissions (for distributed). The current grid electricity mix in most locations results in greenhouse gas emissions in large-scale electrolysis systems. Low-cost, carbon-free electricity generation is needed. Electrolysis systems that can produce both hydrogen and electricity need to be evaluated. (Renewable electricity costs are being addressed by the DOE EERE renewable power programs – Solar, Wind, Hydropower, Geothermal, and Biomass.)

J. Renewable Electricity Generation Integration (for central). More efficient integration with renewable electricity generation is needed to reduce costs, improve performance, and increase on-stream time (i.e., increase the number of hours per year the renewable electricity is available). Development of integrated renewable electrolysis systems is needed, including optimization of power conversion and other system components from renewable electricity to provide high-efficiency, low-cost integrated renewable hydrogen production.

K. Manufacturing. Currently, the electrolysis units are produced in low volumes. Since development of fabrication technologies is capital intensive, manufacturers must have assurance that there will be high demand for the product in order to produce adequate returns on investments. The cost of water electrolysis systems is driven up by the high cost of BOP, the short lifespan of system components, and site-specific fabrication of system components.

L. Operations and Maintenance. The O&M cost for electrolysis are currently too high. Durability, maintenance, reliability, and demand management are similar to those of the distributed natural gas reforming systems. Operating efficiency, component durability, purification of water, and transients and changes in duty cycles need to be addressed.

M. Control and Safety. Barriers in control and safety include the efficiency of start-up and shut-down processes, turn-down capability, and the capability for rapid on-off cycling. Control and safety costs still remain high due to complex system designs and high-cost sensors. For commercialization of this technology, reliability and safety of these units is a key qualification target.

Biomass Gasification Hydrogen Production

N. Feedstock Cost and Availability. Feedstock costs are high. Improved feedstock/agricultural technologies (higher yields per acre, etc.), lower cost feedstock collection, and improved feedstock preparation are needed. Because biomass feedstocks are seasonal in nature, feedstock-flexible processes and cost-effective feedstock storage are needed. (Tasks to overcome these barriers are the responsibility of the DOE Bioenergy Technologies Office and the U.S. Department of Agriculture.)

O. Capital Cost and Efficiency of Biomass Gasification Technology. The capital cost for biomass gasification/pyrolysis needs to be reduced. Process intensification by combining unit operations can significantly reduce capital costs. For example, combining the current two step water-gas shift and PSA separation to a one step water-gas shift with integrated separation, to integrating gasification, reforming, water-gas shift and separation all in one unit operation. Improved process efficiency and higher hydrogen yields and selectivity's through catalyst research, better heat integration, and alternative gas clean-up approaches are needed. Improved catalysts or engineering approaches for tar cracking are also needed.

P. Emissions Gasification produces significant amounts of greenhouse gases (GHGs) even though emissions are much lower than those from coal plants.

Q. Operations and Maintenance. Operation and maintenance costs are too high. More efficient and durable equipment is needed.

R. Control and Safety. Control and safety issues need to be addressed particularly in biomass and biomass-coal co-gasification. Certification codes and standards should be standardized. Gasification operations should have back-up and fail-safe modes to improve safety and operation.

High Temperature, Solar-Driven Thermochemical Production of Hydrogen

There are over 200 potential thermochemical cycles for water splitting driven by concentrated solar power. These cycles have been evaluated and ranked for their suitability.[10] The most promising cycles will require extensive research and development efforts.

S. High-Temperature Robust Materials. High temperatures are required for these thermochemical systems (500-2000°C). Cost-effective, durable materials are needed that can withstand these high temperatures and the thermal duty cycles present in solar concentrator systems.

T. Coupling Concentrated Solar Energy and Thermochemical Cycles. Coupling concentrated solar energy with thermochemical cycles presents many challenges. Receivers, heat transfer systems, as well as reactors, need to be developed and engineered. Cost effective approaches and systems to deal effectively with the diurnal nature of sunlight need to be researched and developed.

U. Concentrated Solar Energy Capital Cost. Concentrated solar energy collection is currently expensive and requires large areas of land. Improved, lower-cost solar concentrator/collection technology, including materials, is needed.[10]

V. Heliostat Development and Cost. Heliostats, a reflective device that tracks the sun to keep the mirrors focused onto a target receiver, are currently too expensive to be economically viable. The

[10] Perret, Robert. (May 2011). "Solar Thermochemical Hydrogen Production Research (STCH)." Technical Report SAND2011-3622, Sandia National Laboratories.

cost needs to be reduced by 50% in order to achieve the targeted $\$120/m^2$ installed. The high costs are due to lack of standardization in design which is associated with inefficient manufacturing and poor durability of the heliostat.

W. Materials and Catalysts Development. The required temperatures for the cycle reactions are often in excess of 1,000°C. Current materials for the reactor, seals, catalysts, and supports are inefficient and do not meet operating requirements at these temperatures. Materials also need to operate in corrosive and reactive environments, some materials meet a few of the requirements but not all.

X. Chemical Reactor Development and Capital Costs. Reactors will need to be efficient, inexpensive, and entail minimal BOP to meet the cost targets. The high cost of material is due to the requirements for high durability and chemical and thermal stability. Thermal losses must be minimized to achieve an efficient process. There are also high capital costs that are associated with hydrogen separation and purification.

Y. Diurnal Operation. Solar power availability and fluctuations will strongly influence the design, performance, and economic viability of this technology.

Z. Control and Safety. Control and safety issues associated with STCH include optimization of start-up and shut-down processes, improved turn-down capability, activated material and thermal storage integration and control, and the capability for rapid on-off cycling. Costs remain high due to system complexity and sensor count to assure reliability. Operation of this system should occur with minimal manual assistance, which will require attributes such as back-up fail-safe modes, remote monitoring, and sparse maintenance schedules. Gaseous chemicals are used and can be harmful.

AA. Feedstock Issues. Water is the primary feedstock of STCH hydrogen production therefore an adequate amount of water must be available. The water must also be free of contaminants.

AB. Chemical and Thermal Storage. Capturing and storing thermal energy during peak solar times will extend the operational time of the STCH reactor. However, storage will require solar power which will add to complexity and cost to receiver-reactor interface. Molten nitrate salts enable temperatures up to 650ºC. Molten carbonates can store higher amounts of thermal energy but are extremely corrosive which can hinder operation. Also, some cycles require higher temperatures (>1,500ºC). In these cases molten metals may be an option but are also highly corrosive.

AC. Solar Receiver and Reactor Interface Development. The solar receiver interface with the chemical reactor is an important consideration in the selection of a solar receiver. For directly heated reactors, the receiver and reactor are integrated, enabling solar flux to heat the reactor. Solid particle and volumetric receivers are heated indirectly by the sun. In these reactors, the heat is absorbed by solid particles or molten salts, which then heat the reactors. In addition to interfacing with the receiver, the reactor must also interface with thermal storage, if used.

AD. Operations and Maintenance. All system components must be considered in O&M, including feed pre-conditioning, heliostats, solar receivers, reactor, hydrogen purification, controls, utilities, sensors, compression, storage, and safety. 24/7 operation may be ideal but not feasible due to variability of the power source. Durability, scheduled maintenance, storage, and hydrogen quality monitoring need to be considered when improving O&M and reducing costs.

Photoelectrochemical Hydrogen Production

Photoelectrochemical (PEC) hydrogen production based on semiconductor photoelectrodes or photocatalysts is in an early stage of development and requires significant advancements in materials, material systems, and reactor concept development. The primary materials-based research in this area is progressing on three fronts: (1) the study of costly high-efficiency materials to establish performance benchmarks and to attain a fundamental understanding of PEC hydrogen generation versus corrosion mechanisms; (2) the study of durable lower-quality/ lower-cost material systems to explore the mitigation of loss mechanisms for improving efficiency toward benchmark values; and (3) the development of sophisticated multi-component devices and systems with the potential to achieve efficient PEC water splitting through the effective combination of functionalized materials specifically optimized for light-absorption, charge transport, and interfacial catalysis. As efficient, durable and cost-effective materials systems are developed with the assistance of state-of-the-art methods in materials theory, synthesis, and characterization, further advanced work will be needed on integration schemes into high-performance photoelectrode or photocatalyst devices and reactors. For long-term practicality, cost-effective methods of engineering and manufacturing the best available PEC materials, devices, and systems need to be identified and developed.

Current material systems for PEC photoelectrodes or photocatalysts can be broadly divided into three categories, each with its own characteristics and research challenges. These groupings are:

(I) highly efficient light absorbers typically with limited lifetimes and relatively high cost (e.g., Group III-V crystalline materials),

(II) stable materials typically with lower visible light absorption efficiency and relatively lower cost (e.g., metal- and mixed-metal oxide thin films), and

(III) hybrid and multi-junction systems which combine multiple functionalized materials in multi-photon device schemes.

The group (I) materials studied to date can exhibit high light conversion efficiencies, often better than 60% incident-photon-to-electron conversion (IPEC) throughout the visible spectrum, but have been susceptible to corrosion. The well-known group (II) materials are characterized by high bandgaps and lower integrated IPEC over the solar spectrum, but have demonstrated good stability in some cases. Many of the groups (I) and (II) materials have majority band edge potentials that are insufficient to drive one of the water-splitting half reactions, necessitating the multi-junction approaches in group (III). It is anticipated that the group (III) material systems can exhibit high efficiency and long lifetime, depending on the material set, but these systems can be complicated and expensive to synthesize. Research in all three categories is deemed necessary for developing systems that meet the ultimate targets reflected in the PEC target table. The research in these categories also needs to include the latest development in nanomaterials and nanotechnology for enhancement of bulk and interface properties.

To date, a range of materials and material systems have met individual 2015 targets for efficiency or durability, but no single material/system has simultaneously met the ultimate efficiency, durability, and cost targets, which is the primary research challenge for photoelectrochemical hydrogen production. Drawing on the ongoing lessons learned from the research and development of group (I), (II), and (III) material systems, PEC researchers continue to make the innovative scientific advances needed to converge on systems incorporating the best improvements in efficiency, durability and cost. The materials-by-design approach facilitated by interactive development of advanced materials theory, synthesis, and characterization methodologies is viewed as an important cornerstone to overcome the barriers in this PEC materials systems research. Specific technical barriers are related to the efficiency, durability and cost of PEC materials, interfaces, devices, systems and reactors. These include:

AE. Materials Efficiency - Bulk and Interface. PEC semiconductor efficiency is limited by light absorption, charge separation, and transport in the bulk, and by energetics and charge transfer at the solid/liquid interface. Semiconductor materials with smaller bandgaps more efficiently utilize the solar spectrum but are often less energetically favorable for hydrogen production because of the bandedge mismatch with respect to either hydrogen or oxygen redox potentials. Large bandgap semiconductors can provide favorable energetics for splitting water at the interface but are poor bulk absorbers of light. Material systems must be developed with

- appropriate bandgap for light absorption,
- bandedges aligned energetically for hydrogen and oxygen evolution,
- low-loss charge separation and transport in the solid state, and
- interfaces kinetically favorable for the photoelectrochemical water-splitting half reactions.

Theory, synthesis, and characterization methods in materials discovery and screening are important tools.

AF. Materials Durability - Bulk and Interface. PEC semiconductor/electrolyte junctions are prone to both dark and light-induced degradation due to corrosion reactions which compete with water-splitting half-reactions at the interfaces, and which can propagate into the bulk. Intrinsically durable materials with the appropriate characteristics for photoelectrochemical hydrogen production that meet the ultimate program goals have not been identified. The high-efficiency materials currently available corrode quickly during operation, and the most durable materials are inefficient for hydrogen production. Discovery of intrinsically stable and efficient materials would be an ideal solution to this barrier, but represents a significant challenge. Promising alternative approaches focus on modification of surfaces through coatings or dispersions to energetically or kinetically stabilize the interface and protect the bulk. The use of theory, synthesis, and characterization methods can facilitate a better understanding of corrosion mechanisms for development of mitigation schemes to enhance durability.

AG. Integrated Device Configurations. Efficient and stable integrated devices combining the best available semiconductors, surface treatments, and auxiliary linking materials are needed for achieving ultimate targets in PEC solar hydrogen production. These can be planar-integrated devices for photoelectrode reactor configurations, or functionalized particle devices for photocatalyst reactor configurations. Hybrid and other device designs that combine functionalized materials specifically optimized for light-absorption, charge transport, and interfacial catalysis could simultaneously address issues of durability and efficiency. Techniques are needed for synthesizing these integrated device configurations which maintain the integrity of each component material. Appropriate manufacturing techniques based on these synthesis routes are needed to scale device configurations to commercial scales.

AH. Reactor Designs. Solar water-splitting reactor system designs incorporating the most promising device configurations, and using cost-effective, hydrogen-impermeable auxiliary materials, are also needed to implement the photolytic production routes, including PEC. Complete systems evaluations need to consider a range of important operational constraints and parameters, including the diurnal operation limitations and the effects of water purity on performance and lifetime. Preliminary technoeconomic analysis (https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pec_technoeconomic_analysis.pdf) of conceptual reactor types has indicated that the ultimate targets for PEC are most readily achievable in photoelectrode systems with modest concentrations (Type 4 reactors, in the nomenclature of the technoeconomics report) or in dual-bed photocatalysts systems (Type 2 reactors). Both reactor types feature built-in separation of evolved hydrogen and oxygen, and both operate at sufficiently low temperatures to avoid the need for costly high-T materials. Ion transport in the liquid electrolyte, particularly in the Type 2 reactors, can limit the water splitting efficiency, calling for engineering solutions. Type 4 reactors require additional hardware for modest solar concentration. For both reactor types, full engineering options need to be carefully analyzed to minimize capital and operational requirements.

AI. Auxiliary Materials. The functional requirements for auxiliary materials for semiconductor-based PEC hydrogen production must be determined, and the auxiliary materials discovered, developed, and tested to facilitate PEC device and systems development. Auxiliary materials for PEC devices include photoelectrode substrate materials, protective coatings for enhanced durability, catalytic coatings for enhanced interface kinetics, photovoltaic semiconductor under-layers for enhanced energetics, and interface and contact materials. Auxiliary materials for PEC reactors include hydrogen impervious materials, stable and transparent coverings for light transmission and concentration, electrolyte components, and ionic conduits.

AJ. Synthesis and Manufacturing. Synthesis and manufacturing techniques need to be developed for the PEC materials, materials systems, devices, and reactors capable of solar water-splitting at high efficiency, long durability and low cost. For materials and devices, the synthesis techniques need to be scalable and affordable and need to preserve the integrity of all integrated component materials. For the systems and reactors, manufacturing techniques need to be on scales consistent with implementation in commercial installations.

AK. Diurnal Operation Limitations. Photolytic processes are discontinuous because they depend on sunlight, which is unavailable at night and available only at low intensities on cloudy days. This variability results in increased capital costs for larger facilities to accommodate higher short-term production rates and larger hydrogen storage needs. Diurnal operation conditions are explicitly included in the cost estimate analyses.

AL. Operations and Maintenance. Potential costs, including labor, required for PEC hydrogen production could make the technology too costly to compete in the marketplace. Barriers to minimizing these costs will need to be addressed in a number of areas.

AM. Control and Safety. Control issues dealing with PEC hydrogen include optimizing start up and shutdown processes, turn-down capability (for cloudy days), and rapid on-off cycling. The system should be able to operate with minimal manual assistance, which will require a back-up fail-safe mode, remote monitoring, and sparse maintenance schedules.

Biological Hydrogen Production

A number of technologies for biological hydrogen production are available, but they are not mature at present. Technical barriers related to each individual technology must be overcome, integrated models must be developed, and barriers related to an integrated system must be identified. Methods for engineering and manufacturing these systems have not been fully evaluated.

Barriers are listed below for each technology, followed by a model for how these different technologies could be integrated and a list of barriers for the integrated process.

Photolytic Hydrogen Production from Water (green algae or cyanobacteria)

AN. Light Utilization Efficiency. The microorganisms used for photobiological hydrogen production possess large arrays of light-capturing antenna pigment molecules, which absorb more light than can be utilized by the photosynthetic electron transport apparatus, resulting in heat dissipation and loss of up to 80% of the absorbed sunlight. Research is needed to identify ways to increase the light conversion efficiency, including genetic engineering to improve microorganism light utilization mechanisms and the identification of natural strains with better light utilization.

AO. Rate of Hydrogen Production. The current hydrogen production rate from photolytic microorganisms is too low for commercial viability. The low rates have been attributed to (a) the non-dissipation of a proton gradient across the photosynthetic membrane, which is established during electron transport from water to the hydrogenase (the hydrogen producing enzyme) under anaerobic conditions, and (b) the existence of competing metabolic flux pathways for photosynthetic reductant. Genetic means to overcome the restricting metabolic pathways may be used to significantly increase the rate of hydrogen production. Under aerobic conditions, with an oxygen tolerant hydrogenase catalyzing hydrogen production, the competition between carbon dioxide fixation and hydrogenase will have to be addressed.

AP. Oxygen Accumulation. Along with hydrogen, photolytic microorganisms such as algae co-produce oxygen, which inhibits the hydrogenase enzyme activity and can create a safety issue if stoichiometric mixtures of the two gases are reached. Both issues could be addressed by affecting the ratio of photosynthesis to respiration by a variety of means, such that oxygen is consumed as quickly as it is produced and does not accumulate in the medium, while maintaining the quantum yield of photosynthesis and full hydrogenase activity (see details under Integrated System). The inhibition may also be addressed through engineering or identifying a naturally occurring less oxygen sensitive enzyme or separating the oxygen and hydrogen production cycles. Options to address the safety issue may include ensuring ignition sources are not present and/or mechanical separation of the gases.

AQ. Systems Engineering. System requirements for cost-effective implementation of photolytic hydrogen-production technologies have not been adequately evaluated. Analysis and research are needed on inexpensive/transparent materials for hydrogen containment, hydrogen collection systems, continuous bioreactor operation, monoculture maintenance, land area requirements, and capital costs.

AR. Diurnal Operation Limitations. The same issues apply as for photoelectrochemical systems (see Barrier AK).

Photosynthetic Bacterial Hydrogen Production, Required for an Integrated System:

AS. Light Utilization Efficiency. Same issues apply as for photolytic systems (see barrier AN).

AT. Net Hydrogen Production. Metabolic processes in photosynthetic bacteria can reduce net hydrogen production by using the produced hydrogen and through metabolic pathways that compete with hydrogen production for electron donors. Genes controlling these pathways must be inactivated to maximize hydrogen production or alternative metabolic enzymes must be identified or engineered.

AU. Carbon/Nitrogen Ratio. To maximize nitrogenase activity, the proper ratio of carbon to nitrogen (C/N) nutrients must be maintained. The C/N nutrient content in the photo reactor (algal and cyanobacteria) and in the dark fermenter needs to be evaluated to assess whether the media composition is suitable for subsequent photosynthetic bacterial hydrogen production. Enzyme engineering approaches may be needed to alleviate inhibition of nitrogenase by elevated levels of nitrogen nutrient.

AV. Systems Engineering. The same issues apply as for photolytic systems (see barrier AQ), except for the mixture of gases. Photosynthetic bacteria do not co-evolve hydrogen and oxygen but release hydrogen and carbon dioxide. The cost of hydrogen and carbon dioxide separation must be evaluated.

AW. Diurnal Operation Limitation. The same issues apply as for photoelectrochemical systems (see barrier AK).

Dark Fermentative Hydrogen Production:

AX. Hydrogen Molar Yield. Up to 4 moles of hydrogen can theoretically be produced per mole of glucose through the known fermentative pathways. However, various biological limitations such as hydrogen-end-product inhibition, competition with other metabolic pathways for electron donors, and accumulation of waste byproducts such as organic acids limit the molar yield to around 2 moles per mole glucose consumed. Hydrogen molar yields must be increased significantly through metabolic engineering efforts. Waste byproducts may also require subsequent wastewater treatment. Elimination of these by-product generation pathways and/or subsequent by-product processing (such as in an integrated biological hydrogen production system) of the organic acids by photosynthetic bacteria or MECs (see below) is needed to increase hydrogen yields. Potential release of toxins and their inhibition of the subsequent steps in an integrated system will need to be evaluated.

AY. Feedstock Cost. The glucose feedstock is the major cost driver for economic hydrogen production via fermentation. For renewable hydrogen to be cost competitive with traditional transportation fuels, the glucose cost must be around $0.05 per pound and provide a molar yield of hydrogen approaching 10 (see Barrier AX and Table 3.1.12). Lower-cost methods to use whole biomass are needed including, but not limited to, reducing the cost of conversion to glucose or identifying cellulose-degrading bacteria or consortia that can utilize untreated lignocellulosic biomass directly. Bioprospecting for cellulolytic microbes with a high rate of hydrogen production are also needed to use the cell biomass of the green algal/cyanobacterial and photosynthetic bacterial co-culture (in an integrated biological hydrogen production system).

AZ. Systems Engineering. The same issues apply as in photosynthetic bacterial production (see barrier AQ), plus prevention of methanogen contamination and reduced fermentation time are needed.

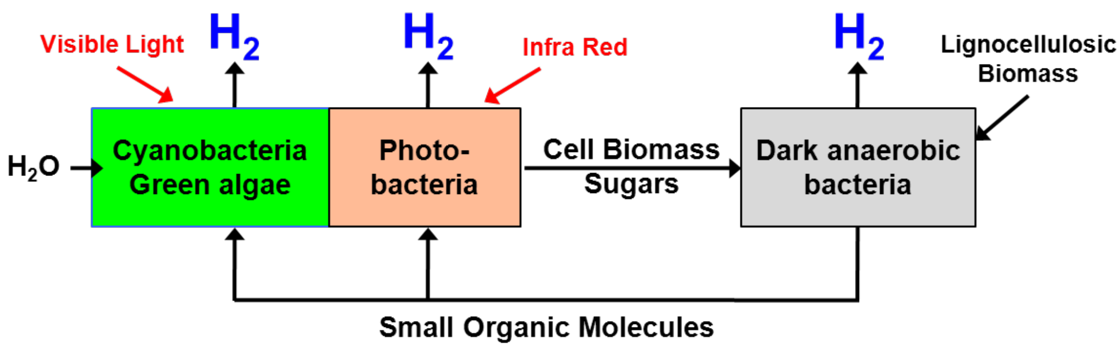
Microbial Electrolysis Cell (MEC):

AAA. Electrode Costs. The cost of the cathode materials remains the largest cost in the system. Early systems used very expensive fuel cell carbon cloth, Pt catalysts, and binders (Nafion). These costs must be reduced by discovering or engineering less expensive materials.

AAB. Solution Density (Production Rate). The hydrogen gas production rate per volume of reactor needs to be increased. Solutions include, but are not limited to, building reactors with more dense packing of electrodes. The early work was conducted with small electrode packing, resulting in 0.37 L of hydrogen gas per liter of reactor per day. Advancement must be made to increase electrode packing and therefore reduce the overall tankage and piping needed to produce hydrogen gas.

Integrated Biological Hydrogen Production System (many configurations are possible, Figure 3.1.3):

AAC. Photosynthesis/Respiration Capacity Ratio. Green algae and cyanobacteria become anaerobic when their P/R (photosynthesis/respiration) capacity ratio is 1 or less. Under such anaerobic conditions, photosynthetic water oxidation produces hydrogen (instead of starch), and the oxygen evolved by photosynthesis is consumed by respiration, producing carbon dioxide. Currently, this process is achieved by nutrient deprivation, but this method decreases the quantum yield of photosynthesis. Alternative mechanisms to bring the P/R ratio to 1 need to be investigated, particularly those methods that will not reduce the quantum yield of photosynthesis. Two further issues will need to be investigated under these conditions: (a) rate limitations due to the non-dissipation of the proton gradient and (b) the ability of the culture to take up a variety of exogenous carbon sources under the resulting anaerobic conditions.



Illustrative Scenario: Anaerobically, co-culture cyanobacteria or green algae with photosynthetic bacteria in a photoreactor, and dark anaerobic bacteria in a fermentor. Feedstock for the dark anaerobic bacteria is derived from the cell biomass/sugars of the cyanobacteria or green algae and the photosynthetic bacteria. Additional feedstock for the dark anaerobic bacteria is derived from lignocellulosic products. The small organic molecule by-products of the dark anaerobic bacterial fermentation are subsequently utilized as feedstock for the cyanobacteria, green algae and photosynthetic bacteria.

Figure 3.1.3 Integrated Biological System

AAD. Co-Culture Balance. To extend the absorption spectrum of the hydrogen photoproducing cultures into the infrared, the possibility of co-cultivating oxygenic photosynthetic organisms with anoxygenic photosynthetic bacteria should be investigated. Another option to be investigated is further genetic modifications to integrate pigments and the single photosystem from Purple Non-Sulfur (PNS) photobacteria to the oxygenic photosynthetic organisms.

AAE. Concentration/Processing of Cell Biomass. In an integrated system, cell biomass from either green algae/cyanobacteria or photosynthetic bacteria can serve as the substrate for dark fermentation. Pretreatment of cell biomass may be necessary to render it more suitable for dark fermentation. Methods for cell concentration and processing will depend on the type of organism used and how the biological system is integrated.

3.1.6 Technical Task Descriptions

The technical task descriptions and the barriers associated with each task are presented in Table 3.1.13. Concerns regarding safety and environmental effects will be addressed within each task in coordination with the appropriate sub-program.

Table 3.1.13 Technical Task Descriptions

Task	Description	Barriers
1	**Distributed Reforming of Renewable Liquid Feedstocks** • Analyze and research options for alternative renewable feedstocks (e.g., ethanol, methanol, sugars, sugar alcohols, bio-oils, bio-based Fischer-Tropsch liquids) for distributed production. • Develop catalysts for optimized feedstock utilization and H_2 yield. • Utilizing the technology concepts developed for distributed natural gas reforming, develop efficient, integrated, compact, robust process technology for bio-derived liquid feedstocks. • Explore novel technology, such as low temperature aqueous phase processing, for reforming bio-derived renewable liquid feedstocks that could result in a cost breakthrough. • Verify achievement of 2015 and 2020 cost and efficiency targets through the operation of bench scale, and small (up to 30 kg/day) pilot scale development units respectively, for reforming of a bio-derived liquid.	A, B, C, D, E
2	**Advanced Electrolysis Technologies** • Evaluate low cost electrolysis pathways by developing a model for analyzing various options for low cost renewable and nonrenewable electricity and then analyzing distributed and central electrolysis. • Reduce distributed electrolyzer capital and operating costs by reducing system cost and increasing system energy efficiency, developing novel compression designs, integrating system components, advanced BOP designs and developing efficient manufacturing process technology. • Develop central renewable integrated electrolysis technologies by evaluating viable renewable electricity integration approaches, developing advanced power electronics interface components, developing a stack module pilot scale (250 - 500 kW) electrolysis system suitable for renewable and grid electricity integration, and integrating and verifying feasibility of renewable hydrogen production at pilot scale.	F, G, H, I, J, K, L, M

Table 3.1.13 Technical Task Descriptions		
Task	**Description**	**Barriers**
3	**Hydrogen Production from Biomass Gasification** • Reduce the cost and increase the feedstock flexibility of biomass feedstock preparation (e.g., handling, size reduction, etc.) (Bioenergy Technologies Office). • Research and develop more cost-effective, efficient, and robust biomass product gas clean-up technologies for feeding into reforming operations, including hot-gas clean-up, tar cracking, and other related technologies. (This will be coordinated with the Office of Fossil Energy for coal-gasifier product gas clean-up technologies and with the EERE Bioenergy Technologies Office.) • Investigate opportunities for catalyst and reactor improvement for tar cracking, reforming, and conditioning of gasifier product gases. • Improve hydrogen yield and selectivity and overall heat integration to improve energy efficiency and reduce cost. • Reduce the capital cost by combining/integrating process steps and operations. This integration could include single step water-gas shift with an integrated membrane, combining shift and reforming into one operation, combining gasification, tar cracking, and reforming into one operation, etc. Develop a gasification system with internal reforming that produces hydrogen and makes a stand-alone tar cracking/reforming system unnecessary. • Investigate and develop alternative biomass gasification technology approaches such as biomass hydrolysis followed by aqueous phase reforming. • Verify an integrated biomass gasification system for hydrogen production at targeted costs. • Reduce the cost of emission control systems that handle pollutants from coal and biomass. Also, reduce carbon capture and sequestration mechanism costs, and improving efficiency. • Improve system durability, robustness, and lifespan to reduce the time needed for maintenance and to lower O&M costs.	N, O, P, Q, R

Table 3.1.13 Technical Task Descriptions		
Task	**Description**	**Barriers**
4	**High-Temperature, Solar-Driven, Thermochemical Processes** • Evaluate and research potential high-temperature, solar driven thermochemical water-splitting cycles and down-select to the most promising cycles. • Optimize sub-cycle reactions and verify effective hydrogen production at laboratory scale. • Verify stability of reaction materials under extended lab-scale thermochemical cycling • Determine active material cost and durability requirements to meet targets. • Optimize electrolytic processes, electrode and catalyst materials, and cells. • Verify cycle operation and durability of materials of reaction during on-sun tests. • Quantify and verify conversion efficiency and kinetics for reaction cycles. • Develop lower capital cost solar heliostat, secondary concentrators, and solar tower technology. (This will leverage the efforts in the EERE Solar Program.) • Develop cost-effective, high-temperature materials of construction compatible with thermochemical processes. These materials must have minimal hydrogen and heat loss. • Develop cost-effective solar receivers, heat transfer medium and systems, and reactors, designs, including materials specifications and testing. • Develop cost-effective thermal and chemical storage methods. • Develop a viable integrated, solar-driven high-temperature thermochemical water-splitting process. • Verify an integrated, solar-driven high-temperature thermochemical water-splitting cycle with targeted costs. • Develop a solar field configuration and design to match chemical plant requirements. • Identify strategies for full integration of solar thermal energy collection and storage with the chemical reaction cycle for thermochemical water-splitting. • Verify performance of a semi-integrated system at small scale (5-100 kW). • Verify performance of a semi-integrated system at pilot scale (0.5-5 MW). • Verify that a fully-integrated system can achieve 2020 targeted costs and yields.	S, T, U, V, W, X, Y, Z, AA, AB, AC, AD

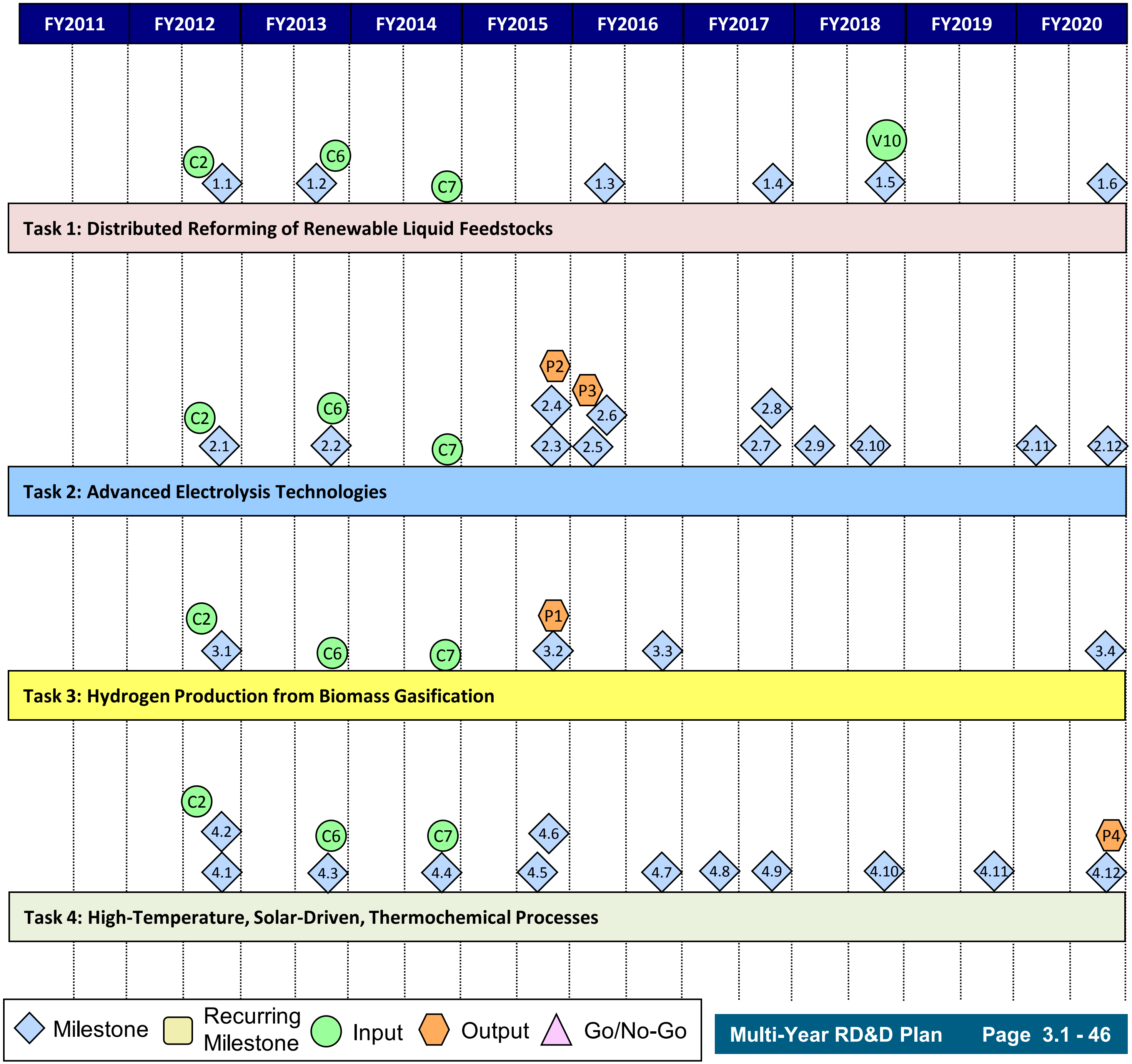
Table 3.1.13 Technical Task Descriptions		
Task	**Description**	**Barriers**
5	**Materials and Systems for Photoelectrochemical Hydrogen Production** **Development of Materials for Photoelectrochemical Hydrogen Production** • Develop theory/synthesis/characterization cycles to identify new semiconductor materials compatible with devices meeting long-term targets. • Develop and optimize the current state-of-the-art materials for meeting near term efficiency and durability targets in photoelectrode and photocatalyst device configurations. • Develop and characterize, utilizing theory-driven combinatorial or other screening methods, new materials for meeting long-term efficiency, durability, and cost targets in photoelectrode and photocatalyst device configurations. • Develop cost-effective synthesis techniques for fabricating the most promising semiconductor materials systems. **Development of Devices for Photoelectrochemical Hydrogen Production** • Evaluate device configurations, including multi-junction configurations and other advanced designs for both photoelectrode and photocatalyst devices, to achieve improved efficiency and durability and to lower device cost. • Identify and develop auxiliary materials and components necessary for photoelectrochemical hydrogen production devices, including protective surface coatings, catalysts, interface and contact materials, and photovoltaic under-layers. • Develop cost-effective fabricating techniques that are scalable and manufactureable for the most promising materials systems, devices, and configurations. • Develop testing and accelerated testing protocols to evaluate and validate long-term system efficiencies and durability. • Demonstrate prototype scale devices using best available materials systems and device configurations. **Development of Systems for Photoelectrochemical Hydrogen Production** • Identify and develop reactor designs that optimize light-capture efficiency, hydrogen production, gas collection and reactor life – including utilization of novel geometries and electrolyte options. • Identify or develop auxiliary materials and components necessary for photoelectrochemical hydrogen production systems, including cost effective transparent, hydrogen-impermeable materials for reactors. • Apply economic modeling tools for predicting cost potentials for photolytic production technologies. • Develop methods to overcome diurnal operation limitations. • Implement DFMA/High-volume equipment manufacturing to reduce overall cost of the system. • Develop automated process control to minimize maintenance cost and improve production. • Demonstrate field prototype reactors using best available PEC materials systems, device configurations, and auxiliary materials.	AE, AF, AG, AH,AI, AJ, AK, AL, AM

Table 3.1.13 Technical Task Descriptions		
Task	**Description**	**Barriers**
6	**Biological Hydrogen Production** **Systems Engineering for All Biological Hydrogen Production Systems** • Optimize photoreactor material and system designs (including system scale-up and alternative reactor beds and alternative immobilization material systems for photolytic production). • Discover and develop cost-effective, transparent, H_2-impermeable materials for biological H_2 production systems. • Develop hydrogen collection and gas-separation technologies. **Molecular and Physiological Engineering of Organisms for Photolytic Hydrogen Production from Water** • Generate organisms with O_2-tolerant hydrogenases, that have increased light conversion efficiency, allow more efficient photosynthetic electron transport toward H_2, and eliminate competing pathways for enhanced H_2 production. Eliminate H_2 uptake pathways in cyanobacteria. • Research and develop systems in which water photolysis occurs under anaerobic conditions (i.e., in which the ratio of O_2-producing photosynthesis to O_2-consuming respiration (P/R) is ≤1). Test different methods to achieve that ratio without affecting H_2 production. **Molecular Engineering of Organisms for Photosynthetic Bacterial Hydrogen Production** • Generate photosynthetic bacteria that have increased sunlight conversion efficiency and display more efficient photosynthetic electron transport. Eliminate competitive pathways such as H_2 oxidation and polymer accumulation. Engineer organisms to remove the repression of fixed nitrogen on nitrogenase expression and have a functional nitrogenase at elevated nitrogen-nutrient concentration. Investigate the H_2-production activity and solar efficiency of organisms containing alternative nitrogenases. **Molecular and Systems Engineering for Dark Fermentative Hydrogen Production** • Research and develop improved cellulolytic microbes or a consortium with high rates of biomass degradation and H_2 production. • Increase rates of H_2 production and eliminate competing pathways for H_2 production. **Molecular and Systems Engineering for MECs** • Research and develop systems with reduced reactor material costs and increased hydrogen production rate per volume of reactor (including but not limited to increased electrode packing).	AN, AO, AP, AQ, AR, AS, AT, AU, AV, AW, AX, AY, AZ, AAA, AAB, AAC, AAD, AAE

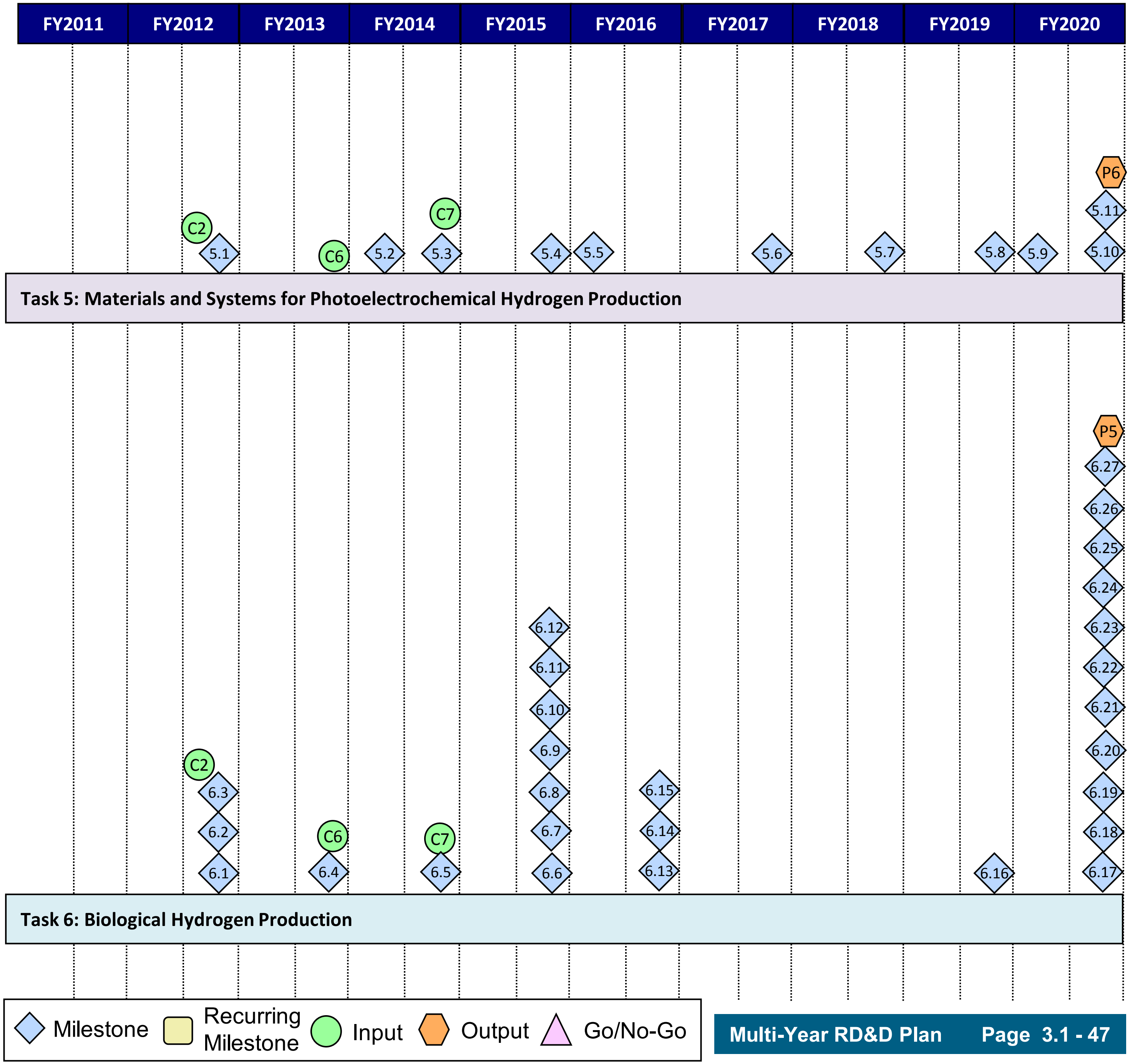
3.1.7 Milestones

The following chart shows the interrelationship of milestones, tasks, supporting inputs from other sub-programs, and technology outputs for the Hydrogen Production sub-program from FY 2012 through FY 2020. The input-output relationships are also summarized in Appendix B.

Production Milestone Chart



Production Milestone Chart



Task 1: Distributed Reforming of Renewable Liquid Feedstocks	
1.1	Demonstrate a cumulative 100 hours of catalyst operation in an integrated bench-scale production system. (Q4, 2012)
1.2	Determine technical and economic feasibility of hydrogen from reforming of pyrolysis oil. (Q3, 2013)
1.3	Verify 2015 cost and efficiency targets through the operation of a bench scale development unit for reforming of a bio-derived liquid. (Q2, 2016)
1.4	Select and optimize feedstock, catalyst, and reforming reactor for system integration, construction, and scale up testing. (Q4, 2017)
1.5	Verify through H2A analysis the feasibility of achieving less than $4.00/gge (delivered) from bio-derived renewable liquid fuels. (Q4, 2018)
1.6	Verify 2020 cost and efficiency targets through the operation of a small scale (up to 30 kg/day) pilot scale development unit for reforming of a bio-derived liquid. (Q4, 2020)

Task 2: Advanced Electrolysis Technologies	
2.1	Verify the capital cost of the electrolyzer stacks against the 2012 target of <$400/kW projected for high volume. (Q4, 2012)
2.2	Verify the system performance against the 2012 targets for efficiency and production rate. (Q4, 2013)
2.3	Verify the stack and system efficiencies against the 2015 targets. (Q4, 2015)
2.4	Develop technologies for producing hydrogen through electrolysis at centralized facilities using renewable power for a cost ≤$3.00/gge at the plant gate. (Q4, 2015)
2.5	Verify the total capital investment for a central electrolysis system against the 2015 targets using H2A. (Q1, 2016)
2.6	Verify the total capital investment for a distributed electrolysis system against the 2015 targets using H2A. (Q2, 2016)
2.7	Verify 2015 distributed hydrogen production levelized cost target through pilot scale testing coupled with H2A analysis to project economies of scale cost reduction. (Q3, 2017)
2.8	Verify 2015 central hydrogen production levelized cost target through pilot scale testing coupled with H2A analysis to project economies of scale cost reduction. (Q4, 2017)
2.9	Verify the BOP's ability to meet the 2020 system efficiency targets. (Q1, 2018)
2.10	Create modularized designs for optimized central electrolysis systems projected to meet 2020 capital and hydrogen production cost targets. (Q3, 2018)
2.11	Verify the stack and system efficiencies against the 2020 targets. (Q1, 2020)
2.12	Build an integrated renewable energy source and electrolysis pilot system for target verification and durability testing. (Q4, 2020)

Task 3: Hydrogen Production from Biomass Gasification	
3.1	Demonstrate that a biomass gasification membrane reactor can achieve a projected high volume H_2 cost of <$2.00/kg based on preliminary process design and H2A cost analysis. (Q4, 2012)
3.2	Demonstrate that a biomass gasification membrane reactor can achieve the 2015 cost target of $2.10/gge based on preliminary process design and H2A cost analysis. (Q4, 2015)
3.3	Verify 2015 cost and energy efficiency targets through the operation of an integrated biomass gasification development unit. (Q4, 2016)
3.4	Verify techno-economic feasibility for a 2000 dry ton per day plant producing hydrogen at $2.00/gge. (Q4, 2020)

Task 4: High-Temperature, Solar-Driven, Thermochemical Processes	
4.1	Demonstrate that a particle reactor has the potential to achieve >30% solar-to-H_2 thermal efficiency based on a theoretical analysis of the particle reactor performance. (Q4, 2012)
4.2	Design a central receiver based hydrogen production system capable of achieving an annual average solar to hydrogen production efficiency in excess of 14%. (Q4, 2012)
4.3	Determine active material cost and durability requirements to meet 2020 and Ultimate targets. Develop a characterization protocol for a standard metric for metal oxide reaction materials. (Q4, 2013)
4.4	Demonstrate electrolyzer performance at required cell potential and current density to meet 2015 targets for hydrogen production. (Q4, 2014)
4.5	Demonstrate 100 hours on-sun hydrogen production for a solar thermochemical reaction cycle. (Q3, 2015)
4.6	Verify the successful on-sun operation of a promising high-temperature solar-driven thermochemical cycle that projects to the 2015 cost and efficiency targets. (Q4, 2015)
4.7	Design and test a “cold” prototype reactor (T_{max} ~200°C). (Q4, 2016)
4.8	Complete thermal reactor/receiver, storage and heat transfer system designs including materials specifications and testing. (Q2, 2017)
4.9	Verify the successful on-sun operation of a promising high-temperature solar-driven thermochemical cycle for direct solar-to-hydrogen production that projects to a cost target of ≤$5.00/gge at the plant gate for central production. (Q4, 2017)
4.10	Design and test a “warm” prototype reactor (T_{max} ~900°C). (Q4, 2018)
4.11	Design and test a fully operational hydrogen production prototype reactor at the 5kW (thermal input) level (T > 1,200°C). (Q4, 2019)
4.12	Verify 2020 cost and energy efficiency targets for an integrated system. (Q4, 2020)

Task 5: Materials and Systems for Photoelectrochemical Hydrogen Production	
5.1	Identify material systems compatible with photoelectrode reactors demonstrating stabilized STH ≥10%. (Q4, 2012)
5.2	Verify material systems with stabilized STH ≥10% in a photoelectrode configuration. (Q2, 2014)
5.3	Identify material systems compatible with photocatalyst particle reactors demonstrating stabilized STH ≥1%. (Q4, 2014)
5.4	Identify material systems compatible with photoelectrode reactors demonstrating stabilized STH ≥15%. (Q4, 2015)
5.5	Verify material systems with stabilized STH ≥1% in a photocatalyst particle configuration. (Q1, 2016)
5.6	Build a lab-scale PEC system based on best available 2015 technology to validate technoeconomic analysis. (Q4, 2017)
5.7	Identify material systems compatible with photocatalyst particle reactors demonstrating stabilized STH ≥5%. (Q4, 2018)
5.8	Verify material systems compatible with photoelectrode reactors with stabilized STH ≥15%. (Q4, 2019)
5.9	Verify material systems with stabilized STH ≥5% in a photocatalyst particle configuration. (Q1, 2020)
5.10	Identify material system compatible with photoelectrode reactors demonstrating stabilized STH ≥20%. (Q4, 2020)
5.11	Demonstrate plant-scale-compatible photoelectrochemical water-splitting systems to produce hydrogen at solar-to-hydrogen energy conversion efficiencies ≥15%. (Q4, 2020)

Task 6: Biological Hydrogen Production	
6.1	Generate or identify a naturally occurring Fe-hydrogenase with a half-life of 5 min in air for photolytic hydrogen production. (Q4, 2012)
6.2	Characterize an algal strain with 25% primary utilization efficiency of incident solar light energy. (Q4, 2012)
6.3	Increase the duration of H_2 production by immobilized, sulfur-deprived algal cultures to 2 months. (Q4, 2012)
6.4	Produce one cyanobacterial recombinant evolving H_2 from water through an O_2-tolerant NiFe-hydrogenase. (Q4, 2013)
6.5	Complete research to develop a photosynthetically efficient green algae/cyanobacterial system in which the P/R ratio is $\leq$ 2. (Q4, 2014)
6.6	For photolytic hydrogen production, achieve the 2015 targets for solar-to-hydrogen conversion ratio. (Q4, 2015)

Task 6: Biological Hydrogen Production (continued)	
6.7	Identify or generate a Fe-hydrogenase that achieves 2015 target duration half-life in air for photolytic hydrogen production. (Q4, 2015)
6.8	For photosynthetic bacterial hydrogen production, achieve the 2015 targets for efficiency of incident solar light energy to H_2 (E0*E1*E2) from organic acids, yield of carbon conversion to H_2, and continuous photoproduction. (Q4, 2015)
6.9	For dark fermentative hydrogen production, achieve 2015 targets for molar yield of H_2 production from glucose and continuous production duration. (Q4, 2015)
6.10	Complete research to determine the efficacy of green algae/cyanobacteria and photosynthetic bacteria to metabolize carbon substrates ($C \leq 4$) and produce H_2 in integrated systems, including co-cultivation, immobilized cultures or a single oxygenic photosynthetic organism with genetic modifications to add the pigments and single photosystem from PNS. (Q4, 2015)
6.11	For an MEC system, achieve 2015 targets (Table 3.1.12) for production rates and electrode costs. (Q4, 2015)
6.12	Increase production rate of combined fermentation/MEC system to 2015 targets. (Q4, 2015)
6.13	Complete research to generate photosynthetic bacteria that have 50% smaller (compared to wild-type) Bacteriochlorophyll (Bchl) antenna size and display increased sunlight conversion efficiency. (Q4, 2016)
6.14	Complete research to engineer photosynthetic bacteria with a 30% expression level of a functional nitrogenase/hydrogenase at elevated nitrogen-carbon ratios (expression level is defined relative to that detected at low N:C ratios). (Q4, 2016)
6.15	Complete research to inactivate competitive uptake of H_2 by hydrogenase (also a priority for Dark Fermentative systems). (Q4, 2016)
6.16	Complete research to develop a photosynthetically efficient green algae/cyanobacterial system in which the P/R ratio is ~ 1. (Q4, 2019)
6.17	Demonstrate H_2 production in air in a cyanobacterial recombinant. (Q4, 2020)
6.18	For photolytic hydrogen production, achieve the 2020 targets for solar-to-hydrogen conversion ratio when averaged over production and growth phases, reactor costs, and H_2 production costs. Specifically, demonstrate plant-scale compatible photobiological water splitting systems to produce hydrogen at a solar-to-hydrogen energy efficiency of 5%. (Q4, 2020)
6.19	Complete research to generate photosynthetic bacteria that have 70% smaller (compared to wild-type) Bchl antenna size and display increased sunlight conversion efficiency. (Q4, 2020)
6.20	Complete research to engineer photosynthetic bacteria with a nitrogenase/hydrogenase at that is functional at elevated nitrogen-carbon ratios to at least 60% of the expression level at low N:C ratios. (Q4, 2020)
6.21	Complete research to inactivate the photosynthetic bacterial metabolic pathways leading to polymer accumulation that competes with H_2 production. (Q4, 2020)
6.22	For photosynthetic bacterial hydrogen production, achieve the 2020 targets for efficiency of incident solar light energy to H_2 (E0*E1*E2) from organic acids, maximum molar yield of carbon conversion to H_2, projected hydrogen production cost, and duration of continuous photoproduction. (Q4, 2020)

Task 6: Biological Hydrogen Production (continued)	
6.23	For dark fermentative hydrogen production, achieve 2020 targets for molar yield of H_2 production from glucose, hydrogen production costs, and continuous production duration. (Q4, 2020)
6.24	For an MEC system, achieve 2020 targets (Table 3.1.11) for production rates and electrode costs. (Q4, 2020)
6.25	Increase production rate of combined fermentation/MEC system to 2020 targets. (Q4, 2020).
6.26	Complete research to regulate growth/competition between different organisms in co-cultivation (e.g., to maintain optimal Chl/Bchl ratios). (Q4, 2020)
6.27	Complete research to identify cell-growth inhibitors and eliminate transfer of such compounds from bacterial fermenters to photo reactors. (Q4, 2020)

Outputs

P1 Output to Technology Validation and Manufacturing: 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 Output to Technology Validation and Manufacturing: 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 Output to Technology Validation and Manufacturing: 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 Output to Technology Validation: 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 Output to Technology Validation: Solar hydrogen production system based on photolytic biological hydrogen production from water at a solar to hydrogen conversion efficiency of 5%. (4Q, 2020)

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

Inputs

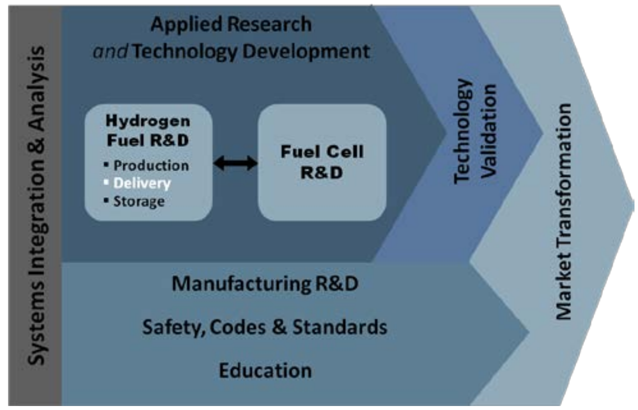
C2 Input from Safety, Codes and Standards: Hydrogen fuel quality standard (SAE J2719). (3Q, 2012)

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)

V10 Input from Technology Validation: 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)

3.2 Hydrogen Delivery



Delivery is an essential component of any future hydrogen infrastructure. It encompasses those processes needed to transport hydrogen from a central or semi-central production facility to the final point of use and those required to load the energy carrier directly onto a given fuel cell system. Successful commercialization of hydrogen-fueled fuel cell systems, including those used in vehicles, back-up power sources, and distributed power generators, will likely depend on a hydrogen delivery infrastructure that provides the same level of safety, convenience, and functionality as existing liquid and gaseous fossil fuel based infrastructures. Because hydrogen can be produced from a variety of domestic resources, its production can take place in large, centralized plants or in a distributed manner, directly at fueling stations and stationary power sites. As such, the hydrogen delivery infrastructure will need to integrate with these various hydrogen production options. It is estimated that for hydrogen to become an economically viable energy carrier for light duty vehicles, the combined cost of its production and delivery must achieve the threshold of <$4.00/gallon of gasoline equivalent (gge) (untaxed).[1] Currently, the levelized cost of dispensed hydrogen lies well above this limit.

3.2.1 Technical Goal and Objectives

Goal

Develop technologies that reduce the costs of delivering hydrogen to a level at which its use as an energy carrier in fuel cell applications is competitive with alternative transportation and power generation technologies.

Objectives

- By 2012, identify optimized delivery pathways that meet an as-dispensed hydrogen cost of <$4/gge (~$1.00/100 standard cubic feet [scf], including the average cost of hydrogen at current production facilities) for the emerging fuel cell powered material handling equipment (MHE) market.
- By 2014, reduce the cost of hydrogen delivery from the point of production to the point of use for fuel cell powered MHE to <$3/gge (~$0.75/100 scf).
- By 2015, reduce the cost of hydrogen delivery from the point of production to the point of use for emerging regional consumer and fleet vehicle markets to <$4/gge.[2]

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[1] DOE-FCTP Record #11007, "Hydrogen Threshold Cost Calculation." http://hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.pdf. All costs in this plan are in 2007 dollars to be consistent with EERE planning which uses the energy costs from the 2009 Annual Energy Outlook.

[2] Note that first generation consumer vehicles will likely require gaseous hydrogen compressed to 70 MPa, twice as high as that needed for gas storage onboard MHE. The higher level of compression will incur higher delivery cost.

- By 2020, reduce the cost of hydrogen delivery from the point of production to the point of use in consumer vehicles to <$2/gge.[3]

3.2.2 Technical Approach

The Hydrogen Delivery sub-program is focused on meeting its objectives through research, development and demonstration (RD&D) investments made in: (1) innovative technologies and processes to address the challenges of low cost, reliable hydrogen delivery and (2) infrastructure modeling, including delivery pathway analysis and optimization. Toward this end, the Delivery sub-program's efforts will be coordinated with other sub-program endeavors in the Fuel Cell Technologies Program (FCT Program), other DOE programs that have similar objectives, and related activities conducted by the U.S. Departments of Transportation and Commerce. Individual projects will address the barriers outlined in Section 3.2.5 and progress toward meeting sub-program objectives will be measured against the technical targets outlined in Tables 3.2.3 and 3.2.4.

Hydrogen Transport and Fueling Options

The production of hydrogen is a relatively large and growing industry. In the United States alone, over twenty million metric tons of gaseous hydrogen is produced annually,[4] mostly for use as an industrial feedstock. The majority is produced at or near petroleum refineries and ammonia plants – the primary users of industrial hydrogen. More than 1200 miles of existing hydrogen pipelines serve regions with high concentrations of industrial hydrogen users, along the Gulf coast, near Los Angeles, and near Chicago along the lower portion of Lake Michigan.[5] The comparatively smaller merchant hydrogen market is serviced by cryogenic liquid hydrogen trucks or gaseous hydrogen tube trailers.

With respect to fuel cell use, processes associated with the delivery of hydrogen can be categorized either as transport operations, involving the transmission and distribution of hydrogen from one point to another, or as fueling operations involving the transfer of hydrogen into the final receiving device (e.g., to an onboard storage tank). Hydrogen delivery from a centralized or semi-centralized production facility requires both transport and fueling operations, while delivery operations associated with distributed production (i.e., on-site production directly at the point of use) typically involve only fueling operations. There are three means by which hydrogen is commonly transported, shown schematically in Figures 3.2.1 (a) – (c), as a liquid by cryogenic tank truck or as a compressed gas by tube trailer or by pipeline. Also shown in Figure 3.2.1 (d) is a fourth option, transport in solid or liquid carrier form – an approach that is still in the research and development phase. While the

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[3] This target is for a well-established hydrogen market demand for transportation (e.g., 15% market penetration in an urban population with a population of approximately 1M). The specific scenario examined assumes central production of H_2 that serves a city of moderately large size (population: ~1.2M), that the distance between the plant and city is 100 km (or 62 mi), and that the average fueling station capacity is 1000kg/day.

[4] M.D. Garvey, "The Hydrogen Report," CryoGas International, February 2011.

[5] By comparison, over 320,000 miles of natural gas transmission pipeline exists in the United States, Ref: "PHMSA Calendar Year 2009 Annual Reports for Gas Transmission and Gathering, Gas Distribution and Hazardous Liquid," PHMSA Calendar Year 2009 NPMS submissions for LNG Plants; http://primis.phmsa.dot.gov/comm/PipelineBasics.htm.

first three pathways involve the transport of molecular hydrogen, the latter approach employs a material that chemically binds or physisorbs hydrogen.

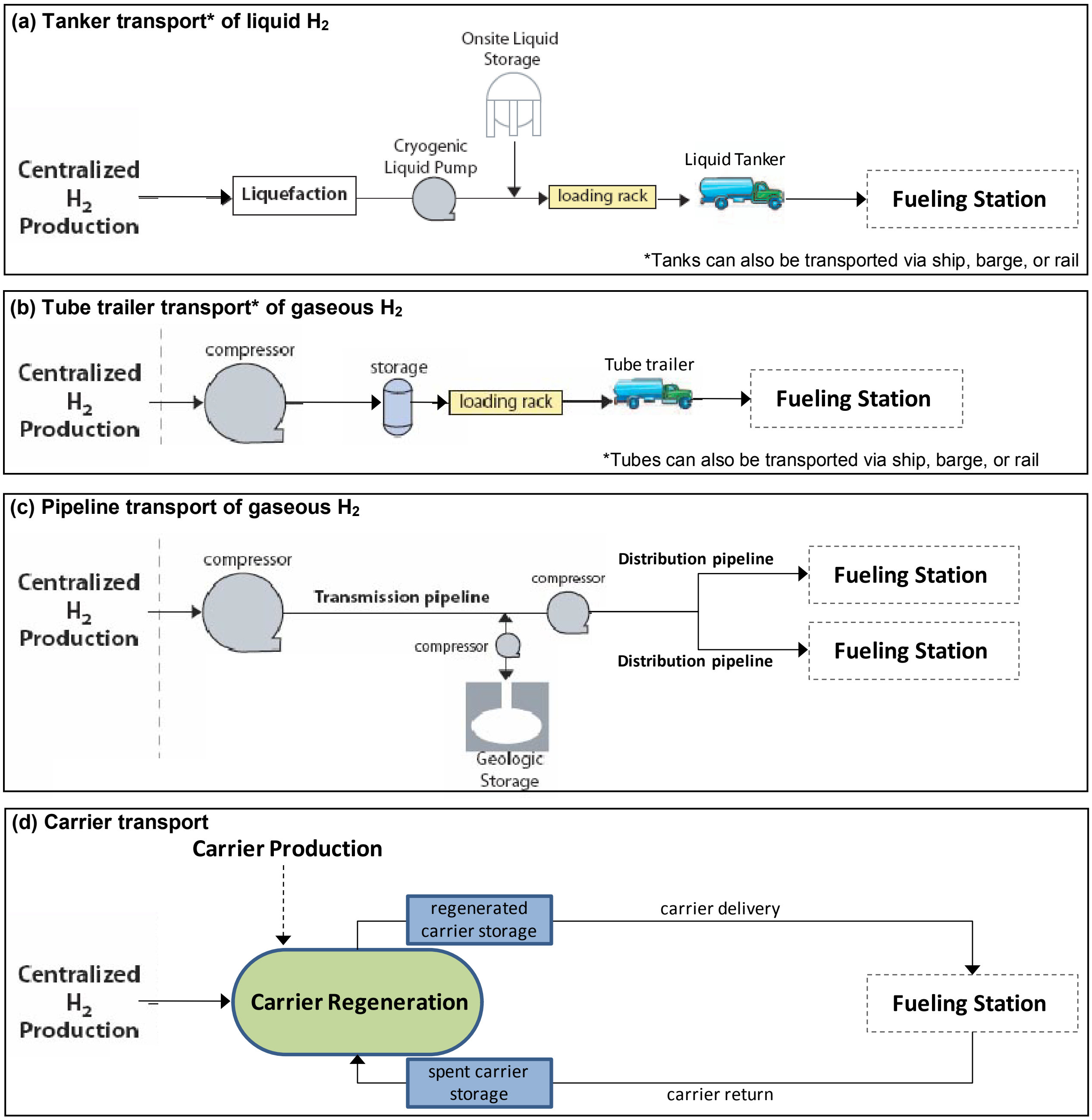


Figure 3.2.1 Basic hydrogen transport pathway options.

Each transport option consists of a series of process operations that in turn are comprised of a set of individual process components. Conceivably, alternative pathways could be chosen that combine elements from two or more of these basic approaches. For example, gaseous hydrogen can be transported by pipeline to a terminal where it is liquefied for distribution by cryogenic tank truck (a practice currently employed at several North American facilities) or it could be transformed at the terminal into a carrier for subsequent distribution. To minimize delivery costs, transport logistics are optimized by geographic location, availability of operational resources (e.g., transmission and distribution pipelines, trucks, compressors, etc.), market size and type (urban, interstate, or rural), and customer needs. These pathways have evolved over time with the growth of the industrial gas market and will continue to do so as various fuel cell markets emerge and expand and as new delivery technologies are developed and implemented.

The final point in the delivery chain for fuel cell applications are the fueling sites. At present, there are approximately 60 fueling stations in the U.S. that cumulatively have been supplying more than 1,500 kg/day of hydrogen to over 200 light-duty fuel cell electric vehicles (FCEVs) and 20 fuel cell buses. While the majority of these stations reside in Southern California, approximately a dozen each are located in the Midwest and Mid-Atlantic states. Most were constructed as demonstration projects, designed to provide data on the installation and operation of hydrogen fueling equipment, including cost. They generally do not include other retail features, such as a convenience store, fast food outlet, or car wash. The cost of dispensed hydrogen at these facilities can vary significantly depending on a number of factors, one of which is station capacity, or the maximum amount of hydrogen that can be dispensed daily at a given site. This quantity impacts the upstream method of hydrogen transport. For example, stations with capacities at or above 100 gge/day often rely on

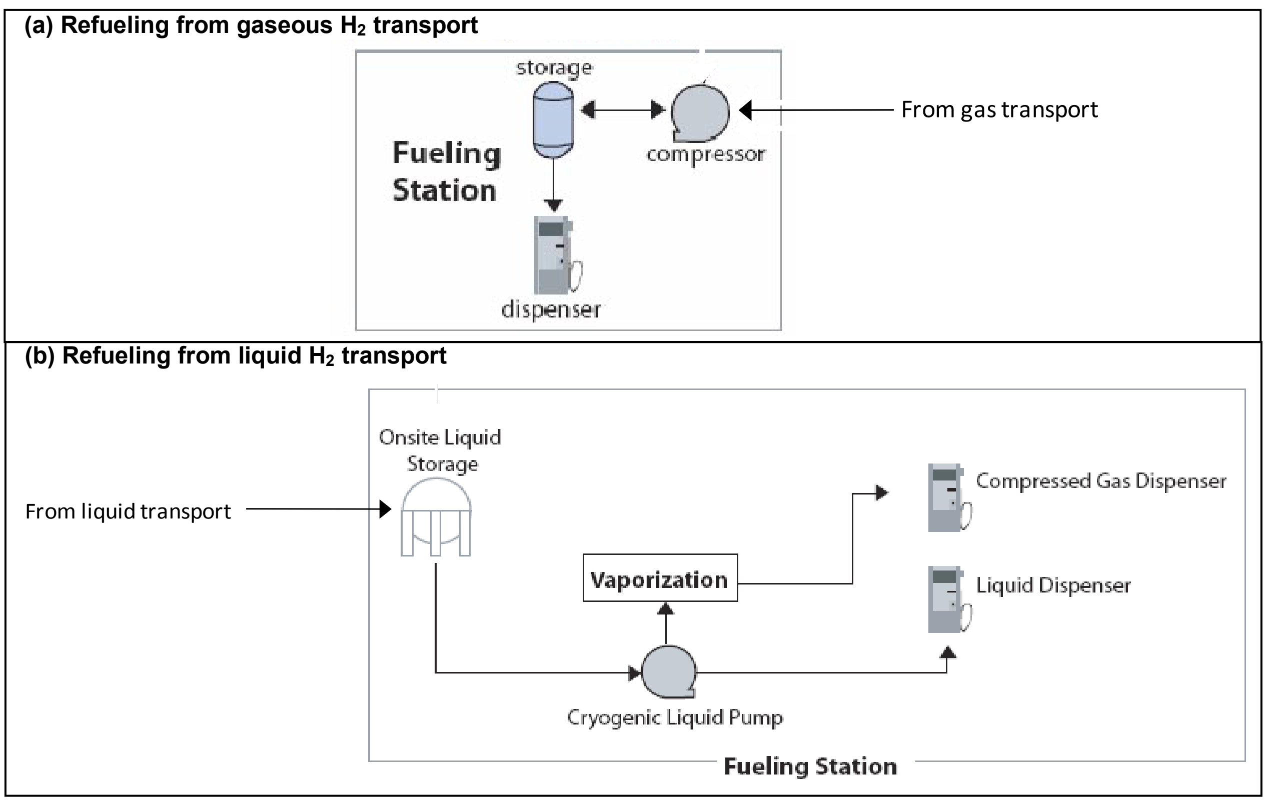


Figure 3.2.2 Typical hydrogen fueling options.

liquid transport, with the resulting dispensed gas ranging in price from $5.70 to $8.00/gge.[6] In comparison, smaller stations (capacities on the order of 10 – 20 gge/day) depend on direct gas transport via tube trailer, with an as-dispensed cost that can be approximately three times higher. In addition, a growing number of manufacturing facilities and distribution centers in the U.S. employ fuel cell powered MHE, such as forklifts,[7] and are equipped with on-site fueling operations. For nearly all current MHE and light-duty FCEVs, as well as back-up power generators, hydrogen is stored onboard at room temperature as a high-pressure compressed gas inside a steel or composite vessel. Shown in Figure 3.2.2 are the key process operations employed at present-day liquid- and gas-based hydrogen fueling stations. Note that delivery of a hydrogen-bearing carrier would require a different series of fueling operations. In all cases, the costs associated with the fueling station are significant, representing as much as half of the overall delivery cost.

Hydrogen Transport and Fueling Operations and Components

Along many product delivery pathways are regional terminals that receive large volumes of the product and further process, apportion, and/or package it for final distribution to small retail outlets. In the case of hydrogen, the terminal might receive hydrogen (for example in gaseous form from a pipeline) and further purify, compress, and load it onto tube trailers for distribution to various fueling sites. As seen from the schematic for this in Figure 3.2.3, there are a number of commonalities between process operations at each stage. As a result, improved technology developed for one stage of hydrogen delivery might also be applied at other points of the infrastructure. For example, improved storage technology could be used at both terminals and fueling stations. There is also the potential for pathway optimization through technology advances to reduce overall delivery cost. An example of this would be the development of high-pressure tube trailers that could deliver hydrogen gas to fueling stations at the desired dispensing pressure, thereby partially offsetting the need for multiple-stage, small-scale compressors at each of these sites using a single set of large-scale compression units at the terminal. Listed in Table 3.2.1 are the individual process components employed for both transport and fueling, along with a brief description of the commercial status of each. As outlined in Section 3.2.5, many of these will require improvement in order to establish a cost-effective hydrogen delivery infrastructure that meets the objectives defined above.

[6] California Fuel Cell Partnership, "Hydrogen Fuel Cell Vehicle and Station Deployment Plan: A Strategy for Meeting the Challenge Ahead," Feb. 2009.

[7] As of 7/2011, fuel cell powered forklifts were deployed at 36 U.S. facilities; http://www.fuelcells.org/resources/charts/

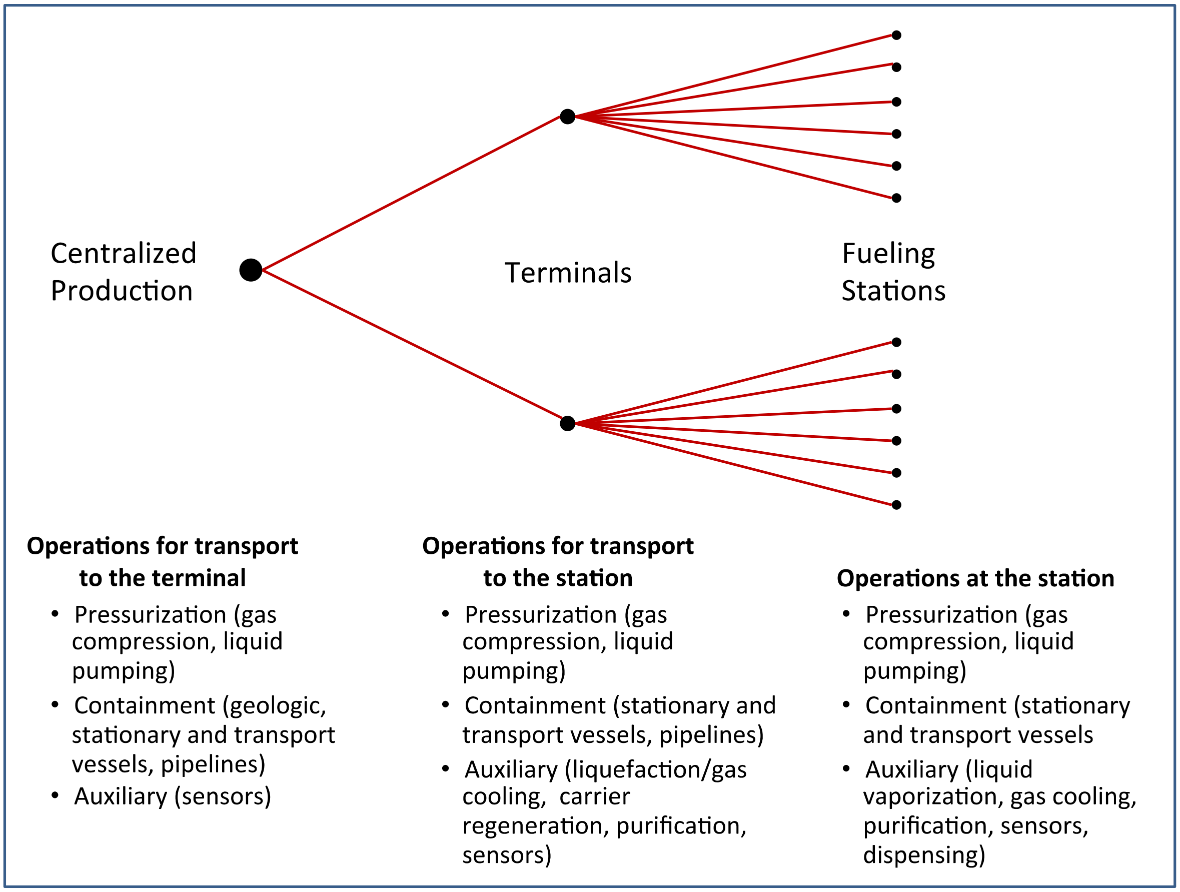


Figure 3.2.3 Commonality of process operations along a generic hydrogen delivery pathway.

Table 3.2.1 Hydrogen Delivery Infrastructure Components		
	Delivery Component	**Current Status**
Pressurization	Gas compressors	Compression operations can be differentiated based on capacity and pressurization needs. For pipeline transport, high flow rates (thousands of kg/hr) and relatively low pressures (<10MPa) and compression ratios (10:1) are required. The opposite is true at fueling stations, where compressor flow rates may be 5 - 100kg/hr and compression pressures as high as 90 MPa (900 bar). Loading operations at terminals generally have intermediate needs. High flow rate reciprocating piston compressors are typically employed for pipeline transport and terminal pressure vessel loading operations and high-pressure diaphragm compressors are used at hydrogen fueling stations (although small reciprocating and intensifier compressors are also used). Ionic liquid compressors are beginning to be commercialized for use in low-to-moderate flow rate and high-pressure gas compression operations.
Pressurization	Liquid pumps	Liquid H_2 is typically pressurized with specially designed centrifugal pumps. Cryogenic reciprocating pumps have also been employed.
Containment	Pipelines	This is the perceived lowest cost option for large volume H_2 transport. However, because the capital investment for pipelines is high, there must be a steady, high volume gas demand to justify the investment cost. Transmission line pressures are typically 3 – 15 MPa (30 – 150 bar), while distribution line pressures range from 1 – 5 MPa (10 – 50 bar).[a] Materials of construction are mild, low carbon steels. Embrittlement concerns for these materials are far less than for higher strength steels and are further mitigated by proper pipeline design (there are some concerns with combined fatigue effects due to pressure surging in the lines and with poor welds at pipe joints). Long pipelines for liquid hydrogen are currently cost prohibitive.
Containment	Gas storage	The most common pressure vessel construction is the Type 1 steel tube. These are capable of storing gaseous H_2 at pressures of 13.5 – 41 MPa (135 – 410 bar) and can be interconnected to increase overall storage capacity. Storage pressure is limited for over the road transport based on DOT regulations, which depend on vessel construction, vessel size, and transport container design. Current carrying capacity for steel tube trailers is only about 300 kg (at ~18 MPa, or 180 bar). Because of the limited amount of H_2 that can be transported by steel tube trailer, this transport approach is economically constrained to a radius of ~ 300 km from the point of production. Compressed hydrogen gas can also be delivered by rail, ship, and barge. Composite pressure vessels are also available. Typically these cost more than steel vessels of equivalent size, but generally will store H_2 at higher pressures (and therefore higher capacity) and storage costs on a "per kg of H_2 stored" basis are often lower. The use of composite vessels for tube trailer transport and for onsite storage is being developed.
	Geologic storage	Geologic storage is commonly used in the natural gas delivery infrastructure to store large quantities of gas at modest pressures (~15 – 20MPa, or ~150 – 200 bar). Caverns are typically formed in impermeable salt domes to minimize gas loss. There is one H_2 storage salt cavern site in the U.S. at Lake Jackson, TX that has been in operation for several decades and two others that have been built recently (also in Texas).

	Table 3.2.1 Hydrogen Delivery Infrastructure Components	
	Delivery Component	**Current Status**
Auxiliary Processing	Liquefaction systems	Over 90% of merchant hydrogen is transported in liquid form, which is currently the most economical means of truck transport for large market demands (> 100 kg/day) and for distances greater than ~300 km.[b] There are ten liquefaction plants in North America, each varying in capacity from 5,400 – 32,000 kg/day.[c] These plants employ multiple cooling cycles (including pre-cooling with liquid N_2, a Brayton cycle, and a Joule-Thompson cycle) and are energy intensive, consuming electricity ~⅓ of the energy in the hydrogen.
Auxiliary Processing	Gas cooling systems	70 MPa (700 bar) dispensing of gaseous H_2 into Type IV tanks at a fill rate of 1.6 kg/min currently requires pre-cooling of the gas to overcome the heat of compression and the consequent effects on pressure vessel strength.[c] Several early-design 70 MPa (700 bar) dispensing systems employ liquid N_2 cooling to about -40°C.
Auxiliary Processing	Separators/ purifiers	Common practice is to use pressure swing adsorption to remove impurities from gaseous hydrogen for use in fuel cells. This is done at the point of production. Other technologies include membrane and cryogenic separation. Compressor lubricants are removed by filtration.
Auxiliary Processing	Dispensers	Commercial vehicle station gas dispensers often consist of a locking nozzle equipped for communication with the tank to ensure proper pre-programmed fill rates, safety breakaway hoses, electronically controlled delivery valving, and temperature/pressure compensated metering in packaging that resembles a standard gasoline dispenser. Dispenser systems exist that handle either 35 or 70 MPa (350 or 700 bar) gas pressure.
Auxiliary Processing	Sensors	Hydrogen is colorless and odorless and its flames are virtually invisible in daylight. Commercial hydrogen sensor technology currently can be categorized as one of six basic types: electrochemical, palladium and palladium alloy film, metal oxide, pellistor, thermal conductivity, and optical/acoustic devices.
Auxiliary Processing	Evaporators	Used to generate gas from liquid H_2 at a given pressure, these units are usually composed of a series of finned heat exchangers that can be heated indirectly by air, water, or steam.
Carrier	Carrier systems	Currently not employed for H_2 transport. Preliminary assessments of ammonia, liquid hydrocarbons, metal hydrides, adsorbents, and chemical hydrides indicate that these materials may not offer a significant economic advantage relative to molecular hydrogen solely for delivery needs. However, results from the Storage sub-program may yet show a benefit for the combination of H_2 delivery and onboard storage. In addition, methane is currently being considered as a potentially viable carrier of hydrogen.

[a] Nexant, Inc., "Hydrogen Delivery Infrastructure Options Analysis, Final Report." DE-FG36-05GO15032, Dec. 2008.

[b] http://hydrogen.pnl.gov/cocoon/morf/hydrogen.

[c] DOE-FCTP Record #9013, "Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs."

Research Strategy

Hydrogen can become a key energy carrier in the U.S. only after critical economic and technical barriers to the development of a more expanded infrastructure are overcome. The needs for RD&D range from incremental improvements to major advances in technology. Research activities can be staged; i.e., it is anticipated that certain needs must be satisfied in the near term to solidify early fuel cell markets, while others do not need to be fully met until there are appropriate signs for more widespread consumer demand. In addition, there are several factors that will impact the strategic choices made for Delivery sub-program RD&D investment, including:

- Emergence of potentially sustainable fuel cell markets – Sub-program support for emerging market applications will be critical in developing commercial acceptance and demand for fuel cell technology, as well as establishing low cost delivery technologies that can serve future markets. Nascent markets, such as the use of fuel cells in back-up power sources and material handling equipment, will likely continue to take advantage of the present merchant hydrogen infrastructure. However for these markets to grow and become sustainable, the levelized, as-dispensed cost of hydrogen must be reduced, including the delivery portion of that cost. Advances in delivery technology and process optimization that commercially entrench these early markets will also make the next set of market applications in the evolutionary chain (e.g., delivery vehicles and larger-scale distributed power generation) more economically attractive and therefore more viable.

- Hydrogen production strategy – The Fuel Cell Technologies Program's threshold for the untaxed, as-dispensed cost of hydrogen includes the costs of both production and delivery. Under several scenarios, there may be inherent trade-offs between the cost of production and the cost of delivery. Distributed hydrogen production, for example at the fueling site, eliminates costs associated with transporting hydrogen from a centralized or semi-centralized production facility. However, economies of scale associated with the latter two would result in lower production costs than experienced with a smaller size, on-site production system. In addition, it is possible to produce hydrogen at pressures higher than that delivered in current steam methane reformation practice. Again, there is a trade-off in the higher costs incurred with high-pressure production equipment versus the reduction in compression cost downstream at the fueling site.

- Required form of hydrogen for application storage – Fuel cell powered forklifts currently utilize 350 bar compressed hydrogen gas (CHG), while light-duty FCEVs will initially require 700 bar CHG for full range. The latter requires higher compression capability at FCEV fueling stations and a means of cooling the gas prior to dispensing (to avoid issues associated with hydrogen heating as it is compressed into the vehicle's tank), both of which represent higher fueling cost. In addition, the Storage sub-program is developing next generation storage strategies that may require the delivery of cryogenic liquid hydrogen to FCEV fueling stations, a different level of gas cooling, or liquid delivery of chemical hydrides that require off-board regeneration, each of which would require a different set of process operations than those currently used to serve MHE.

- Safety, codes, and standards considerations – The implementation of codes and standards by regulating authorities govern safe equipment/facility design, construction, and operation for every aspect of the hydrogen delivery infrastructure – including truck, rail, and pipeline transport; tank and geologic storage; handling at the terminal; and handling and dispensing at the fueling site. By nature, they also affect the costs for all of these operations, as well as for other factors such as insurance. Possible elimination or mitigation of processes constrained by regulation in favor of those less constrained can potentially reduce overall delivery cost. The development of safety equipment that facilitates approved use of a lower cost operation, less land use, lower cost facility design (e.g. fueling station), or reduced insurance costs can have the same effect.

With the above in mind, the Delivery sub-program will be aligned along the following RD&D thrusts:

1) Innovative Technologies and Processes to Address the Challenges of Low Cost, Reliable Hydrogen Delivery

The largest RD&D activity will concentrate on developing innovative process technologies that can reduce hydrogen transport and fueling costs. Investment decisions for these technologies will be guided by results from process and pathway optimization studies, as outlined for the analysis activity below. Stakeholder input and results from recent analyses indicate for long-term, high market penetration of light-duty fuel cell vehicles that advancements in the following delivery components would offer the greatest opportunity toward meeting the Program's threshold cost for as-dispensed hydrogen:

- Low cost, high efficiency pressurization equipment – including gas compressors and cryo-compression liquid pumps.
- Advanced containment technology – including low-cost pipelines and high pressure gas transport and stationary storage vessels.
- Auxiliary process units and enabling technologies – including novel hydrogen liquefaction or gas cooling systems; low-cost, high reliability dispensers; and advanced materials and sensors that promote more economic delivery processes.

2) Infrastructure Modeling

a. *Delivery Pathway Analysis*

The publicly available Hydrogen Delivery Scenario Analysis Model (HDSAM)[8] links together various hydrogen delivery component functions and costs to develop capacity/flow parameters for a variety of different potential hydrogen delivery infrastructure options. The model can be used to calculate the full cost of a given hydrogen delivery pathway, define underlying individual cost contributions, and examine the economic effects of new delivery technologies as a function of hydrogen demand, transport distance, underlying finance

[8] HDSAM V2.3; http://www.hydrogen.energy.gov/h2a_delivery.html

factors (e.g., internal rate of return, insurance, land costs, etc.). In addition to stakeholder feedback, this modeling tool provides a means of identifying those processes or factors likely to have the greatest impact on delivery cost for future sub-program technology development. Future efforts will include: (i) refining the cost inputs and assumptions made to the model as new data become available, (ii) assessing the potential impact of current technology development projects on hydrogen delivery cost as a means of measuring individual project progress towards the targets listed in Tables 3.2.3 and 3.2.4, and (iii) evaluating the impact of hydrogen production and onboard storage technologies on delivery pathway options, operations, and costs. Of particular strategic importance to the Program is an investigation of delivery pathway options for emerging markets such as MHE to identify key near-term technical and cost barriers for these.

b. Delivery Pathway Optimization

HDSAM also allows one to examine trade-offs between components and process operations along any potential delivery pathway and determine the effects of individual process or equipment optimization in minimizing overall cost; in essence carrying out a "deep-dive" to frame the engineering limits for competing process technologies. While the infrastructure analysis activity described above will identify key cost contributors, this research thrust will investigate how these contributors can be mitigated or eliminated through hypothetical, but practical changes in technology. This will afford a more deliberate basis for making investments in new delivery technology. The example of advanced high-pressure tube trailers discussed previously is one possible technology topic for consideration. Another includes understanding hydrogen temperature effects. For example, a recent preliminary analysis suggests that cooling hydrogen to 70 – 90 K at a production site or terminal, transporting it in insulated tube trailers, and charging cold gas to the vehicle may offer significant delivery cost advantages, as well as achieve a higher volumetric FCEV storage efficiency due to the higher density of the cold hydrogen gas relative to ambient gas. Again, initial efforts will focus on emerging markets to provide immediate value to the FCT Program.

3.2.3 Programmatic Status

Projects currently funded by the Delivery sub-program are shown in Table 3.2.2. Activities focused on pressurization technology development include the design of centrifugal compressors for high hydrogen flow rates, an electrochemical means of achieving high compression ratios for fueling applications, and the evaluation of ionic liquid compression of hydrogen gas and reciprocating pumping of hydrogen liquid. Advanced pressurized containment technology being developed includes the design of high-pressure gas vessels for transport and stationary storage, the characterization of hydrogen embrittlement enhanced fatigue in base and weld metal sections of common pipeline steels, and the evaluation of fiber reinforced polymers as alternative pipeline materials. In addition, magnetic refrigeration is being explored for hydrogen liquefaction. Analysis efforts include the use of HDSAM and other models to benchmark the projected costs of technologies in development against those of technologies currently employed by industry, to evaluate various delivery pathway costs for the MHE market, and to carry out a detailed optimization analysis of gas compression.

Table 3.2.2 Current Hydrogen Delivery Projects		
Challenge	**Approach**	**Activities**
Analysis Identify the cost effective options for hydrogen delivery	Evaluate pathways and process for delivering gaseous or liquid H2 and novel carriers under various technology market, and financial assumptions	Argonne National Laboratory and Pacific Northwest National Laboratory: Evaluate delivery options for MHE and carry out a detailed engineering evaluation of compression technology and evaluate the trade-offs between compression and storage pressure/temperature at various points along competing delivery pathway options.
Pressurization Compression: Increase the reliability, reduce the cost, and improve the energy efficiency of gaseous hydrogen compressors.	Develop improved compression technologies for gaseous hydrogen.	Concepts NREC and Mohawk Innovative Technologies Independently develop high flow rate centrifugal compression technology suitable for hydrogen. Fuel Cell Energy: Develop electrochemical hydrogen compression technology. National Renewable Energy Laboratory: Evaluate the operation and maintenance requirements for ionic liquid compression at a fueling site.
Pumps: Increase the reliability, reduce the cost, and improve the energy efficiency of liquid hydrogen pumps.	Develop improved compression technologies for liquid hydrogen.	Lawrence Livermore National Laboratory (LLNL): Evaluate the operation of a new reciprocating cryo-pump design.
Containment Pipelines: reduce installed costs and ensure safety, reliability, and durability.	Resolve hydrogen embrittlement of steel concerns and evaluate new materials for pipeline delivery of hydrogen.	Sandia National Laboratories: Pipeline and weld materials testing and modeling. Oak Ridge National Laboratory (ORNL) and Savannah River National Laboratory: Evaluate low-cost fiber reinforced polymer (FRP) composite pipelines.
Tube trailer and storage vessels reduce capital cost on a $/kg H_2 stored basis while ensuring safety, reliability, and durability	Develop vessels that can store gas under higher pressure and/or reduced temperature.	Lincoln Composites: Develop a high-pressure, composite tube trailer vessels. LLNL: Evaluate composite materials and structures for high-pressure/reduced temperature stationary and transport storage. ORNL: Develop an in-ground reinforced concrete based vessel.
Auxiliary Liquefaction – reduce the capital cost and improve the energy efficiency of hydrogen liquefaction.	Explore new approaches to hydrogen liquefaction.	Prometheus, Inc.: Develop an alternative method of cryogenically cooling H_2 to <20 K via magnetic refrigeration.

3.2.4 Technical Challenges

Cost and Energy Efficiency

The overarching techno-economic challenge for this sub-program is to reduce the cost of hydrogen delivery so that stakeholders can achieve the return on the investment required for infrastructure build out. Without cost competitive hydrogen sourcing, fuel cell technology will not be economically viable for broad market application. To meet the long-term target of <$2.00/gge (i.e. the delivery half of the upper threshold cost) [9] significant improvements in delivery technology are required. For example, if pipeline transport is to be employed at greater scale, the capital cost for pipeline procurement and installation needs to be reduced, while maintaining the same level of safety and reliability that has been achieved for the last 50+ years in the industrial gas market experience. If cryogenic liquid transport is to be used in higher volume, the capital cost and energy efficiency associated with liquefaction must be improved dramatically and losses due to vaporization need to be minimized. The use of gaseous tube trailers could be very attractive if their carrying capacities can continue to be increased, perhaps through the use of higher pressure and/or cooled gas or the use of a novel carrier in the tubes. The gas compression technology used at terminals and fueling sites must be more reliable (i.e., reducing the need for back up units), require less/easier maintenance, and be lower cost. In general, the costs at fueling sites need to be brought down to a level that ensures a positive return on investment can be realized far more quickly than is currently projected.

Hydrogen Purity Requirements

Polymer Electrolyte Membrane (PEM) fuel cell stacks requires very high quality hydrogen (see Appendix C). If the hydrogen is produced at the required specifications, then design of the delivery infrastructure must either guard against contamination or provide for a final purification step just prior to dispensing. Alternatively, hydrogen could be produced at lower purity levels and purified to specification further downstream along the delivery pathway prior to dispensing. The optimum purification strategy that will minimize overall costs will depend on the nature of the potential contamination issues and thus the technologies employed across production and delivery. The delivery research plan includes inputs and outputs across Hydrogen Production, Delivery, Storage, Fuel Cells, and Systems Analysis to coordinate this strategy.

Hydrogen Leakage

Diatomic hydrogen is a very light molecule and can diffuse at much higher rates than other fuel or energy carrier gases, such as natural gas. This property introduces unique challenges in designing process equipment and selecting suitable materials of construction that mitigate hydrogen leakage. Currently, significant leakage issues are avoided in the handling and use of large quantities of hydrogen in industrial settings because process operations are highly monitored and equipment is maintained and operated by trained, skilled operators. The establishment of hydrogen as a major energy carrier, where it will be handled in more open settings at times by the general public (e.g.,

[9] DOE-FCTP Record 12001, "H_2 Production and Delivery Cost Apportionment." http://www.hydrogen.energy.gov/program_records.html

vehicle fueling), will require robust system design and engineering and appropriate safety measures for many of the processes discussed above.

Analysis of Infrastructure Trade-Offs

The development of HDSAM offers a means of identifying key cost contributors for various delivery scenarios. To date, its use for this purpose has specifically focused on long-term fuel cell applications, notably a light-duty FCEV market. However, it is recognized that the infrastructure for long-term markets will likely grow out of that which initially develops around smaller near-term fuel cell applications markets. Analysis of the delivery options and challenges for these early markets is needed. In addition, a subsequent analysis must be undertaken that focuses on how potentially interdependent process operations (e.g., high-pressure storage and gas compression) can be optimized to reduce overall pathway costs. Other trade-off studies that should be conducted include: (1) evaluation of the effects of production strategy (e.g., distributed and high-pressure production) on the as-dispensed cost of hydrogen, (2) further investigation of a cold (~80K) delivery pathway, and (3) an initial delivery operations analysis of the chemical hydrides being developed for onboard FCEV storage in the Storage sub-program.

Technical and Threshold Cost Targets

The key to achieving the sub-program's goal and objectives is to reduce capital and operating costs and improve performance reliability for major delivery process technologies: pressurized containment (for stationary and transport operations), pressurization (compression and pumping), and liquefaction. The sub-program targets listed in Tables 3.2.3 and 3.2.4 are designed to meet the Program's threshold cost target for as-dispensed hydrogen. They are based on an analysis of current technology and costs and estimates of what might be possible with technology advances and on the projected market-driven requirements for the total delivery system costs. The current technology costs are derived from a recently updated version of HDSAM [10] that includes the latest information from stakeholders. Delivery system costs are a complex function of the technology, delivery distances, system architecture, and hydrogen demand. The 2020 cost targets in the table are the estimated costs needed for these technologies to meet an overall delivery system cost contribution of <$2.00/gge[11] of hydrogen. Initial targets are also given for cold hydrogen gas delivery and liquid-carrier technologies that could prove useful for hydrogen delivery and vehicle storage.

[10] HDSAM V2.3; http://www.hydrogen.energy.gov/h2a_delivery.html.
[11] DOE-FCTP Record 12001, "H_2 Production and Delivery Cost Apportionment." http://www.hydrogen.energy.gov/program_records.html

Table 3.2.3 Threshold Cost Targets for Hydrogen Delivery [a, bb]				
Category	**2005 Status[y]**	**FY 2011 Status**	**FY 2015 Target**	**FY 2020[z] Target**
Hydrogen Delivery Sub-Program Threshold Cost Targets				
Delivery costs associated with distributed H_2 production[aa]				
Aggregate fueling station cost ($/gge)	1.90	2.50	2.15	<1.70
Delivery costs associated with centralized H_2 production[aa]				
Cost of transport and distribution ($/gge)	2.10 – 2.30	1.90 – 2.20	1.40	<1.30
Aggregate fueling station cost ($/gge)	1.30 – 1.60	1.70 - 2.20	1.60	<0.70

Table 3.2.4 Technical Targets for Hydrogen Delivery Components [a, bb]				
Category	**2005 Status[y]**	**FY 2011 Status**	**FY 2015 Target**	**FY 2020[z] Target**
Gaseous Hydrogen Delivery				
Pipelines: Transmission				
Total Capital Investment ($/mile for an 8-in. equivalent pipeline) [excluding right-of-way][b]	765,000	765,000	735,000	710,000
Pipelines: Distribution: Trunk and Service Lines				
Total Capital Investment ($/mile for a 1-in. pipeline) [excluding right-of-way][b]	440,000	440,000	375,000	250,000
Pipelines: Transmission and Distribution				
Reliability/Integrity (including 3rd-party damage issues)[c]	Acceptable for current service	Acceptable for current service	Acceptable for current service	Acceptable for current service
H_2 Leakage (kg-H_2/mile-yr)[d]	Unknown	Undefined	Undefined	<780 (Transmission) <160 (Distribution)

Table 3.2.4 Technical Targets for Hydrogen Delivery Components [a, bb] (continued)				
Category	**2005 Status[y]**	**FY 2011 Status**	**FY 2015 Target**	**FY 2020[z] Target**
Large Compressors: Transmission Pipelines, Terminals, Geological Storage				
Reliability[e]	Low	Low	Improved	Improved
Compressor Efficiency (Isentropic)[f]	88%	88%	>88%	>88%
Losses (% of H_2 throughput)	0.5%	0.5%	0.5%	<0.5%
Uninstalled Capital Cost ($) (based on 3,000 kW motor rating)[g]	2.7M	2.7M	2.3M	1.9M
Maintenance (% of Installed Capital Cost)	4%	4%	3%	2%
Contamination[h]	Varies by design	Varies by design	Varies by design	None
Small Compressors: Fueling Sites				
Reliability[i]	Low	Improved	Improved	High
Compressor Efficiency (Isentropic)[j]	65%	65%	73%	80%
Losses (% of H_2 throughput)	0.5%	0.5%	0.5%	<0.5%
Uninstalled Capital Cost ($) (based on 1000 kg/day station, [~100 kg H_2/hr peak compressor flow][k]	530,000 (Three compressors at $176,666 each. Two at 50% throughput each, and one backup)	675,000 (Three compressors at $225,000 each. Two at 50% through-put each, and one backup)	400,000 (Two compressors at $200,000 each. Both at 50% through-put each, no backup) or $360,000 (one compressor, no backup)	240,000 (one compressor, no backup)
Maintenance (% of Installed Capital Cost)	4%	4%	2.5%	2%
Outlet Pressure Capability (bar)[l]	430	860	860	860

Table 3.2.4 Technical Targets for Hydrogen Delivery Components [a, bb] (continued)				
Category	**2005 Status[y]**	**FY 2011 Status**	**FY 2015 Target**	**FY 2020[z] Target**
Compression Power (kW)	200 (20 bar at inlet)	300 (20 bar at inlet)	260 (20 bar at inlet)	240 (20 bar at inlet)
Contamination[m]	Varies by design	Varies by design	Varies by design	None
Stationary Gaseous Hydrogen Storage Tanks (for fueling sites, terminals, or other non-transport storage needs)[n]				
Low Pressure (160 bar) Purchased Capital Cost ($/kg of H_2 stored)	1000	1000	850	700
Moderate Pressure (430 bar) Purchased Capital Cost ($/kg of H_2 stored)	1100	1100	900	750
High Pressure (860 bar) Purchased Capital Cost ($/kg of H_2 stored)	N/A	1,450	1,200	1000
Tube Trailers[o]				
Delivery Capacity (kg of H_2)	280	560	700	940
Operating Pressure Capability (bar)	180	250	400	520
Purchased Capital Cost ($)	260,000	470,000	510,000	540,000
Geologic Storage[p]				
Installed Capital Cost[q]	Assumed equal to natural gas caverns	Assumed equal to natural gas caverns	Assumed equal to natural gas caverns	Assumed equal to natural gas caverns
Liquid Hydrogen Delivery				
Small-Scale Liquefaction (30,000 kg H_2/day)				
Installed Capital Cost ($)[r]	54M	54M	42M	29M
Energy Required (kWh/kg of H_2)[s]	10	10	8.0	6.5

Table 3.2.4 Technical Targets for Hydrogen Delivery Components [a, bb] (continued)				
Category	**2005 Status[y]**	**FY 2011 Status**	**FY 2015 Target**	**FY 2020[z] Target**
Large-Scale Liquefaction (300,000 kg H_2/day)				
Installed Capital Cost ($)[r]	186M	186M	150M	110M
Energy Required (kWh/kg of H_2)[s]	8	8	7.0	5.4
Liquid H_2 Pumps (Fueling)[t]				
Uninstalled Capital Cost ($) (430 bar pressure capability, 100 kg/h)	100,000	100,000	85,000	70,000
Uninstalled Capital Cost ($) (870 bar pressure capability, 100 kg/h)	N/A	N/A	150,000	150,000
Cold Gas Delivery[u]				
Cold Gas Fueling Compressors (same requirements as fueling compressors above except the following)[v]				
Uninstalled Capital Cost ($K) (based on a 1000 kg/day refueling station, 75 kW [50 kg H_2/hr peak compressor flow]	Undefined	97,000	85,000	75,000
Outlet Pressure Capability (bar)	Undefined	350	350	350
Temperature Capability (K)	Undefined	90	90	70 - 90
Cold Gas Delivery (Off-Board Storage)[w]				
Low Pressure Storage Vessel Cost (160 bar; $/kg-$H_2$)	Undefined	Undefined	Undefined	750
High Pressure Storage Vessel Cost (430 bar; $/kg-$H_2$)	Undefined	Undefined	Undefined	800
Temperature Capability	Undefined	Undefined	Undefined	40 K - ambient
Cold Gas Delivery (Tube Trailer Transport)[w]				
Temperature Capability (K)	Undefined	Undefined	Undefined	60 K to ambient
Delivery Capacity at 90K (kg of H_2)	Undefined	Undefined	Undefined	1,500
Operating Pressure Capability (bar)	Undefined	Undefined	Undefined	340
Purchased Capital Cost ($)	Undefined	Undefined	Undefined	<600,000

Table 3.2.4 Technical Targets for Hydrogen Delivery Components [a, bb] (continued)				
Category	**2005 Status[y]**	**FY 2011 Status**	**FY 2015 Target**	**FY 2020[z] Target**
Liquid Carrier Based Hydrogen Delivery[x]				
Carrier H_2 Content (kg of H_2/m^3)	Undefined	Undefined	Undefined	>70
Cost to regenerate	Undefined	Undefined	Undefined	<$1.00/kg of H_2
Carrier System Energy Efficiency (from the point of H_2 production through dispensing at the fueling station) (%)	Undefined	Undefined	Undefined	≥70
Gas Dispenser				
Uninstalled cost/dispenser ($ at the design pressure specified, two hoses per dispenser)	30,000 (430bar)	50,000 (860bar)	40,000 (860bar)	35,000 (860bar)

[a] All costs in Table are in 2007 dollars to be consistent with EERE planning which uses the energy costs from the 2009 Annual Energy Outlook.

[b] Pipeline Capital Costs: The 2005 and 2011 costs are from HDSAM, V2.3. (For more details on the HDSAM, see www.hydrogen.energy.gov.) The model uses historical costs published by Brown et al (Brown, D., J. Cabe, and T. Stout, *National Lab Uses OGJ Data to Develop Cost Equations*, Oil & Gas Journal, Jan. 3, 2011 for natural gas steel pipelines as a function of pipeline diameter. It is assumed that hydrogen steel pipelines costs are 10% higher than natural gas pipelines based on discussions with industrial gas companies who build and operate the current system of hydrogen pipelines in the U.S. The costs are broken down into materials, labor, and miscellaneous costs in HDSAM. Because they vary widely based on the location of pipeline installation, right-of-way costs have been excluded in the analysis. However they can account for a significant fraction of installation cost, particularly in urban areas. The 2020 target costs are based on projected potential costs for spoolable FRP pipelines of less than 6" diameter similar to those used for natural gas gathering lines. (Note: An 8" transmission line service could use two 6" FRP pipelines for equivalent service.) Transmission line pressures are assumed to be as high as 150 bar, trunk lines as high as 50 bar, and service lines as high as 30 bar.

[c] Pipeline reliability refers to maintaining integrity of the pipeline relative to potential hydrogen embrittlement, third party damage, or other issues causing cracks or failures. The 2020 target is intended to be at least equivalent to that of today's natural gas pipeline infrastructure.

[d] Hydrogen leakage is hydrogen that permeates or leaks from fittings, etc., from the pipeline as a percent of the amount of hydrogen put through the pipeline. The 2020 target is based on being equivalent to today's natural gas pipeline infrastructure based on the article: David A. Kirchgessner, et al, "Estimate of Methane Emissions from the U.S. Natural Gas Industry," Chemososphere, Vol.35, No 6, pp. 1365-1390, 1997.

[e] Large Compressor Reliability: Currently the only hydrogen compressor technology available for pipeline transmission service and other high throughput, modest pressure boost service (e.g., a compression ratio of 1.5 to 10) is reciprocating compression. Due to the large number of moving parts and other challenges with hydrogen purity, this technology has low reliability. This translates to installing multiple compressors to ensure high availability. The status (2005, 2011) of "Low" is modeled in HDSAM, V2.3 as installing three compressors, each rated at 50% of the system peak flow. The 2020 target of "Improved" reliability assumes two compressors each rated at 50% of the peak flow for pipeline transmission and truck loading service and one compressor for hydrogen storage service. Reciprocating compression technology will need significant improvement or new technology (e.g., centrifugal compression applicable to hydrogen) may be needed to achieve these levels of reliability.

[f] Large Compressor Efficiency: The current status (2011) of 88% isentropic energy efficiency for the compressor itself is typical for large reciprocating compressors used for hydrogen. Isentropic efficiency of compressors is defined as "the increase in the enthalpy of hydrogen due to compression" divided by "the total mechanical energy used by the compressor" under isentropic conditions of compression. The difference between these two is dissipated as waste heat in the compression operation. The 2020 target is set to at least maintain this efficiency.

[g] Large Compressor Capital Cost: These 2005 and 2011 status cost is based on HDSAM, V2.3. The model uses capital cost estimates for large two- and three-stage reciprocating compressors based on data supplied by various vendors. (For more details on the large compressor capital cost data see "Hydrogen Delivery Infrastructure Options Analysis, Final Report." Nexant Inc., DE-FG36-05GO15032, Dec. 2008). The 2020 target cost is set at 70% of the 2011 cost to achieve overall delivery cost objectives.

[h] Large Compressor Contamination: Some reciprocating gas compressor designs require oil lubrication that results in some oil contamination of the gas compressed. Due to the stringent hydrogen quality specifications for PEM fuel cells, the 2020 target is to ensure no possibility of lubricant contamination of the hydrogen from compression. As an alternative, it may be possible to remove such contamination at refueling sites just prior to charging the hydrogen to vehicles if this is not cost prohibitive.

[i] Fueling Compressor Reliability: Currently several compressor technologies are being demonstrated for refueling station service. The main employed technology is the diaphragm technology, but piston technology and intensifiers are also being used. There are concerns about reliability for this service. This translates to potentially installing multiple compressors to ensure high availability. The 2005 status of "Low" is modeled in the HDSAM V2.3 as installing three compressors each rated at 50% of the station peak hourly flow. The 2011 status of "improved" represents some improvement in this area and is modeled as two compressors each rated at 50% of peak station flow. The 2020 Target of "High" assumes only one compressor is needed at the station and can handle 100% of the peak station flow. This is deemed necessary to achieve the overall hydrogen delivery cost targets.

[j] Fueling Compression Efficiency: The 2005 and 2011 status of 65% isentropic energy efficiency for the compressor itself, is typical for the size of hydrogen refueling station compressors. Isentropic efficiency of compressors is defined as "the percentage of mechanical energy that ends up utilized as compression energy" divided by "the total energy used by the compressor" under isentropic conditions of compression. The difference between these two is dissipated as waste heat in the compression operation. The 2020 target represents new or improved technology to increase the compressor isentropic energy efficiency to 80%.

[k] Fueling Compressor Capital Cost: the 2005 cost is based on compression for 350 bar hydrogen dispensing. The 2011 cost is based on compression to 860 bar for 700 bar dispensing. Both costs are modeled using HDSAM, V2.3. The model uses a cost correlation as a function of motor kW required based on information obtained from a number of hydrogen compressor vendors. The 2020 target cost is set at 35% of the 2011 cost to achieve the overall delivery cost objectives.

[l] Fueling Hydrogen Fill Pressure: Light-duty fuel cell vehicles planned to be rolled out by OEMs in the 2015 timeframe will require 700 bar fills for full vehicle range, which in turn requires station compression capability of 860 bar. This is already being demonstrated at some fueling sites. The long term goal of the DOE is to develop solid or liquid carrier or other systems for vehicle storage tanks that allow for at least 300 miles of driving between refueling with more modest pressure storage (<500 bar psi). The DOE has set targets that include 700 bar fills in 2020 to allow for the introduction of hydrogen fuel cell vehicles with high pressure vehicle gas storage technology prior to achieving commercialization of the ultimate goal of lower pressure vehicle storage technology.

[m] Fueling Compressor Contamination: Some gas compressor designs with dynamic seals require oil lubrication that results in some oil contamination of the gas compressed. Due to the stringent hydrogen quality specifications for PEM fuel cells, the 2020 target is to ensure no possibility of lubricant contamination of the hydrogen from fueling station compression.

[n] Stationary Gaseous Storage Tank Capital Costs: Several different pressures are likely for stationary storage purposes in a hydrogen delivery infrastructure. Low pressure storage at terminals and fueling stations where storage is needed but cost dictates lower pressures; moderate pressures for 350 bar refueling and high pressures for 700 bar refueling. The 2005 and 2011 status represents the cost of standard steel and composite tanks. The 2020 target is set at 65% of the 2011 cost to achieve the overall delivery cost objectives.

[o] Tube Trailers: The 2005 and 2011status tube trailer characteristics and costs are based on the HDSAM, V2.3, which uses available information on tube trailers from vendors. The 2020 cost targets are set to achieve the overall delivery cost objectives. There are several possible technology approaches to achieve these 2020 targets. It may be possible to develop more cost effective composite structures to increase the working pressure of gaseous tube trailers. The pressures in the Target Table are based on the pressure required to achieve the targeted hydrogen capacity. Another approach would be to utilize solid carrier technology and/or to employ low temperature hydrogen gas. It may also be possible to utilize some combination of these approaches. The key targets are hydrogen capacity and tube trailer capital cost.

[p] Geologic Cavern Capacity Availability: Transportation vehicle fuel demand is significantly higher in the summer than in the winter. To handle this demand surge in the summer without building prohibitively expensive excess production capacity, there will need to be significant hydrogen storage capacity within the hydrogen delivery system. Geologic storage is a very cost effective storage method for these types of demand swings and is used very effectively for similar demand swings for natural gas. There are only a few currently operating geologic storage sites for hydrogen in the world (in Texas and one in Teeside, England). Greater knowledge needs to be developed on the availability and suitability of hydrogen geologic storage sites. Technology development may also be required to ensure suitability for hydrogen.

[q] Geologic Cavern Capital Cost: This is based on HDSAM V2.3 which uses information from a U.S. hydrogen geologic storage site in Texas and assumes that hydrogen geologic caverns have the same capital cost as natural gas caverns. However, this is very limited information and is for a salt dome cavern only. This capital cost target is simply stating that hydrogen geologic storage capital costs need to be about the same as current natural gas geologic storage to make geologic storage of hydrogen cost effective and to enable achieving the overall delivery cost objectives. For more details, see: A.S. Lord, P.H. Kobos, G.T. Klise, and D.J. Borns, "A Lifecycle Cost Analysis Framework for Geologic Storage of Hydrogen: A User's Tool," Sandia Report: SAND2011-6221, Sept. 2011.

[r] Liquefaction Installed Capital: The 2005 and 2011 status costs are based on HDSAM, V2.3 which uses a correlation as a function of capacity derived from information obtained from industrial gas companies and other sources. The 2020 target cost is set to achieve the overall delivery cost objectives.

[s] Liquefaction Energy Use: The 2005 and 2011status energy requirements are based on HDSAM, V2.3 which uses a correlation as a function of capacity derived from information obtained from industrial gas companies and other sources. The 2020 target is set to achieve the overall energy efficiency objectives as well as information based on magnetic liquefaction technology that is being developed.

[t] Liquid Hydrogen Pumps: The 2005 status is based on delivery of liquid hydrogen to refueling stations where it is stored in a cryogenic tank, pumped to an evaporator and then charged to vehicles as a gas for 350 bar refueling with the aid of a cascade charging vessel system. The pump cost correlation is based on information from vendors on hydrogen liquid pumps available in 2005. The 2011 status is based on a technology similar to that available in 2005, except that the pump that charges liquid hydrogen to700 bar prior to passing the evaporator. The pump costs are based on information from developers who are currently beginning to demonstrate this technology with low hydrogen leakage rates and a maximum pumping capacity of 100kg/h is assumed. This is all modeled in HDSAM V2.3. The 2020 target is set to achieve the overall delivery cost objectives

[u] Cold Gas Delivery is a concept now being considered to reduce the cost of delivery and improve vehicle storage volumetric efficiency. The status and Targets are derived based on one promising scenario. At the terminal, hydrogen is cooled to about 90 K using liquid nitrogen. The hydrogen is transported to the refueling station in super insulated tube trailers capable of a 340 bar operating pressure. The tube trailer is dropped off at the station where it is used for storage. A compressor and insulated cascade storage vessel system is used to charge the cold hydrogen to a vehicle at 350 bar. The final temperature of the hydrogen on the vehicle would be about 200K assuming the vehicle came to the station with a tank one quarter full at about 50K which might be typical. The targets for the Cold Gas Delivery scenario are very preliminary and can only be refined when a more detailed analysis of this delivery pathway is completed. Preliminary status and Targets are provided for key components based on this scenario.

[v] Cold Gas Fueling Compressor: The 2011 capital costs are based on information from vendors who are starting to offer compressors for cold hydrogen gas. The 2020 target is based on achieving overall hydrogen delivery cost objectives. The pressure and temperature capability targets are based on the Cold Gas scenario used (see note [u]).

[w] Cold Gas Storage Vessels and Tube Trailers: These targets are based the Cold Gas scenario (see note [u]) and achieving the overall delivery cost objectives. The values include consideration of their ambient temperature component counterpart targets and inclusion of expected costs for insulation.

[x] Liquid Carrier Based Hydrogen Delivery: Hydrogen liquid carriers are being researched for onboard vehicle storage. In this case, the hydrogen is chemically bound and is released on the vehicle for use by the fuel cell. Liquid carriers might meet the volumetric storage efficiency targeted for vehicle storage. However, the spent liquid carrier must be returned to fairly large, semi-central facilities to be chemically processed and "recharged" with hydrogen (carrier regeneration). If the liquid carrier has a high enough hydrogen content, as indicated in the Target Table, its delivery costs could be quite low based on preliminary analysis. This might leave sufficient cost for regeneration and still meet the overall cost objectives for hydrogen delivery. The targets in the Target Table are very preliminary and can only be refined when the cost of regeneration is known and a more detailed analysis of this delivery pathway is completed. The target for carrier hydrogen content is based on achieving delivery capacity of about 1,500 kg of hydrogen in a standard 8,800 gallon gasoline type tanker. These tankers are DOT weight limited when delivering gasoline. Delivery modeling of truck delivery shows a very low cost for this delivery pathway if the truck has sufficient hydrogen delivery capacity.

[y] "2005 Status" numbers retained in the 2011 update to this MYRD&D section to show the differences between 2005 and 2011.

[z] 2020 targets are based on a well-established hydrogen market demand for transportation (15% market penetration). The specific scenario examined assumes central production of H_2 that serves a city of moderately large size (population: ~1M) and that the fueling station average dispensing rate is 1000kg/day.

[aa] Costs associated with distributed production refers to an apportionment of the costs required to capitalize, build, and operate a fueling station that are directly attributable to non-production operations, namely gas compression, on-site gas storage (to account for daily and weekly variations in demand), and gas dispensing. Costs associated with centralized production account for the above station costs as well as those required in transmitting the hydrogen from the production facility to the fueling station. Note that station costs associated with distributed production are somewhat higher than those for centralized production. This is because the former requires a higher level of on-site storage to account for seasonal variations in fueling demand. Seasonal variations for the latter are accounted for via geologic and/or terminal storage. The apportionment between the fuelling station cost and the transport and delivery cost is presented in program records 12022 and 12022d.

[bb] Details in this table are being revised to match recent changes in the high level cost target.

3.2.5 Technical Barriers

A. Lack of Hydrogen/Carrier and Infrastructure Options Analysis

While options and trade-offs for hydrogen/carrier delivery from central and semi-central production to the point of use are generally well described for long-term market scenarios, this is not true for early markets. Possible means of *optimizing* delivery for either long-term or short-term market scenario are not well established. The distributed production of hydrogen is another option to be considered in greater detail. Additional analysis is needed to better understand the advantages and disadvantages of the various possible approaches and technology advancements, as well as potential site-specific and regional issues. In all cases, upstream delivery pathway inputs are tied to production outputs and downstream delivery outputs must meet the needs of the onboard storage system. This interdependency between hydrogen production, delivery, and onboard storage needs to be evaluated in order to understand the possible scenarios for minimizing overall life cycle cost, energy use, and environmental impact.

B. Reliability and Costs of Gaseous Hydrogen Compression

Current compression technology used for hydrogen requires frequent maintenance, which results in the need for redundant compressors to minimize downtime and leads to high cost. Centrifugal compression is the lowest cost approach for pipeline compression needs (for example in natural gas transmission) but the current technology does not work with hydrogen and new concepts have yet to be demonstrated. Lubricants used in normal compression applications can result in unacceptable levels of contamination for PEM fuel cell use. Refueling station compression currently have a high capital cost per unit throughput. The need for high-pressure (70 MPa), onboard storage in first generation light-duty fuel cell vehicles adds to the challenge. More reliable, lower-cost, and higher efficiency gas compression technologies are needed for pipelines, terminals, and fueling sites.

C. Reliability and Costs of Liquid Hydrogen Pumping

Cryogenic liquid pumps currently have lower capital cost per unit pumping capacity compared to gaseous compressors. However, the hydrogen entering the pump must be in the liquid state at all times. Any vaporization will cause cavitation that in turn can damage the pump. Boiloff associated with frequent cooling and heating of the pump requires the installation of recovery compression/ storage system which adds to the overall fueling cost. In addition, periodic recharging of the pump is required to purge any frozen or trapped gases, which results in expensive downtime for the pumping process. Technologies that overcome these challenges are needed to ensure a reliable liquid hydrogen transport option.

D. High As-Installed Cost of Pipelines

Existing hydrogen pipelines are very limited in extent and location and are not adequate to broadly distribute hydrogen. Labor, materials, and other associated costs result in a large capital investment for new pipelines. Land acquisition or Right of Way can also be very costly. Hydrogen embrittlement of steel is not completely understood, in particular the effects on low cycle fatigue. Current joining technology for steel pipes is a major part of the labor costs and impacts the steel microstructure in a manner that can exacerbate hydrogen embrittlement issues. The use of fiber reinforced polymer (FRP) composite pipelines recently introduced for natural gas for gathering at well heads has the potential to reduce capital cost and is being investigated. However additional effort is needed to understand the reliability, durability, and safety considerations (e.g. third party damage) of this alternative transport option. Also needed is the development of innovative materials and technologies, such as seals, components, sensors, and safety and control systems.

E. Gaseous Hydrogen Storage and Tube Trailer Delivery Costs

Gaseous hydrogen storage at various points of use (such as production facilities, fueling stations, and terminals) and for tube trailer transport and pipeline system surge capacity adds cost to the delivery infrastructure. Understanding and optimizing for these storage needs, while adjusting for daily and seasonal hydrogen demand cycles, will be important in minimizing cost. Technologies that satisfy these storage requirements at a lower capital cost per kg of hydrogen stored will also reduce overall delivery costs. Possible approaches to technology improvement include maximizing storage pressure per unit of dollar of capital cost, utilizing cold hydrogen gas, and/or utilizing a solid carrier material in the storage vessel. Advancements of this type for transport via tube trailer will likely require additional considerations to ensure DOT approval. In addition, there are specific materials issues associated with gaseous storage. Like pipelines, steel tanks can be impacted by hydrogen embrittlement exacerbated by material fatigue due to pressure cycling, as discussed in Barrier D. Research into new materials, coatings, and fiber or other composite structures is needed. Costs might also be reduced through the use of Design for Manufacture and Assembly (DFMA) and improved manufacturing technology for high volume production of identical storage units.

F. Geologic Storage

The feasibility of extensive geologic hydrogen storage needs to be addressed. There are currently only a few hydrogen geologic storage sites in the world. Identification of geologic structures with particularly promising permeability characteristics may be needed. Potential hydrogen contamination and environmental impacts need to be further investigated.

G. Low Cost, High Capacity Solid and Liquid Hydrogen Carrier Systems

Novel solid or liquid carriers that can release hydrogen without significant processing operations are possible options for hydrogen transport or for use in stationary bulk storage. Current solid and liquid hydrogen carrier technologies have high costs, insufficient energy density, and/or poor hydrogen release and regeneration characteristics. Substantial improvements in current technologies or new technologies are needed. Materials-based storage approaches are currently the focus of significant R&D activity supported through the Hydrogen Storage sub-program; refer to the Hydrogen Storage MYRD&D section.

H. High Cost and Low Energy Efficiency of Hydrogen Liquefaction

Cryogenic liquid hydrogen has a much higher energy density than gaseous hydrogen. As a result, in the absence of an extensive hydrogen pipeline infrastructure, transporting liquid hydrogen by cryogenic tank truck is significantly less costly than transporting compressed hydrogen by gaseous tube trailer. However, liquefaction is very energy intensive and inefficient (see Table 3.2.3, Liquid Hydrogen Delivery – Liquefaction) and the cost of this process step represents nearly half of the overall liquid hydrogen delivery cost. Improvements in liquefaction technology are needed to reduce the cost of this delivery pathway. Possibilities include increasing the scale of these operations and improving efficiencies of compressors and expanders; integrating these operations with hydrogen production, power production, or other operations that improve energy efficiency; and developing completely new liquefaction technologies such as magnetic or acoustic liquefaction or other approaches. In addition, hydrogen boil-off from cryogenic liquid storage tanks needs to be addressed and minimized for improved cost and energy efficiency.

I. Other Fueling Site/Terminal Operations

Other potential operations at refueling sites and terminals need to be low cost (capital and operating). Rugged, reliable dispensers are needed to transfer hydrogen in required form to the onboard fuel cell storage system. Hydrogen cooling may be required for cold stationary or onboard vehicle storage, for high-pressure vehicle fills (70 MPa, or 700 bar), or for thermal management during the charging of material-based onboard storage systems. Final purification may be required at refueling sites. Other systems may be needed for handling particular two-way carrier technologies being explored for onboard vehicle storage (refer to the Storage section of the Multi Year Research, Development, and Demonstration Plan).

J. Hydrogen Leakage and Sensors

The hydrogen molecule is light and diffuses more rapidly than other gases. This makes it more challenging to design equipment, seals, valves, and fittings to avoid hydrogen leakage. Current industrial hydrogen processes are monitored and maintained by trained, skilled operators. A delivery infrastructure designed specifically for hydrogen's use as a major energy carrier will need to rely heavily on sensors and robust designs and engineering. Low cost hydrogen leak detector sensors are needed. Suitable odorant technology for hydrogen leak detection may also be needed for hydrogen distribution pipelines. The odorant would need to be completely miscible with hydrogen gas and be easily removed or non-damaging to onboard storage systems and fuel cells. The development and use of mechanical integrity sensors that can be built into pipelines and vessels could provide additional protection against mechanical failures that might be caused by third-party damage or other potential mechanical failures. Additionally, purity sensors will be required to verify fuel quality prior to or during dispensing for fuel cell applications.

K. Safety, Codes and Standards, Permitting

Appropriate codes and standards are needed to ensure a reliable and safe hydrogen delivery infrastructure. Some of the hydrogen delivery elements such as tube trailers and cryogenic liquid hydrogen trucks are in commerce today, while others are not. Applicable codes and standards are needed for stationary storage at fueling sites and upstream in the hydrogen supply chain. Siting and permitting hurdles need to be overcome. The plan to address these issues is in the Safety, Codes and Standards section of the Multi-Year Research, Development and Demonstration Plan.

3.2.6 Technical Task Descriptions

The technical task descriptions are presented in Table 3.2.5. Concerns regarding safety and environmental effects will be addressed within each task in coordination with the appropriate sub-program.

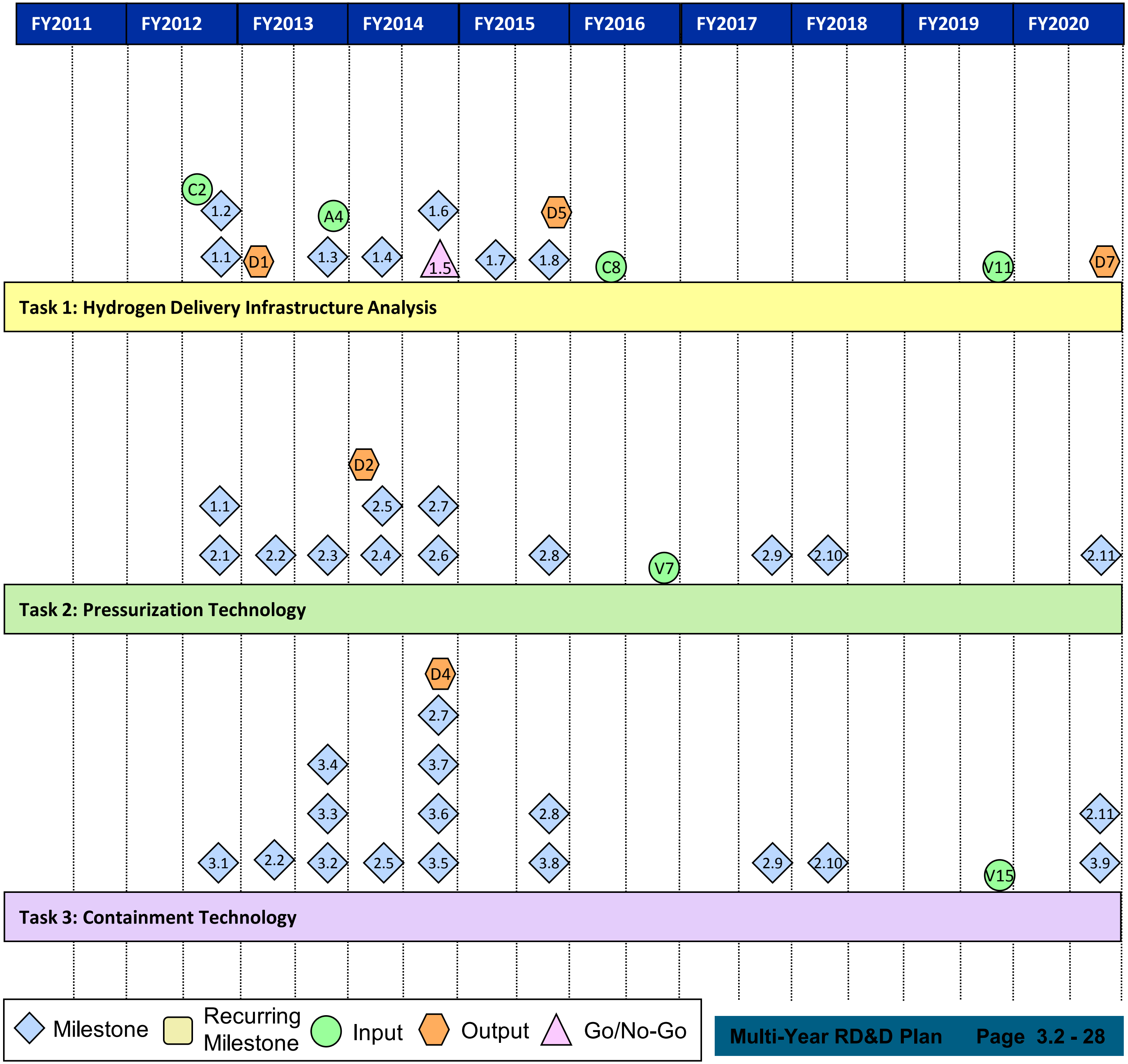
Table 3.2.5 Technical Task Descriptions		
Task	**Description**	**Barriers**
1	**Delivery Infrastructure Analysis** • Characterize the cost and energy efficiency of current and possible future delivery components and pathways and identify the key improvements needed. • Characterize the delivery costs for candidate liquid hydrogen carriers. • Examine the effects of centralized and distributed production output conditions and onboard storage needs (for various markets) on delivery pathway options and cost. • Perform optimization analyses to evaluate the trade-offs between various process operations that can minimize overall delivery cost for near-term markets. • Perform optimization analyses to evaluate the trade-offs between various process operations that can minimize overall delivery cost for mid-and long-term markets.	A, B, C, D, E, F, G, H, I, J
2	**Reliable, Energy-Efficient, and Lower Cost Pressurization Technology** • Research gas compression and liquid pumping technologies that can improve reliability, eliminate contamination, and reduce cost. • Develop reliable, low cost, energy-efficient gas compression technology for hydrogen pipeline transport service and terminal needs. • Develop reliable, low cost, energy-efficient gas compression technology for hydrogen fueling needs. • Develop reliable, low cost, energy-efficient cryogenic liquid pumping technology for transport and fueling needs	B, C, I, K
3	**Safe, Lower Cost Containment Technologies** • Research and develop technologies for steel pipeline materials that resolve potential embrittlement concerns. • Research and develop alternative materials for H_2 pipelines that could reduce installed cost, while providing safe and reliable operation. • Research and develop more cost effective gaseous H_2 bulk storage and tube trailer technology, including: higher pressure and/or cryogenic vessels, novel solid carriers, vessel materials and architecture, and the use of DFMA and high throughput production methods. • Develop improved and lower cost valves, fittings, and seals to reduce hydrogen leakage. • Develop mechanical integrity monitoring and leak detection technology. • Research the feasibility of geologic and pipeline storage as a low cost high volume storage option.	D, E, F, G, I, J, K

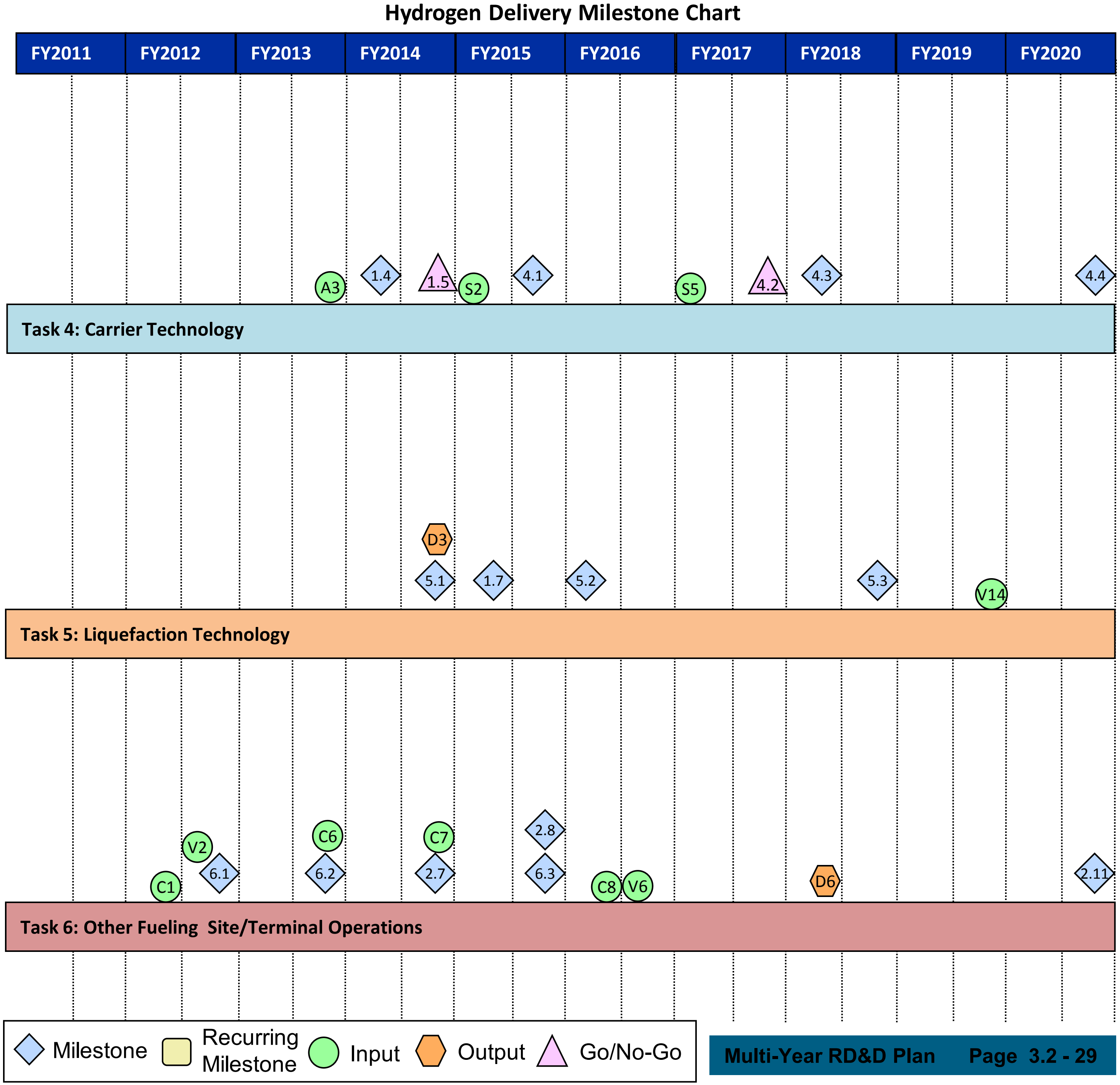
Table 3.2.5 Technical Task Descriptions (continued)		
Task	**Description**	**Barriers**
4	**Low Cost Carrier Technologies (In collaboration with the Hydrogen Onboard Storage Sub-Program)** • Develop novel liquid hydrogen carrier technologies for high volumetric energy density, low-cost hydrogen transport. • Develop novel solid carrier technology for hydrogen bulk stationary storage. • Develop technologies for transport/off-board regeneration of chemical hydrides.	B, C, E, G, I, J, K
5	**Lower Cost, Energy-Efficient Hydrogen Liquefaction Technology** • Investigate cost and energy efficiency gains for larger scale operations, achieving additional energy integration, and improving refrigeration schemes. • Explore new, potential breakthrough technologies, such as magneto-caloric liquefaction.	H
6	**Other Fueling Site/Terminal Operations** • Identify and define other potential operational needs for fueling sites and terminals that may include gas cooling, final purification, thermal management during vehicle refueling, robust dispensers, and systems for two-way onboard vehicle storage technologies. • Develop low cost, energy-efficient, and safe technology as appropriate for these operations.	E, I, J, K

3.2.7 Milestones

The following chart shows the interrelationship of milestones, tasks, supporting inputs from other sub-programs, and technology program outputs for the Hydrogen Delivery sub-program from FY 2011 through FY 2020. The inputs/outputs are also summarized in Appendix B.

Hydrogen Delivery Milestone Chart




Hydrogen Delivery Milestone Chart
FY2011
FY2012
FY2013
FY2014
FY2015
FY2016
FY2017
FY2018
FY2019
FY2020
A3
1.4
1.5
S2
4.1
S5
4.2
4.3
4.4
Task 4: Carrier Technology
D3
5.1
1.7
5.2
5.3
V14
Task 5: Liquefaction Technology
V2
C6
C7
2.8
C1
6.1
6.2
2.7
6.3
C8
V6
D6
2.11
Task 6: Other Fueling Site/Terminal Operations
Milestone
Recurring Milestone
Input
Output
Go/No-Go

Task 1: Delivery Infrastructure Analysis	
1.1	Complete deep dive analysis of compression technology. (4Q, 2012)
1.2	Coordinating with the H_2 Production and Storage sub-programs, identify optimized delivery pathways that meet an as-dispensed H_2 cost of <$4/gge (~$1.00/100 ft^3) for the emerging fuel cell powered MHE market. (4Q, 2012)
1.3	Coordinating with the H_2 Production and Storage sub-programs, identify optimized delivery pathways that meet an as-dispensed H_2 cost of <$4/gge for emerging regional consumer and fleet vehicle markets. (4Q, 2013)
1.4	Complete deep dive analysis of potential hydrogen carrier technology. (2Q, 2014)
1.5	Go/No-Go on the use of liquid hydrogen carriers as an effective means of hydrogen delivery. (4Q, 2014)
1.6	Evaluate the projected costs for the transport/off-board regeneration of chemical hydrides. (4Q, 2014)
1.7	Complete deep dive analysis of potential liquefaction technology. (2Q, 2015)
1.8	Coordinating with the H_2 Production and Storage sub-programs, identify optimized delivery pathways that meet an as-dispensed H_2 cost of <$2/gge for use in consumer vehicles. (4Q, 2015)

Task 2: Pressurization Technology	
2.1	Complete performance and cost evaluation of ionic liquid gas compression. (4Q, 2012)
2.2	Down select two to three H_2 pressurization and/or containment technologies that minimize delivery pathway cost for near-term markets. (2Q, 2013)
2.3	Complete performance and cost evaluation of centrifugal gas compression of H_2. (4Q, 2013)
2.4	Complete performance and cost evaluation of electrochemical gas compression. (2Q, 2014)
2.5	Down select two to three H_2 pressurization and/or containment technologies that minimize delivery pathway cost for mid-term markets. (2Q, 2014)
2.6	Complete performance and cost evaluation of liquid H_2 reciprocating pump. (4Q, 2014)
2.7	By 2014, reduce the cost of hydrogen delivery from the point of production to the point of use for fuel cell powered MHE to <$0.75/100 standard ft^3 (~$3/gge). (4Q, 2014)
2.8	By 2015, reduce the cost of hydrogen delivery from the point of production to the point of use for emerging regional consumer and fleet vehicle markets to <$4/gge. (4Q, 2015)
2.9	Down select two to three H_2 pressurization and/or containment technologies that minimize delivery pathway cost for long-term markets. (4Q, 2017)
2.10	Verify 2020 targeted cost and performance for H_2 pressurization and/or containment technologies that minimize delivery pathway cost for long-term markets. (2Q, 2018)

Task 2: Pressurization Technology (continued)	
2.11	By 2020, reduce the cost of hydrogen delivery from the point of production to the point of use in consumer vehicles to <\$2/gge. (4Q, 2020)
1.1	Complete deep dive analysis of compression technology. (4Q, 2012)

Task 3: Containment Technology	
3.1	Complete performance and cost evaluation of glass fiber reinforced tube trailer technology. (4Q, 2012)
3.2	Complete characterization of the combined effects of fatigue and embrittlement on pipeline steel performance. (4Q, 2013)
3.3	Complete performance and cost evaluation of carbon fiber reinforced tube trailer technology. (4Q, 2013)
3.4	Complete performance and cost evaluation of stationary reinforced concrete vessel technology. (4Q, 2013)
3.5	Verify 2015 targeted cost and performance for hydrogen pipelines. (4Q, 2014)
3.6	Complete the research to establish the feasibility and define the cost for geologic hydrogen storage. (4Q, 2014)
3.7	Develop a technology for system mechanical integrity monitoring and leak detection of FRP pipeline. (4Q, 2014)
3.8	Complete evaluation of FRP pipe for H_2 pipeline and storage applications. (4Q, 2015)
3.9	Verify the feasibility of achieving the 2020 geologic storage cost and performance targets. (4Q, 2020)
2.2	Down select two to three H_2 pressurization and/or containment technologies that minimize delivery pathway cost for near-term markets. (2Q, 2013)
2.5	Down select two to three H_2 pressurization and/or containment technologies that minimize delivery pathway cost for mid-term markets. (2Q, 2014)
2.7	By 2014, reduce the cost of hydrogen delivery from the point of production to the point of use for fuel cell powered MHE to <\$0.75/100 standard ft^3 (~\$3/gge). (4Q, 2014)
2.8	By 2015, reduce the cost of hydrogen delivery from the point of production to the point of use for emerging regional consumer and fleet vehicle markets to <\$4/gge. (4Q, 2015)
2.9	Down select two to three H_2 pressurization and/or containment technologies that minimize delivery pathway cost for long-term markets. (4Q, 2017)
2.10	Verify 2020 targeted cost and performance for H_2 pressurization and/or containment technologies that minimize delivery pathway cost for long-term markets. (2Q, 2018)
2.11	By 2020, reduce the cost of hydrogen delivery from the point of production to the point of use in consumer vehicles to <\$2/gge. (4Q, 2020)

Task 4: Carrier Technology	
4.1	Initial down select of potential carrier systems for hydrogen delivery and bulk storage based on Go/No-Go decision. (3Q, 2015)
4.2	Go/No-Go on the economic viability of liquid hydrogen carriers for minimizing hydrogen delivery cost. (4Q, 2017)
4.3	Down select on hydrogen delivery carrier system technologies to achieve the 2020 cost and performance targets. (2Q, 2018)
4.4	Verify 2020 targeted cost and performance for H_2 carrier technologies that minimize delivery pathway cost for long-term markets. (4Q, 2020)
1.4	Complete deep dive analysis of potential liquid carrier technology. (2Q, 2014)
1.5	Go/No-Go on the use of liquid hydrogen carriers as an effective means of hydrogen delivery. (4Q, 2014)

Task 5: Liquefaction Technology	
5.1	Complete performance and cost evaluation of magneto caloric liquefaction technology. (4Q, 2014)
5.2	Down select one to two alternative improvements to liquefaction technologies. (1Q, 2016)
5.3	Verify 2020 targeted cost and performance for hydrogen liquefaction. (4Q, 2018)
1.7	Complete deep dive analysis of potential liquefaction technology. (2Q, 2015)

Task 6: Other Fueling Site/Terminal Operations	
6.1	Define potential R&D activities for other near-term market fueling/terminal needs. (4Q, 2012)
6.2	Define potential R&D activities for other mid-term market fueling/terminal needs. (4Q, 2013)
6.3	Define potential R&D activities for other long-term market fueling/terminal needs. (4Q, 2015)
2.7	By 2014, reduce the cost of hydrogen delivery from the point of production to the point of use for fuel cell powered MHE to <$0.75/100 ft^3 (~$3/gge). (4Q, 2014)
2.8	By 2015, reduce the cost of hydrogen delivery from the point of production to the point of use for emerging regional consumer and fleet vehicle markets to <$4/gge. (4Q, 2015)
2.11	By 2020, reduce the cost of hydrogen delivery from the point of production to the point of use in consumer vehicles to <$2/gge of hydrogen. (4Q, 2020)

Outputs

D1 Output to Technology Validation, Market Transformation, and Systems Analysis: 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 Output to Technology Validation: Provide candidate station compression technologies for potential technology validation. (1Q, 2014)

D3 Output to Technology Validation: Provide candidate liquefaction technologies for potential validation. (4Q, 2014)

D4 Output to Technology Validation: Recommended pipeline technology for validation. (4Q, 2014)

D5 Output to Technology Validation, Market Transformation, and Systems Integration: 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)

D6 Output to Safety, Codes and Standards: Technology and material characteristics of advanced delivery systems. (2Q, 2018)

D7 Output to Technology Validation, Market Transformation, and Systems Integration: Provide options that meet <$2/gge for hydrogen delivery from the point of production to the point of use in consumer vehicles. (4Q, 2020)

Inputs

A3 Input from Systems Analysis: Preliminary well-to-wheel power plant efficiency analysis for advanced material systems. (4Q, 2013)

A4 Input from Systems Analysis: Analysis for costs for optimal hydrogen pressure contributions at each point in the system from production to dispensing at point of use. (4Q, 2013)

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)

S2 Input from Storage: Technical and economic update from storage on promising storage material system. (1Q, 2015)

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

V2 Input from Technology Validation: 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)

V6 Input from Technology Validation: Validate 700-bar fast fill fueling stations against DOE fueling targets. (3Q, 2016)

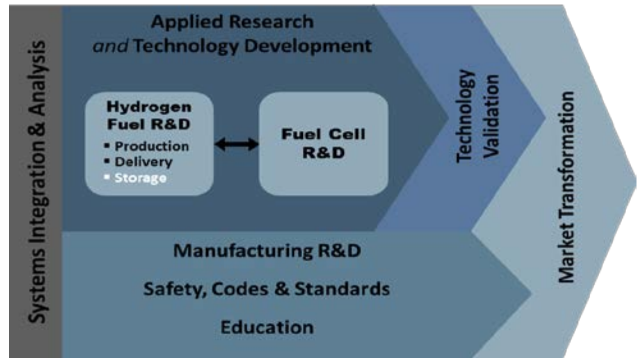
V7 Input from Technology Validation: Validate novel hydrogen compression technology durability and efficiency. (4Q, 2016)

V11 Input from Technology Validation: Validate station compression technology provided by the delivery team. (4Q, 2019)

V14 Input from Technology Validation: Validate liquefaction technology provided by the delivery team. (4Q, 2019)

V15 Input from Technology Validation: Validate pipeline technology provided by the delivery team. (4Q, 2019)

3.3 Hydrogen Storage



Hydrogen storage is a key enabling technology for the advancement of hydrogen and fuel cell technologies that can provide energy for an array of applications, including stationary power, portable power, and transportation. Also, hydrogen can be used as a medium to store energy created by intermittent renewable power sources (e.g., wind and solar) during periods of high availability and low demand, increasing the utilization and benefits of the large capital investments in these installations. The stored hydrogen can be used during peak hours, as system backup, or for portable, transportation, or industrial applications. The U.S. Department of Energy's (DOE's) efforts through 2011 have primarily been focused on the Research, Development and Demonstration (RD&D) of onboard vehicular hydrogen storage systems that will allow for a driving range of 300 miles or more, while meeting packaging, cost, safety, and performance requirements to be competitive with conventional vehicles. As of 2011, there were over 180 fuel cell light-duty vehicles and over 20 fuel cell buses utilizing compressed hydrogen storage. In the DOE's Technology Validation sub-program National Fuel Cell Electric Vehicle (FCEV) Learning Demonstration project,[1] automakers have validated vehicles with more than a 250-mile driving range. Additionally, at least one vehicle has been demonstrated capable of 430 miles on a single fill of hydrogen[2]; however the driving range must be achievable across the range of light-duty vehicle platforms and without compromising space, performance or cost.

There is a host of early or near-term power applications in which fuel cell technologies are expected to achieve wide-scale commercialization prior to light-duty vehicles. The early market applications can generally be categorized into three market segments:

- stationary power such as back-up power for telecommunications towers, emergency services, and basic infrastructure (e.g., water and sewage pumps).
- portable power such as personal laptop battery rechargers, portable generator sets (gen-sets), or mobile lighting.
- material handling equipment such as forklift trucks, pallet jacks, and airport baggage and pushback tractors.

Currently, these applications are suggested to be the largest markets for fuel cells until fuel cell vehicles are commercialized.[3] Thus, DOE is initiating efforts to establish performance requirements and targets as well as RD&D efforts to address hydrogen storage technology gaps for these

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[1] Wipke, K.; Sprik, S.; Kurtz, J.; Ramsden, T.; Ainscough, C.; Saur, G. "National Fuel Cell Electric Vehicle Learning Demonstration Final Report," National Renewable Energy Laboratory, July 2012, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/learning_demo_final_report.pdf

[2] Wipke, K.; Anton, D.; Sprik, S. "Evaluation of Range Estimates for Toyota FCHV-adv Under Open Road Driving Conditions," National Renewable Energy Laboratory and Savannah River National Laboratory, August 2009, http://www.nrel.gov/hydrogen/pdfs/toyota_fchv-adv_range_verification.pdf

[3] 2011 Fuel Cell Technologies Market Report, July 2012, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/2011_market_report.pdf

applications. Also of interest is to analyze and define the economic feasibility of hydrogen as an energy storage medium to expand the use of renewable energy generation.

3.3.1 Technical Goal and Objectives

Goal:

Develop and demonstrate viable hydrogen storage technologies for transportation, stationary, portable power, and specialty vehicle applications (e.g., material handling equipment (MHE), airport ground support equipment (GSE), etc.).

Objectives:

- By 2015, develop and verify a single-use hydrogen storage system for portable power applications achieving 0.7 kWh/kg system (2.0 wt.% hydrogen) and 1.0 kWh/L system (0.030 kg hydrogen/L) at a cost of \$0.09/Wh_{net} (\$3/g $H_{2\ stored}$).
- By 2020, develop and verify onboard automotive hydrogen storage systems achieving 1.8 kWh/kg system (5.5 wt.% hydrogen) and 1.3 kWh/L system (0.040 kg hydrogen/L) at a cost of \$10/kWh (\$333/kg $H_{2\ stored}$).
- By 2020, develop novel precursors and conversion processes capable of reducing the high-volume cost of high-strength carbon fiber by 25% from \$13 per pound to ~\$9 per pound.
- By 2020, develop and verify a rechargeable hydrogen storage system for portable power applications achieving 1.0 kWh/kg system (3.0 wt.% hydrogen) and 1.3 kWh/L system (0.040 kg hydrogen/L) at a cost of \$0.4/Wh_{net} (\$13/g $H_{2\ stored}$).
- By 2020, develop and verify a hydrogen storage system for MHE applications achieving 1.7 kWh/L system (0.050 kg hydrogen/L) at a cost of \$15/kWh_{net} (\$500/kg $H_{2\ stored}$).
- Enable an ultimate full-fleet[4] target of 2.5 kWh/kg system (7.5 wt.% hydrogen) and 2.3 kWh/L system (0.070 kg hydrogen /L) at a cost of \$8/kWh (\$266/kg $H_{2\ stored}$) for onboard automotive hydrogen storage.

3.3.2 Technical Approach

Hydrogen storage research and development (R&D) focuses on advancing technologies to lower the cost and increase the efficiency of both physical storage (e.g., compressed hydrogen) and materials-based storage (e.g., sorbents, metal hydrides) technologies that can enable widespread commercialization of fuel cell systems for diverse applications across stationary, portable, and transportation sectors. Each application – light-duty vehicles, material handling equipment, gen-sets for back-up power, and portable power for consumer electronics – has specific market-driven requirements for technology development.

[4] Full-fleet is defined as virtually all light-duty vehicle platforms (e.g., makes and models)

Hydrogen storage technology development for near-term, early market fuel cell applications is focused on developing technologies that can provide an adequate amount of hydrogen to enable efficient operation of the fuel cell to meet customer-driven performance metrics in a safe, convenient, and cost-effective package. Targeted metrics are closely related to the operating requirements of the application, such as capacity (i.e., run-time), refill and discharge kinetics, durability, and operability. However, for hydrogen fuel cells to be competitive with more established incumbent technologies, such as batteries and diesel gen-sets, costs must be reduced for all system components, including hydrogen storage.

Onboard hydrogen storage to enable a driving range of greater than 300 miles across all light-duty vehicle platforms is a long-term focus of the Hydrogen Storage sub-program. This driving range must be accomplished while meeting the vehicular packaging, cost, and performance requirements necessary to achieve significant market penetration of hydrogen fueled vehicles. R&D activities for vehicle refueling technologies, including the vehicle/forecourt interface, and off-board hydrogen storage will be coordinated with the Hydrogen Delivery sub-program. Hydrogen delivery entails delivering hydrogen from the point of production to the dispenser connection interface onboard the vehicle, including hydrogen storage at the fueling station (see Hydrogen Delivery Multi-Year Research, Development and Demonstration (MYRD&D) plan section for a complete description of off-board storage).

Physical hydrogen storage (e.g., high-pressure compressed gas cylinders and cryogenic liquid tanks) has thus far been the main hydrogen storage technology used in prototype hydrogen-powered vehicles and is currently the most mature technology for use onboard vehicles. In order to enable widespread use in commercial vehicle platforms, current physical storage efforts focus on reducing the cost of the carbon fiber composite portion of the pressure vessel, which dominates the cost of the compressed gas systems (see Figure 3.3.1). While compressed hydrogen storage is typically at ambient temperatures, cold (i.e., sub-ambient but greater than 150 K) and cryogenic (150 K and below) compressed hydrogen storage is also being investigated due to the higher hydrogen densities achievable. Furthermore, cost-effective pressure vessels and cryogenic tank designs may be required for material-based storage approaches to meet performance requirements. Hence, efforts in advancing physical storage RD&D may also include novel concepts that would benefit material-based hydrogen storage technologies.

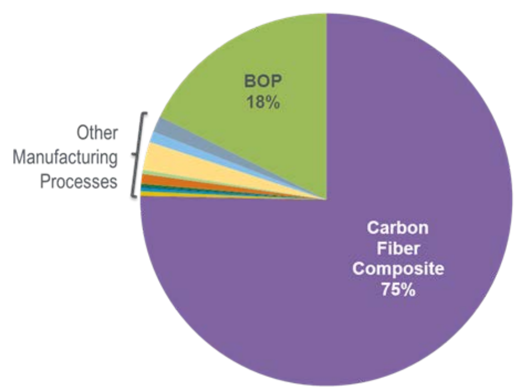


Figure 3.3.1 Systems Analysis sub-program cost analysis of a 700 bar Type IV hydrogen storage system shows >75% of cost is in the filament wound carbon fiber composite layer.

Material-based R&D approaches currently being pursued include reversible metal hydrides, hydrogen sorbents, and regenerable chemical hydrogen storage materials. In addition, for regenerable hydrogen storage materials, it is critical that there are cost effective and energy efficient spent fuel regeneration technologies available to complete the fuel cycle. Therefore, the Hydrogen

Storage sub-program will continue to investigate and develop viable spent fuel regeneration technologies for promising regenerable chemical hydrogen storage materials.

The applied materials-based hydrogen storage technology RD&D is focused on developing materials and systems that have the potential to meet the 2015 early market and 2020 light-duty vehicle system targets with the overarching goal of meeting the 2020 early market and ultimate full fleet light-duty vehicle system targets. Specifically:

- Metal hydride materials research focuses on improving the volumetric and gravimetric capacities, hydrogen adsorption/desorption kinetics, and reaction thermodynamics of potential material candidates. Long-term cycling effects will also be investigated.
- Sorbent materials research focuses on increasing the dihydrogen binding energies, optimizing the material's pore size, increasing pore volume and surface area, and investigating effects of material densification.
- Chemical hydrogen storage materials research focuses on improving volumetric and gravimetric capacity, transient performance, other system performance requirements, and the efficient regeneration of the spent storage material.

Additionally, the Hydrogen Storage sub-program's RD&D portfolio includes engineering RD&D to address the engineering challenges posed by various storage technologies. These efforts include comprehensive system modeling and engineering analyses and assessments of material-based storage system technologies for detailed comparisons against the DOE performance targets for light-duty vehicles. Engineering system component RD&D, including bench-scale testing and evaluation, and conceptual design validation, is conducted to address deficiencies and enable progress towards meeting the storage system level targets.

As technologies with potential for onboard storage are down-selected, future activities on vehicle refueling requirements and technology needs will be coordinated with the Delivery sub-program. Vehicle refueling connection devices will need to be compatible with high-pressure and cryogenic storage in the near-term. In the long-term, as progress is made on material-based technologies, vehicle refueling issues such as thermal management or by-product reclamation will need to be addressed.

Beyond vehicle and early market applications, the Hydrogen Storage sub-program will begin addressing the potential of hydrogen storage in grid energy storage applications. For hydrogen use in grid energy storage applications, electrical energy that is generated in excess of the immediate demand can be used to generate hydrogen through use of an electrolyzer or reversible fuel cell. The hydrogen produced by the excess electrical energy is then stored for later consumption – conversion back to electricity when electricity demand exceeds generation capacity or in other applications such as an automotive transportation fuel. Grid energy storage is expected to facilitate the penetration of renewable energy sources, especially intermittent types such as wind and solar, and improve the flexibility, reliability, and efficiency of the grid. Cost, overall efficiency, and durability are all key barriers associated with implementing hydrogen into grid energy storage applications. Further, RD&D and analyses are required to identify the specific grid energy storage applications where hydrogen is a practical option and to determine additional engineering and technology developments required to meet key performance criteria. RD&D activities will be conducted in coordination and collaboration with the DOE Office of Electricity Delivery and Energy Reliability.

Interactions with the DOE Office of Science are ongoing to define and coordinate the basic research activities for hydrogen storage materials. The Hydrogen Storage sub-program will also conduct analyses to examine the system level performance, lifecycle cost, energy efficiency, environmental impact of the technologies, any changes in the system-level requirements that might alter the technical targets, and the progress of each technology development effort toward achieving the technical targets.

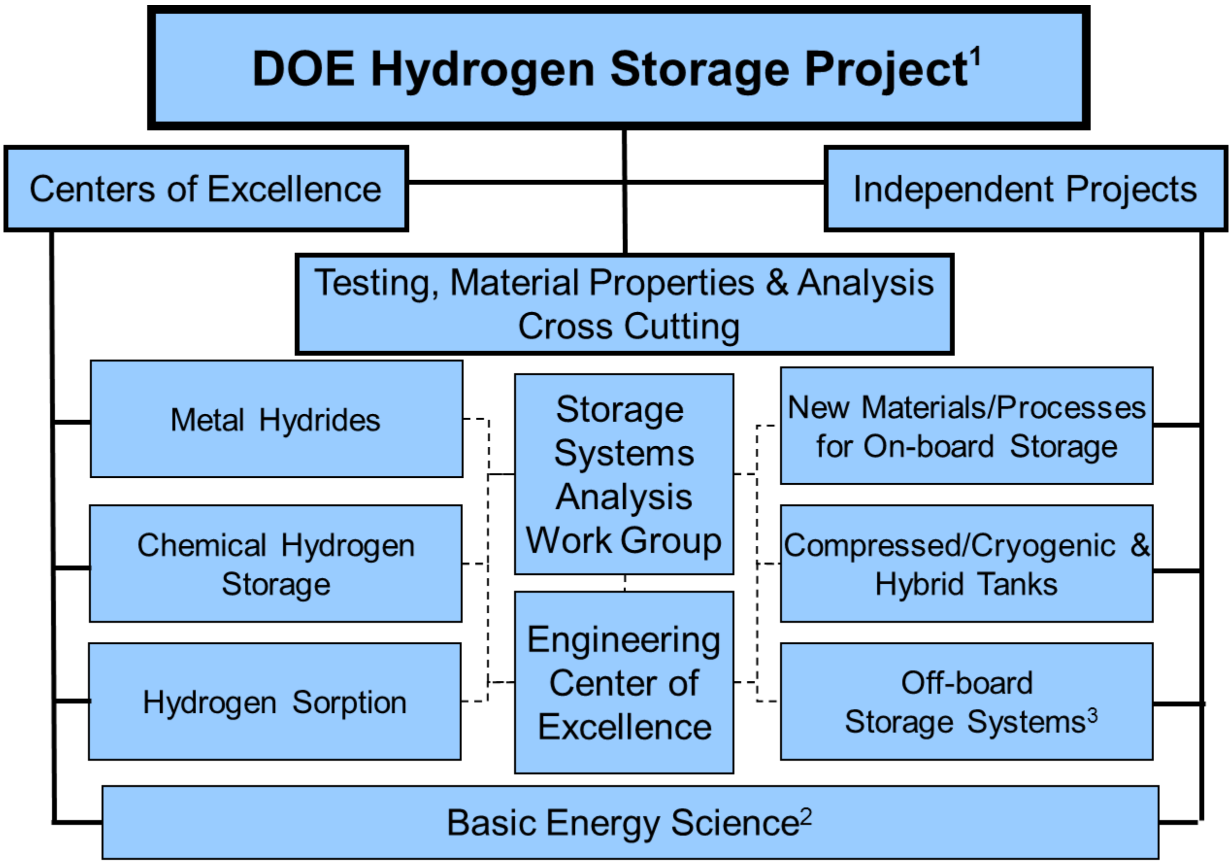
3.3.3 Programmatic Status

Hydrogen storage RD&D efforts were previously conducted under the framework of the National Hydrogen Storage Project. The National Hydrogen Storage Project included independent projects and Centers of Excellence (CoEs) in applied hydrogen storage RD&D funded by the DOE Office of Energy Efficiency and Renewable Energy and basic research projects for hydrogen storage funded by the DOE Office of Science.

During that time, the Hydrogen Storage sub-program established three competitively selected CoEs that operated from 2005 to 2010 for a concerted effort to discover and develop low-pressure hydrogen storage materials. The three CoEs focused on the development of: 1) high-capacity metal hydrides including borohydrides, destabilized metal hydrides, and lightweight multinary alloys; 2) chemical hydrogen storage materials including liquid chemical hydrogen carriers and boron-based materials; and 3) sorbents including novel metal-carbon hybrids, metal-organic framework materials, polymers, and other nanostructured, high surface area materials. The three CoEs made significant progress in discovering and developing new and innovative hydrogen storage materials as well as progress towards meeting the onboard vehicular hydrogen storage targets. However, while this effort led to the discovery of many new types of hydrogen storage materials, no current material can meet all of the onboard targets simultaneously. Therefore, the Hydrogen Storage sub-program will continue to add new material development R&D projects to its portfolio. Final reports from each of the three CoEs are available through the Fuel Cell Technologies website at: http://www1.eere.energy.gov/hydrogenandfuelcells/hydrogen_publications.html#h2_storage.

Current Activities

To address the critical challenge of hydrogen storage for stationary, portable, and transportation applications, as well as energy storage for variable renewables, the Hydrogen Storage sub-program continues with its overarching strategy to conduct RD&D through a comprehensive portfolio of competitively awarded projects that include applied, target-oriented research of advanced concepts, innovative chemistries, and novel materials, as well as engineering RD&D with the potential to meet onboard vehicular, material handling equipment, and/or portable power hydrogen storage targets. The organization of the Hydrogen Storage project portfolio is shown in Figure 3.3.2. The Hydrogen Storage portfolio consists of independent and collaborative efforts led by universities, companies, and Federal and National laboratories. Within the portfolio, activities exist that address both physical and materials-based technologies as well as cross-cutting activities of testing and analysis. The sub-program rigorously assesses emerging technologies based on performance, cost, life-cycle energy efficiencies, and environmental impact through storage systems analysis and engineering activities.



1. Coordinated by DOE Energy Efficiency and Renewable Energy, Fuel Cells Technologies Program
2. Basic science for hydrogen storage conducted through DOE Office of Science, Basic Energy Sciences
3. Coordinated with Delivery Program element

Figure 3.3.2 Structure of the DOE Hydrogen Storage activities

Table 3.3.1 summarizes the FY 2012 activities in the Hydrogen Storage sub-program.

Table 3.3.1 FY 2012 Hydrogen Storage Program Activities

Challenge	Approach	FY 2012 Activities
Materials Storage	<u>**Materials Discovery**</u> • Develop reversible metal hydrides with improved kinetics while maintaining high gravimetric capacity at relevant release temperatures and pressures • Develop sorbent materials with increased binding energy and volumetric capacity • Develop off-board regenerable materials with improved well-to-powerplant efficiency at relevant temperatures and pressures <u>**Engineering**</u> • Develop and validate complete integrated storage system models and designs with appropriate operating parameters necessary to meet fuel cell power plant requirements at acceptable costs	<u>**Metal Hydrides**</u> • **National Institute of Standards and Technology:** Neutron characterization and thermodynamic modeling of hydrogen storage material • **Northwestern University:** Computational and experimental approach to investigate mixtures of chemical hydrogen storage materials and complex hydrides • **Ohio State University:** Development of high-capacity lightweight metal hydrides • **University of Hawaii:** Development of Advanced, High-Capacity, Reversible Metal Hydrides <u>**Sorbents**</u> • **HRL Laboratories:** Development of nano-confined liquids for room temperature hydrogen storage • **Lawrence Berkeley National Laboratory:** Theory guided development of metal-organic framework (MOF) materials with engineered pore spacing and structure optimized for room temperature hydrogen binding • **Northwestern University:** Development of new carbon-based porous materials, such as MOF and polymeric-organic framework materials, with increased heats of adsorption • **National Renewable Energy Laboratory (NREL):** Validation of the weak-chemisorption (hydrogen spillover) mechanism for room temperature storage • **Penn State University:** Synthesis of designer MOF materials mixed with catalysts to enable hydrogen spillover for room temperature storage • **Texas A&M University:** A biomimetic approach to design of new adsorptive MOF materials • **University of Missouri:** Development of multiple surface-functionalized nanoporous carbon derived from corncobs • **University of California, Los Angeles**: Joint theory and experimental project in the high-throughput synthesis of porous covalent-organic framework and zeolitic imidazolate framework materials

Table 3.3.1 FY 2012 Hydrogen Storage Program Activities (continued)		
Challenge	**Approach**	**FY 2012 Activities**
Materials Storage		**Chemical Hydrides** • **Brookhaven National Laboratory:** Synthesis and regeneration of aluminum hydride (alane) for hydrogen storage • **Hawaii Hydrogen Carriers LLC:** Development of a practical hydrogen storage system based on liquid organic hydrogen carriers and a homogeneous catalyst • **Los Alamos National Laboratory (LANL):** Development of fluid phase chemical hydrides (ammonia-borane) • **Savannah River National Laboratory (SRNL):** Development of electrochemical reversible formation of alane • **University of Oregon:** Hydrogen storage by novel carbon, boron, and nitrogen containing heterocyclic materials **Engineering** • **Hydrogen Storage Engineering Center of Excellence – partners include SRNL (lead), Ford Motor Company, General Motors, Jet Propulsion Laboratory, LANL, Lincoln Composites, NREL, Oregon State University, Pacific Northwest National Laboratory (PNNL), and United Technologies Research Center:** Development of complete, integrated hydrogen storage systems that can simultaneously meet or exceed all the DOE targets through the use of system models, advanced engineering concepts, and storage system designs that utilize condensed phase materials as the primary hydrogen storage media (i.e., reversible metal hydrides, sorbents, and chemical hydrogen storage materials)
Physical Storage	**Ambient** • Develop low-cost, high-pressure hydrogen systems while maintaining/improving performance at reduced cost **Cryo-compressed** • Develop and validate operation of pressure-capable cryogenic vessels with improved dormancy and long cycle-life at reduced cost	• **Lawrence Livermore National Laboratory:** Research into extended dormancy, vacuum stability, and para-ortho hydrogen conversion in cryogenic pressure vessels • **Oak Ridge National Laboratory (ORNL):** Development of melt-processable PAN fibers as carbon fiber precursors • **ORNL:** Lifecycle verification of polymeric storage liners for Type IV pressure vessels • **ORNL:** Development of low-cost commercial textile-grade precursors for high strength carbon fiber • **PNNL:** Reduction of high pressure hydrogen storage systems cost through research into advances in carbon fiber and composites, advanced fiber placement, and the use of “cold” hydrogen refueling

Table 3.3.1 FY 2012 Hydrogen Storage Program Activities (continued)		
Challenge	**Approach**	**FY 2012 Activities**
Analysis	• Determine and compare cost and performance metrics of the various hydrogen storage systems under development, both materials-based and physical storage technologies, to guide research towards achieving the performance metrics and identify gaps where further development efforts are required	• **Argonne National Lab:** Systems level analysis of hydrogen storage technologies • **NREL:** Development of a reference document detailing best practices for characterizing hydrogen storage material properties • **NREL:** Sorption capacity measurements on materials-of-interest to determine and provide third-party validation of performance • **Strategic Analysis, Inc.:** Cost analyses of hydrogen storage systems suitable for automotive and near-term applications

3.3.4 Technical Challenges

Cost, packaging and durability are the major challenges facing hydrogen storage systems prior to widespread commercialization of hydrogen fuel cell systems. Automotive system-based hydrogen storage capacities have continuously improved since 2005 as shown in Figure 3.3.3 (a-b); further advancements are needed to meet all automotive performance targets simultaneously. When considering hydrogen storage options, each application must be regarded individually as each has its own distinct set of challenges and performance criteria. For example, one of the most challenging applications, automotive, has very rigorous performance requirements with respect to weight, volume, start-up, rate of refill, transient operation, cost and a number of other performance criteria. In comparison, for material handling equipment applications, such as forklifts, the greatest challenges include system cost and durability; whereas, for man-portable power applications, such as rechargeable battery extenders, the greatest factors to compete with batteries include packaging (i.e., gravimetric and volumetric capacities), cost, and ease of use. Traditional hydrogen storage technologies cannot meet the technical challenges and performance criteria required for all applications.

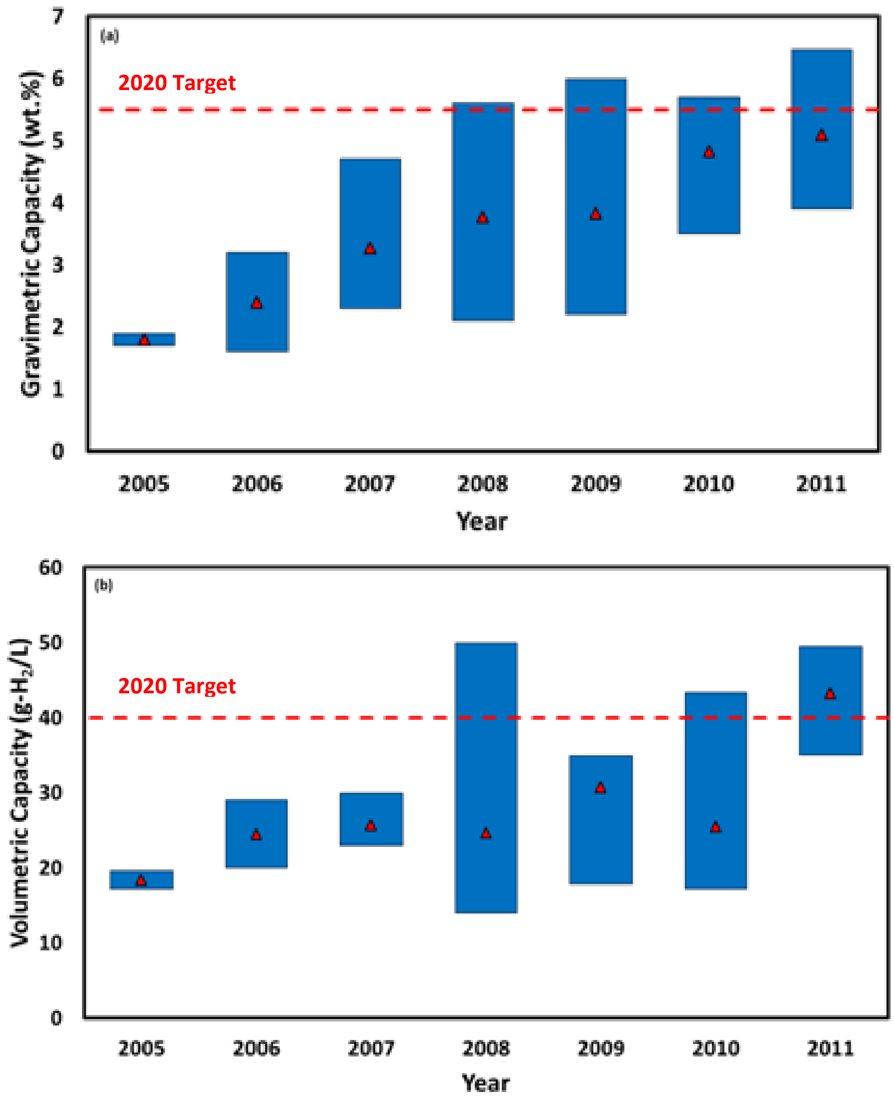


Figure. 3.3.3 (a-b) Estimates of (a) gravimetric and (b) volumetric capacities projected for onboard storage systems that can supply 5.6 kg of usable hydrogen as compared to DOE targets (based upon engineering analyses). Note that the plotted data points are the average value for all systems analyzed during each year while the bars correspond to the range of maximum and minimum values obtained in each year. Also note that systems with predicted capacities exceeding the gravimetric and volumetric targets do not necessarily meet other targets.

Automotive

The overarching technical challenge for hydrogen storage in automotive applications is the ability to store the necessary amount of hydrogen required for a conventional driving range (greater than 300 miles), within the constraints of weight, volume, durability, efficiency, and total cost. The current dominant hydrogen storage technologies for automotive use are 350 and 700 bar (5,000- and 10,000-

psi, respectively) compressed hydrogen systems. Vehicles have been demonstrated that are able to achieve 250 miles driving range (U.S. Environmental Protection Agency adjusted combined drive cycle) with 700-bar compressed hydrogen systems.[5] The hydrogen storage capacities for 350 and 700 bar compressed hydrogen systems ranged from about 2.8 to 4.4 wt.% hydrogen[6] and 0.017 to 0.025 kg hydrogen/L system.[7] Table 3.3.2 includes the current projected status for physical and materials-based hydrogen storage systems. Many important technical challenges for hydrogen storage must be resolved to meet the ultimate performance and safety targets. Substantial improvements must be made in the weight, volume, and cost of these systems for automotive applications. Additionally, durability over the performance lifetime of these systems must be validated, and acceptable refueling times must be achieved.

Table 3.3.2 Projected Performance of Hydrogen Storage Systems [a]

Hydrogen Storage System	Gravimetric (kWh/kg sys)	Volumetric (kWh/L sys)	Cost ($/kWh; projected to 500,000 units/yr)	Year Published
700 bar compressed (Type IV) [b]	1.7	0.9	19	2010
350 bar compressed (Type IV) [b]	1.8	0.6	16	2010
Cryo-compressed (276 bar) [b]	1.9	1.4	12	2009
Metal Hydride ($NaAlH_4$) [c]	0.4	0.4	TBD	2012
Sorbent (AX-21 carbon, 200 bar) [c]	1.3	0.8	TBD	2012
Chemical Hydrogen Storage (AB-liquid) [c]	1.3	1.1	TBD	2012

[a] Assumes a storage capacity of 5.6 kg of usable H_2
[b] Based on Argonne National Laboratory performance and TIAX cost projections[8]
[c] Based on Hydrogen Storage Engineering Center of Excellence performance projections[9]

Early Markets

Successful commercialization of hydrogen fuel cell products in early market applications is expected to help increase public awareness and acceptance of hydrogen fuel cell technologies, generate data on the performance of the technologies in real-world use and help build the supply base, all of which can benefit commercialization of hydrogen fuel cell technologies in automotive applications. For early market applications, the major technical challenge for hydrogen storage is the ability to

[5] DOE's Technology Validation sub-program Fuel Cell Electric Vehicle (FCEV) Learning Demonstration Project Composite Data Product: http://www.nrel.gov/hydrogen/docs/cdp/cdp_2.jpg
[6] Hydrogen Storage Weight % Hydrogen Composite Data Product: http://www.nrel.gov/hydrogen/docs/cdp/cdp_10.ppt
[7] Hydrogen Storage Volumetric Capacity Composite Data Product: http://www.nrel.gov/hydrogen/docs/cdp/cdp_11.ppt
[8] Bowman, Jr., R.C.; Stetson, N.T. "Onboard hydrogen storage systems: projected performance and cost parameters." DOE Hydrogen and Fuel Cells Program Record; 2010, July 02, Available online: http://hydrogen.energy.gov/pdfs/9017_storage_performance.pdf.
[9] Anton, D.L.; Motyka, T.; Hardy, B.; Tamburello, D. "Hydrogen Storage Engineering Center of Excellence (HSECoE)." DOE Fuel Cell Technologies Program Annual Progress Report. Available: http://www.hydrogen.energy.gov/pdfs/progress12/iv_d_1_anton_2012.pdf.

provide an adequate amount of hydrogen to enable operation of the fuel cell to meet customer-driven performance metrics. Hydrogen storage materials have the potential to meet many of the performance demands of the identified applications, specifically portable power and material handling equipment; thus, the primary focus of the Hydrogen Storage sub-program will be the development and demonstration of engineered systems that meet the application specific performance metrics and to lower manufacturing costs. Material optimization and development efforts, such as improvements in gravimetric and volumetric capacities of materials, faster charging/discharging rates and reduced operational temperatures, will be pursued as ways to lower system costs by reducing material usage and increasing system efficiency.

Material Handling Equipment

Hydrogen fuel cells are being successfully commercialized in material handling equipment, however, systems to date almost exclusively rely on high-pressure (350 bar or higher) hydrogen storage. The infrastructure required for refueling at high pressures adds substantial costs and therefore limits deployment to operations with large fleets of material handling equipment (e.g., >10 forklifts). Development of advanced hydrogen storage technology that would eliminate the need for a high-cost, high-pressure infrastructure could lead to deployment of hydrogen fuel cells into operations with small fleets and thus, significantly increase the potential market size.

Portable Power

Portable power systems range in power output from a watt or so to a few hundred watts. The energy storage requirements range from a few watt-hours to a kilowatt-hour or so. For portable power applications, safety and ease of use are critical requirements. System weight and volume are also key constraints; however, due to the relatively low amount of hydrogen required, on a specific energy and energy density basis, they tend to be less stringent than for other applications. Conversely, costs for portable power applications can be more stringent than even automotive applications as consumer electronics operate as a low-cost, low-margin business and fuel cell technology must be priced to compete with incumbent primary and secondary batteries. Both single use and rechargeable technologies are expected to be acceptable, analogous to primary and rechargeable batteries.

Technical Targets

The technical performance targets for hydrogen storage systems onboard light-duty vehicles are summarized in Table 3.3.3. These targets were established through the U.S. DRIVE Partnership, a partnership between DOE, the U.S. Council for Automotive Research (USCAR), energy companies, and utility companies and organizations. The targets are subject to change as more is learned about system-level requirements and as fuel cell technology progresses. The targets are based upon requirements for the "Ultimate Full Fleet," defined as virtually all light-duty vehicle platforms (e.g., makes and models), to achieve significant market penetration of hydrogen fueled vehicles. The Ultimate Full Fleet targets allow for manageable increases in weight and volume over current internal combustion engine vehicle systems and are intended to make hydrogen-fueled propulsion systems competitive across the majority of vehicle classes and models (from small compact cars to light-duty trucks).

A detailed explanation of the targets and the process used in deriving them is provided at: www1.eere.energy.gov/hydrogenandfuelcells/storage/current_technology.html.

Tables 3.3.4 through 3.3.7 list the DOE technical performance targets for material handling equipment and portable power applications. These targets were developed with input to DOE through extensive communications with various stakeholders, industry developers and end-users, including through a 2012 request for information and workshops. Additionally assessments were performned by SNL, NREL and PNNL.[10,11,12] The following useful constants are relative to Tables 3.3.3 through 3.3.7: 0.2778 kWh/MJ; Lower heating value for H_2 is 33.3 kWh/kg H_2; 1 kg H_2 ≈ 1 gal gasoline equivalent (gge).

[10] Hydrogen Storage Needs for Early Motive Fuel Cell Markets, http://www.nrel.gov/docs/fy13osti/52783.pdf
[11] Analysis of H_2 Storage Needs for Early Market Non-Motive Fuel Cell Applications, http://prod.sandia.gov/techlib/access-control.cgi/2012/121739.pdf
[12] Technology and Manufacturing Readiness of Early Market Motive and Non-Motive Hydrogen Storage Technologies for Fuel Cell Applications, http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-21473.pdf

Table 3.3.3 Technical System Targets: Onboard Hydrogen Storage for Light-Duty Fuel Cell Vehicles [a, i]			
Storage Parameter	**Units**	**2020**	**Ultimate**
System Gravimetric Capacity Usable, specific-energy from H_2 (net useful energy/max system mass) [b]	kWh/kg (kg H_2/kg system)	1.8 (0.055)	2.5 (0.075)
System Volumetric Capacity Usable energy density from H_2 (net useful energy/max system volume) [b]	kWh/L (kg H_2/L system)	1.3 (0.040)	2.3 (0.070)
Storage System Cost	$/kWh net ($/kg $H_{2\ stored}$)	10 333	8 266
• Fuel cost [c]	$/gge at pump	2-4	2-4
Durability/Operability			
• Operating ambient temperature [d]	ºC	-40/60 (sun)	-40/60 (sun)
• Min/max delivery temperature	ºC	-40/85	-40/85
• Operational cycle life (1/4 tank to full)	Cycles	1500	1500
• Min delivery pressure from storage system	bar (abs)	5	3
• Max delivery pressure from storage system	bar (abs)	12	12
• Onboard Efficiency [e]	%	90	90
• "Well" to Powerplant Efficiency [e]	%	60	60
Charging / Discharging Rates			
• System fill time (5 kg)	min (kg H_2/min)	3.3 (1.5)	2.5 (2.0)
• Minimum full flow rate	(g/s)/kW	0.02	0.02
• Start time to full flow (20 °C)	s	5	5
• Start time to full flow (-20 °C)	s	15	15
• Transient response at operating temperature 10%-90% and 90%-0%	s	0.75	0.75
Fuel Quality (H_2 from storage) [f]	% H_2	SAE J2719 and ISO/PDTS 14687-2 (99.97% dry basis)	
Environmental Health & Safety			
• Permeation & leakage [g]	-	Meets or exceeds applicable standards, for example SAE J2579	
• Toxicity	-		
• Safety	-		
• Loss of usable H_2 [h]	(g/h)/kg $H_{2\ stored}$	0.05	0.05

[a] Targets are based on the lower heating value of hydrogen, 33.3 kWh/kg H_2. Targets are for a complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and all other balance-of-plant components. All capacities are defined as usable capacities that could be delivered to the fuel cell power plant. All targets must be met at the end of service life (approximately 1500 cycles or 5000 operation hours, equivalent of 150,000 miles).

[b] Capacities are defined as the usable quantity of hydrogen deliverable to the powerplant divided by the total mass/volume of the complete storage system, including all stored hydrogen, media, reactants (e.g., water for hydrolysis-based systems), and system components. Tank designs that are conformable and have the ability to be

efficiently package onboard vehicles may be beneficial even if they do not meet the full volumetric capacity targets. Capacities must be met at end of service life.

c Hydrogen threshold cost is independent of pathway and is defined as the untaxed cost of hydrogen produced, delivered and dispensed to the vehicle.[http://hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.pdf]For material-based storage technologies, the impact of the technology on the hydrogen threshold cost, e.g., off-board cooling, off-board regeneration of chemical hydrogen storage materials, etc., must be taken into account.

d Stated ambient temperature plus full solar load (i.e., full exposure to direct sunlight). No allowable performance degradation from –20 °C to 40 °C. Allowable degradation outside these limits is to be determined.

e Onboard efficiency is the energy efficiency for delivering hydrogen from the storage system to the fuel cell powerplant, i.e., accounting for any energy required for operating pumps, blowers, compressors, heating, etc. required for hydrogen release. Well-to-powerplant efficiency includes onboard efficiency plus off-board efficiency, i.e., accounting for the energy efficiency of hydrogen production, delivery, liquefaction, compression, dispensing, regeneration of chemical hydrogen storage materials, etc. as appropriate. H2A and HDSAM analyses should be used for projecting off-board efficiencies.

f Hydrogen storage systems must be able to deliver hydrogen meeting acceptable hydrogen quality standards for fuel cell vehicles (see SAE J2719 and ISO/PDTS 14687-2). Note that some storage technologies may produce contaminants for which effects are unknown and not addressed by the published standards; these will be addressed by system engineering design on a case-by-case basis as more information becomes available.

g Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces. Storage system must comply with applicable standards for vehicular tanks including but not limited to SAE J2579 and the United Nations Global Technical Regulation. This includes any coating or enclosure that incorporates the envelope of the storage system.

h Total hydrogen lost from the storage system, including leaked or vented hydrogen; relates to loss of range.

i Details in this table are being revised to match changes in the high level cost target.

Table 3.3.4 Technical System Targets [a]: Material Handling Equipment			
Storage Parameter	**Units**	**2015**	**2020**
Hydrogen Capacity	kg	2	2
System Volumetric Capacity • Usable energy density from H_2 (net useful energy/max system volume) [b]	kWh/L (kg H_2/L system)	1.0 (0.03)	1.7 (0.05)
Storage System Cost	\$/kWh net (\$/kg $H_{2\ stored}$)	20 (667)	15 (500)
Durability/Operability • External operating temperature range [c] • Min/max delivery temperature [d] • Operational cycle life (1/10 tank to full) • Min delivery pressure from storage system • Max delivery pressure from storage system	 ºC ºC Cycles bar (abs) bar (abs)	 -40/60 -40/85 5000(5 yr) 3 12	 -40/60 -40/85 10,000(10 yr) 3 12
Shock & Vibration • Shock • Vibration	 g g	 40 5@10Hz – 0.75@200Hz	 40 10@10Hz – 1@200Hz
Charging / Discharging Rates • System fill time (2 kg) • Minimum full flow rate • Start time to full flow (20 °C) • Start time to full flow (-20 °C) • Transient response 10%-90% and 90%-0%	 min (kg H_2/min) (g/s)/kW s s s	 4.0 (0.5) 0.02 5 15 0.75	 2.8 (0.7) 0.02 5 15 0.75
Fuel Purity (H_2 from storage) [e]	% H_2	SAE J2719 & ISO/PDTS 14687-2 (99.97% dry basis)	
Environmental Health & Safety • Permeation & Leakage [f] • Toxicity • Safety	- - -	Meets or exceeds applicable standards, for example CSA HPIT 1	
• Loss of useable H_2 [g]	(g/h)/kg $H_{2\ stored}$	0.1	0.05

[a] The targets are based on the lower heating value of hydrogen, without consideration of the conversion efficiency of the fuel cell power plant. Targets are for the complete hydrogen storage and delivery system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling or heating capacity, and/or other balance-of-plant components. All capacities are defined as usable capacities that could be delivered to the fuel cell power plant during normal use. All targets must be met at the end of service life. Since most applications of material handling equipment (MHE) require extra mass as a counterbalance, the system gravimetric capacity is not specified as it can vary widely among types of MHE. However, system gravimetric capacity should be considered when developing hydrogen storage systems for MHE applications. All targets must be met at the end of service life.

[b] "Net useful energy" or "net" excludes unusable energy (i.e., hydrogen left in a tank below minimum fuel cell power plant pressure, flow, and temperature requirements) and hydrogen-derived energy used to extract the hydrogen from the storage medium (e.g., fuel used to heat a material to initiate or sustain hydrogen release).

[c] Stated ambient temperature. No allowable performance degradation from –20 °C to 40 °C. Allowable degradation outside these limits is to be determined.

[d] Delivery temperature refers to the inlet temperature of the hydrogen to the fuel cell.

[e] Hydrogen storage systems must be able to deliver hydrogen meeting acceptable hydrogen quality standards, such as CSA HPIT 1: Compressed Hydrogen Powered Industrial Trucks (forklifts) On- Board Fuel Storage and Handling Components. Note that some storage technologies may produce contaminants for which effects are unknown and not addressed by the published standards; these will be addressed by system engineering design on a case by case basis as more information becomes available.

[f] Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces. Storage system must comply with appropriate standards, for example CSA HPIT 1: Compressed Hydrogen Powered Industrial Trucks (forklifts) On- Board Fuel Storage and Handling Components. This includes any coating or enclosure that incorporates the envelope of the storage system.

[g] Total hydrogen lost from the storage system, including leaked or vented hydrogen; relates to loss of operational time.

Table 3.3.5 Technical Performance Targets [a]: Hydrogen Storage Systems for Low Power (≤2.5W) Portable Equipment

Storage Parameter	Units	2015		2020	
		Single-Use	Rechargeable	Single-Use	Rechargeable
Hydrogen Capacity	g H_2	≤1			
System Gravimetric Capacity [b]	kWh/kg	0.7	0.5	1.3	1.0
• Usable, specific-energy from H_2 (net useful energy/max system mass) [c]	(kg H_2/kg system)	(0.02)	(0.015)	(0.04)	(0.03)
System Volumetric Capacity	kWh/L	1.0	0.7	1.7	1.3
• Usable energy density from H_2 (net useful energy/max system volume)	(kg H_2/L system)	(0.03)	(0.02)	(0.05)	(0.04)
Storage System Cost	$/Wh net ($/g $H_{2\ stored}$)	0.09 (3.0)	0.75 (25)	0.03 (1.0)	0.4 (13)

Table 3.3.6 Technical Performance Targets [a]: Hydrogen Storage Systems for Medium Power (>2.5W-150W) Portable Equipment

Storage Parameter	Units	2015		2020	
		Single-Use	Rechargeable	Single-Use	Rechargeable
Hydrogen Capacity	g H_2	>1 - 50			
System Gravimetric Capacity [b]	kWh/kg	0.7	0.5	1.3	1.0
• Usable, specific-energy from H_2 (net useful energy/max system mass) [c]	(kg H_2/kg system)	(0.02)	(0.015)	(0.04)	(0.03)
System Volumetric Capacity	kWh/L	1.0	0.7	1.7	1.3
• Usable energy density from H2 (net useful energy/max system volume) [c]	(kg H_2/L system)	(0.03)	(0.02)	(0.05)	(0.04)
Storage System Cost	$/Wh net ($/g H_2 stored)	0.2 (6.7)	1.0 (33)	0.1 (3.3)	0.5 (17)

Table 3.3.7 Portable Power Durability & Operational Targets [a]			
Storage Parameter	**Units**	**2015**	**2020**
		Single-Use & Rechargeable	**Single-Use & Rechargeable**
Durability/Operability			
• External operating temperature range [d]	ºC	-40/60	-40/60
• Min/max delivery temperature [e]	ºC	10/85	10/85
• Min delivery pressure from storage system;	bar (abs)	1.5	1.5
• Max delivery pressure from storage system	bar (abs)	3	3
• External temperature [f]	ºC	≤40	≤40
Discharging Rates			
• Minimum full flow rate	(g/s)/kW	0.02	0.02
• Start time to full flow (20 °C)	s	5	5
• Start time to full flow (-20 °C)	s	10	10
• Transient response 10%-90% and 90%-0%	s	5	2
Fuel Purity (H_2 from storage) [g]	% H_2	Meets applicable standards	
Environmental Health & Safety • Toxicity • Safety • Loss of usable H_2 [h]		Meets ISO-16111:2008; IEC 62282 Part 6; or other applicable standards as appropriate or required for the application and targeted usage	

Footnotes to Tables 3.3.5 - 3.3.7:

[a] The targets are based on the lower heating value of hydrogen, without consideration of the conversion efficiency of the fuel cell power plant. Targets are for the complete hydrogen storage and delivery system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling or heating capacity, and/or other balance-of-plant components. All capacities are defined as usable capacities that could be delivered to the fuel cell power plant during normal use. All targets must be met at the end of service life.

[b] Generally the 'full' mass (including hydrogen) is used; for systems that gain weight on hydrogen release, the highest mass during discharge is used (e.g., hydrogen release through hydrolysis reaction resulting in the formation of oxides/hydroxides). All capacities are net usable capacity able to be delivered to the fuel cell power plant. Capacities must be met at end of service life.

[c] "Net useful energy" or "net" excludes unusable energy (i.e., hydrogen left in a tank below minimum fuel cell powerplant pressure, flow, and temperature requirements) and hydrogen-derived energy used to extract the hydrogen from the storage medium (e.g., fuel used to heat a material to initiate or sustain hydrogen release).

[d] Stated ambient temperature plus full solar load (i.e., if exposed to direct sunlight or stored within a container exposed to direct sunlight for extended periods of time). No allowable performance degradation from –20 °C to 40 °C. Allowable degradation outside these limits is to be determined.

[e] Delivery temperature refers to the inlet temperature of the hydrogen to the fuel cell.

[f] The external device temperature is the maximum temperature generated at the external surface of the hydrogen storage container during operation.

[g] Hydrogen storage systems must be able to deliver hydrogen meeting acceptable hydrogen quality standards, such as ISO-16111:2008 and IEC 62282 Part 6. Note that some storage technologies may produce contaminants for which effects are unknown and not addressed by the published standards; these will be addressed by system engineering design on a case by case basis as more information becomes available.

[h] Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces. Storage system must comply with appropriate standards, such as ISO-16111:2008 and IEC 62282 Part 6. This includes any coating or enclosure that incorporates the envelope of the storage system.

3.3.5 Technical Barriers

The following technical barriers are relevant to all hydrogen storage applications.

A. System Weight and Volume

The weight and volume of hydrogen storage systems are presently too high, resulting in inadequate operation on a single fill compared to incumbent technologies. Storage media, materials of construction, and balance-of-plant components are needed that allow compact, lightweight, hydrogen storage systems while enabling an adequate operating range to meet the user needs (e.g., range greater than 300-miles for light-duty vehicle applications). Reducing weight and volume of thermal management components is also required.

B. System Cost

The cost of hydrogen storage systems is too high, particularly in comparison with conventional storage systems for petroleum fuels. Low-cost media, materials of construction, and balance-of-plant components are needed, as well as low-cost, high-volume manufacturing methods.

C. Efficiency

Energy efficiency is a challenge for all hydrogen storage approaches. The energy required to transfer hydrogen into and out of the storage media or material is an issue for all material options. Life-cycle energy efficiency may be a challenge for chemical hydrogen storage technologies in which the spent media and by-products are typically regenerated off-board. In addition, the energy associated with the compression, cooling, and liquefaction of hydrogen must be considered for compressed, cryogenic, and liquid hydrogen technologies. Thermal management for charging and releasing hydrogen from the storage system needs to be optimized to increase overall efficiency for all approaches.

D. Durability/Operability

Durability of hydrogen storage systems is inadequate. Storage media, materials of construction, and balance-of-plant components are needed that allow hydrogen storage systems with acceptable lifetimes and with tolerance to hydrogen fuel contaminants. An additional durability issue for material-based approaches is the delivery of sufficient quality hydrogen for the application power plant.

E. Charging/Discharging Rates

In general and especially for material-based approaches, hydrogen refueling times are too long. For automotive applications, there is a need to develop hydrogen storage systems with refueling times of less than three minutes for a 5-kg hydrogen charge, over the lifetime of the system. Thermal management that enables quicker refueling is a critical issue that must be addressed. Also, all storage system approaches must be able to supply a sufficient flow of hydrogen to the power plant (e.g., fuel cell or internal combustion engine) to meet the required power demand.

F. Codes and Standards

Applicable codes and standards for hydrogen storage systems and interface technologies, which will facilitate implementation/commercialization and assure safety and public acceptance, are being established for automotive applications and need to be established for early market applications. Standardized hardware and operating procedures, and applicable codes and standards, are required.

G. Materials of Construction

High-pressure containment for compressed gas and other high-pressure approaches limits the choice of construction materials and fabrication techniques, within weight, volume, performance, and cost constraints. For all approaches of hydrogen storage, vessel containment that is resistant to hydrogen permeation and corrosion is required. Research into new materials of construction, such as metal ceramic composites, improved resins, and engineered fibers, is needed to meet cost targets without compromising performance. Materials to meet performance and cost requirements for hydrogen delivery and off-board storage are also needed (see Hydrogen Delivery MYRD&D section).

H. Balance-of-Plant (BOP) Components

Lightweight, cost-effective BOP components are needed for all approaches of hydrogen storage, especially those requiring high-pressure or extensive thermal management. These components include tubing, fittings, check valves, regulators, filters, relief and shut-off valves, heat exchangers, and sensors. System design and optimal packaging of components to meet overall volumetric targets are also required.

I. Dispensing Technology

Requirements for dispensing hydrogen to and from the storage system have not been fully defined for all storage platforms. These include meeting heat rejection requirements during fueling especially for onboard reversible material-based approaches. For chemical hydrogen approaches, methods and technology to recover spent material from the fuel tank for regeneration during "refueling" are needed. Activities will be coordinated with the Delivery sub-program.

J. Thermal Management

For all approaches of hydrogen storage – compressed gas, cryogenic, and materials-based – thermal management is a key issue. In general, the main technical challenge is heat removal during hydrogen fueling of hydrogen for compressed gas and onboard reversible materials within fueling time requirements. Onboard reversible materials typically require heat to release hydrogen. Heat must be provided to the storage media at reasonable temperatures to meet the flow rates needed by the power plant, preferably using the waste heat of the power plant. Depending upon the chemistry, chemical hydrogen approaches often are exothermic upon release of hydrogen to the power plant, or optimally thermal neutral; exothermic systems will require heat rejection during operation.

K. System Life-Cycle Assessments

Assessments of the full life-cycle, cost, efficiency, and environmental impact for hydrogen storage systems are lacking. An understanding of infrastructure implications, particularly for chemical hydrogen storage and approaches to reduce primary energy inputs, is lacking.

Compressed Gas Systems

L. Lack of Tank Performance Data and Understanding of Failure Mechanisms

An understanding of the fundamental mechanisms that govern composite tank operating cycle life and failure due to accident or to neglect is lacking. Research on tank performance and failure is needed to optimize tank structure for performance and cost. In addition, sensors and associated prediction correlations are needed to predict lifetime and catastrophic tank failure.

Cryogenic Liquid and Cryo-compressed Systems

M. Liquefaction Energy Penalty

The energy penalty associated with hydrogen liquefaction, typically about 30% of the lower heating value of hydrogen, is an issue. Methods to reduce the energy requirements for liquefaction are needed.

N. Hydrogen Venting

The boil-off and subsequent pressure rise of liquid and cold hydrogen requires venting, reduces operation range, and presents a potential safety/environmental hazard, particularly when in an enclosed environment. Materials and methods to reduce boil-off and venting from cryogenic systems are needed.

Reversible Materials-Based Storage Systems (Reversible Onboard)

O. Lack of Understanding of Hydrogen Physisorption and Chemisorption

Improved understanding and optimization of adsorption/absorption and desorption kinetics is needed to optimize hydrogen uptake and release capacity rates. An understanding of chemical reactivity and material properties, particularly with respect to exposure under different conditions (air, moisture, etc.) is also lacking.

P. Reproducibility of Performance

Standard test protocols for evaluation of hydrogen storage materials are lacking. Reproducibility of performance both in synthesis of the material/media and measurement of key hydrogen storage performance metrics is an issue. Standard test protocols related to performance over time such as accelerated aging tests as well as protocols evaluating materials safety properties and reactivity over time are also lacking.

Chemical Hydrogen Storage Systems (Typically Regenerated Off-board)

Q. Regeneration Processes

Low-cost, energy-efficient regeneration processes have not been established. Full life-cycle analyses need to be performed to understand cost, efficiency, and environmental impacts.

R. By-Product/Spent Material Removal

The refueling process is potentially complicated by removal of the by-product and/or spent material. System designs must be developed to address this issue and also the infrastructure requirements for off-board regeneration.

3.3.6 Technical Task Descriptions

The technical task descriptions are presented in Table 3.3.8. Issues regarding safety will be addressed within each of the tasks. The barriers associated with each task appear after the task title.

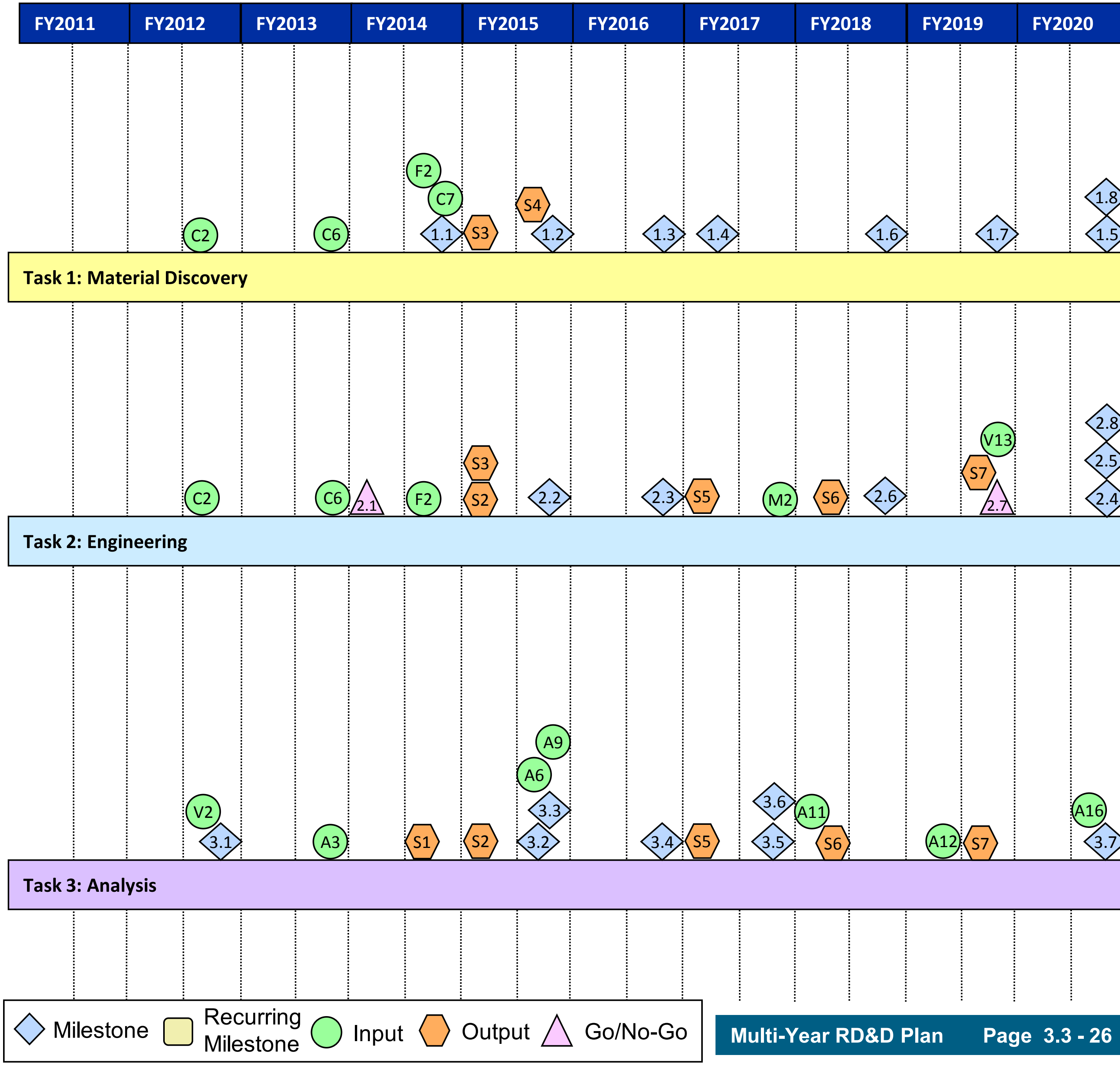
Table 3.3.8 Technical Task Descriptions

Task	Description	Barriers
1	**Material Discovery** • Perform theoretical modeling to provide guidance for materials development. • Determine the decomposition pathways and products of materials to better understand their mechanisms and kinetics. • Determine the hydrogen storage capacity of potential storage materials and demonstrate reproducibility of their synthesis and capacity measurements. • Develop sorbent materials with increased binding energy and volumetric density. • Develop reversible metal hydrides with improved kinetics while maintaining high gravimetric capacity at relevant release temperatures and pressures. • Develop off-board regenerable materials with improved overall efficiency at relevant temperatures and pressures. • Develop cost-effective synthesis processes for promising materials.	A-K, O-R
2	**Engineering** • Develop complete integrated storage systems with appropriate operating parameters necessary to meet fuel cell power plant requirements at acceptable cost. • Develop low-cost, advanced compressed and cryogenic storage systems to meet performance targets. • Develop and optimize lower-cost and improved carbon fiber composites. • Develop lightweight, low-cost, balance-of-plant components for advanced compressed/cryogenic systems. • Coordinate with Delivery and Systems Analysis sub-programs to understand the interrelationship between onboard storage and delivery options (e.g., efficiency, cost, etc.). • Develop cryo-tanks with reduced cost, improved dormancy, and validated system operation and cycle-life at cryogenic temperatures.	A-N, R
3	**Analysis** • Perform analyses to assess cost effectiveness of materials-based hydrogen storage systems including scale-up to high-volume production. • Conduct analyses of high-volume production cost and performance metrics (e.g., well-to-wheels efficiency, greenhouse-gas emissions as well as volumetric/gravimetric capacities and other operating metrics) of competing hydrogen storage materials-based systems to guide research toward the most viable systems. • Evaluate the safety performance of the complete systems. • Ensure compatibility with applicable codes and standards for on-vehicle storage and fueling interface.	A-R

3.3.7 Milestones

The following chart shows the interrelationship of milestones, tasks, outputs, and supporting inputs for the Hydrogen Storage sub-program from FY 2012 through FY 2020. The inputs/outputs are also summarized in Appendix B.

Hydrogen Storage Milestone Chart



Task 1: Material Discovery	
1.1	Material Handling: Determine applicability of hydrogen storage materials for material handling applications. (4Q, 2014)
1.2	Portable Power: Determine applicability of hydrogen storage materials for portable power applications. (4Q, 2015)
1.3	Material Handling: Down-select hydrogen storage materials for material handling applications. (4Q, 2016)
1.4	Portable Power: Down-select hydrogen storage materials for portable power applications. (2Q, 2017)
1.5	Transportation: Evaluate status and down-select adsorbents based on their potential to meet a system gravimetric capacity of 5.5 wt.% H_2 and an energy density of 0.04 kg H_2/L at ambient temperatures. (4Q, 2020)
1.6	Transportation: Evaluate status and down-select endothermic chemical hydrogen storage materials based on technical and economic viability. (4Q, 2018)
1.7	Transportation: Evaluate status and down-select metal hydrides based on their potential to meet a system gravimetric capacity of 6 wt.% H_2 and an energy density of 0.05 kg H_2/L with 90% onboard efficiency. (4Q, 2019)
1.8	Transportation: Evaluate status and down-select chemical hydrides based on their potential to meet a system gravimetric capacity of 6 wt.% H_2 and an energy density of 0.05 kg H_2/L with a well-to-power plant efficiency of 60%. (4Q, 2020)
Task 2: Engineering	
2.1	Transportation: Go/No Go decision on construction of subscale sorbent and chemical hydride prototypes. (1Q, 2014)
2.2	Transportation: Determine material specific properties required for 2020 onboard storage system targets. (4Q, 2015)
2.3	Transportation: Complete subscale prototype and evaluate against 2020 targets. (4Q, 2016)
2.4	Transportation: Develop and verify onboard storage systems achieving capacity of 5.5% by weight and an energy density of 0.04 kg H_2/L. (4Q, 2020)
2.5	Crosscutting: Reduce the high-volume cost of high-strength carbon fiber by 25% from $13 per pound to ~$9 per pound. (4Q, 2020)
2.6	Material Handling: Complete prototype of an onboard sorbent and/or chemical hydrogen system and evaluate against 2015 targets. (4Q, 2018)
2.7	Transportation: Go/No Go decision on materials-based system strategies to meet ultimate onboard system storage targets. (4Q, 2019)

Task 2: Engineering	
2.8	Portable Power: Evaluate a complete prototype against DOE targets. (4Q, 2020)
Task 3: Analysis	
3.1	Quantify performance targets for hydrogen storage for key early market, stationary, and portable fuel cell applications. (4Q, 2012)
3.2	Crosscutting: Evaluate status of carbon fiber cost reduction efforts against the 2010 baseline cost of $32/kg. (3Q, 2015)
3.3	Transportation: Complete economic evaluation of cold hydrogen storage against targets. (4Q, 2015)
3.4	Transportation: Complete well-to-wheels analysis for cost, efficiency, and greenhouse gas emissions of most promising sorbent and chemical hydrogen materials pathways. (4Q, 2016)
3.5	Crosscutting: Evaluate status of composite tank cost compared to 2013 baseline projected cost of $17/kWh. (4Q, 2017)
3.6	Update early market storage targets. (4Q, 2017)
3.7	Transportation: Complete analysis of onboard storage options compared to ultimate targets. (4Q, 2020)

Outputs

S1 Output to Systems Analysis and Manufacturing: Update status of composite tank costs. (3Q, 2014)

S2 Output to Delivery: Technical and economic update from storage on promising storage material system. (1Q, 2015)

S3 Output to Safety, Codes and Standards: Material characteristics and performance data on advanced storage materials and systems. (1Q, 2015)

S4 Output to Fuel Cells and Safety, Codes and Standards: Update of fuel quality from promising storage materials. (Q3, 2015)

S5 Output to Delivery, Technology Validation, Systems Analysis, and Systems Integration: Projected performance of materials-based systems for onboard hydrogen storage. (1Q, 2017)

S6 Output to Systems Analysis: Update status of advanced materials system costs. (2Q, 2018)

S7 Output to Systems Analysis: Projected performance of hydrogen storage systems for non-automotive applications. (3Q, 2019)

Inputs

A3 Input from Systems Analysis: Preliminary well-to-wheel power plant efficiency analysis for advanced material systems. (4Q, 2013)

A6 Input from Systems Analysis: Report on the status of composite tank costs. (3Q, 2015)

A9 Input from Systems Analysis: Update on onboard automotive fuel cell system power, input pressure, degree of hybridization and vehicle refill time. (4Q, 2015)

A11 Input from Systems Analysis: Report on the projected performance of materials-based systems for onboard hydrogen storage. (1Q, 2018)

A12 Input from Systems Analysis: Report on the status of advanced materials system costs. (2Q, 2019)

A16 Input from Systems Analysis: Report on the projected performance of hydrogen storage systems for non-automotive applications. (3Q, 2020)

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)

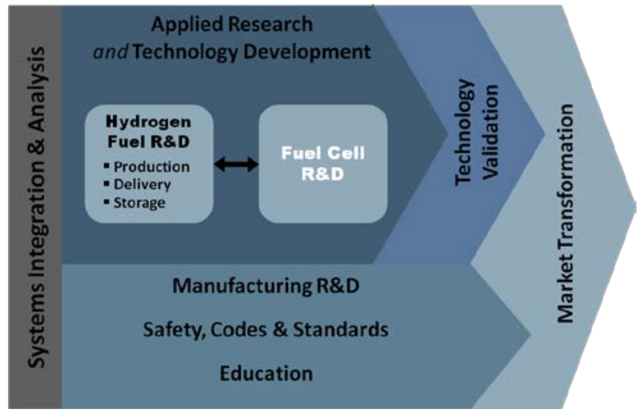
F2 Input from Fuel Cells: Report on the effect of impurities from storage materials on fuel cells. (3Q, 2014)

M2 Input from Manufacturing: Report on fabrication and assembly processes for high pressure hydrogen storage tanks that cost $15/kWh for Type IV, 700 bar tanks. (4Q, 2017)

V2 Input from Technology Validation: 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)

V13 Input from Technology Validation: Validate onboard storage system weight capacity and energy density. (4Q, 2019)

3.4 Fuel Cells



Fuel cells offer a highly efficient way to use diverse energy sources and, as a result, have demonstrated lower energy use and emissions when compared with conventional technologies. They also can be powered by emissions-free fuels that are produced from clean, domestic resources, helping to reduce the nation's dependence on imported petroleum. The largest markets for fuel cells today are in stationary power, portable power, auxiliary power units, and material handling equipment. Approximately 75,000 fuel cells had been shipped worldwide by the end of 2009[1] and approximately 15,000 additional fuel cells were shipped in 2010[2] (>40% increase over 2008). In transportation applications in the U.S., there are currently (August 2011): >200 fuel cell light duty vehicles, >20 fuel cell buses, and ~60 fueling stations. Several manufacturers, including GM, Toyota, Honda, Hyundai, and Daimler, have announced plans to begin commercializing fuel cell vehicles by 2015.

The Fuel Cells sub-program has been addressing the key challenges facing the widespread commercialization of fuel cells for diverse applications. The program supports fuel cells for stationary power due to their high efficiency and the potential to reduce our primary energy use for and emissions from electricity production. The Fuel Cells sub-program is also pursuing polymer electrolyte membrane (PEM) fuel cells as replacements for internal combustion engines (ICEs) in light-duty vehicles to increase vehicle efficiency and support the goals of reducing oil use in and emissions from the transportation sector. In addition, the program supports fuel cells for material handling equipment, portable power, and auxiliary power applications where earlier market entry could assist in the development of a fuel cell manufacturing base. The technical focus is on developing materials, components, and sub-systems, at the stack and system level, that enable fuel cells to achieve the Fuel Cells sub-program objectives, primarily related to system cost and durability.

For transportation applications, the Fuel Cells sub-program is focused on direct hydrogen fuel cells, in which the hydrogen fuel is stored onboard and is supplied by a hydrogen production and fueling infrastructure. Hydrogen production and delivery technologies are being developed in parallel with fuel cell development efforts. For distributed stationary power generation applications, fuel cell systems will likely be fueled with reformate produced from natural gas, liquefied petroleum gas (LPG, consisting predominantly of propane) or renewable fuels such as biogas from wastewater treatments plants. Fuel cells for auxiliary power units in trucks will likely use either diesel or LPG. In material handling equipment and small consumer electronics (portable power), hydrogen or methanol will likely be the fuel of choice for fuel cell systems.

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[1] RNCOS report, "Fuel Cell Industry Analysis," June 2011, http://www.rncos.com/Report/IM102.htm
[2] 2010 Fuel Cell Technologies Market Report, June 2011, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/2010_market_report.pdf

3.4.1 Technical Goal and Objectives

Goal

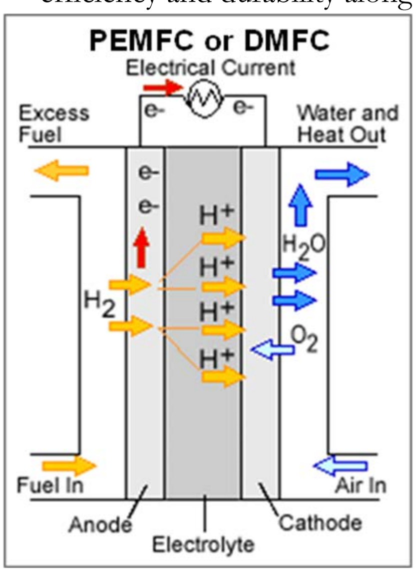
Develop and demonstrate fuel cell power system technologies for transportation, stationary and portable power applications.

Objectives

- By 2015, develop a fuel cell system for portable power (<250 W) with an energy density of 900 Wh/L.
- By 2020, develop a 60% peak-efficient, 5,000 hour durable, direct hydrogen fuel cell power system for transportation at a cost of $40/kW with an ultimate cost target of $30/kW.
- By 2020, develop distributed generation and micro-CHP fuel cell systems (5 kW) operating on natural gas or LPG that achieve 45% electrical efficiency and 60,000 hours durability at an equipment cost of $1500/kW.
- By 2020, develop medium-scale CHP fuel cell systems (100 kW–3 MW) that achieve 50% electrical efficiency, 90% CHP efficiency, and 80,000 hours durability at a cost of $1,500/kW for operation on natural gas, and $2,100/kW when configured for operation on biogas.
- By 2020, develop a fuel cell system for auxiliary power units (1–10 kW) with a specific power of 45 W/kg and a power density of 40W/L at a cost of $1000/kW.

3.4.2 Technical Approach

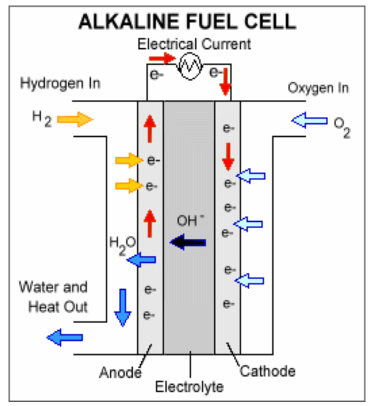
Fuel cell research and development (R&D) will emphasize activities aimed at achieving high efficiency and durability along with low material and manufacturing costs for the fuel cell stack.



R&D to develop lower cost, better performing system balance-of-plant (BOP) components like air compressors, fuel processors, water and heat management systems, and sensors is also being pursued. Each application – light-duty vehicle transportation, material handling equipment, stationary power, auxiliary power units (APUs) for heavy-duty vehicles, and portable power for consumer electronics – has specific market-driven requirements for technology development.

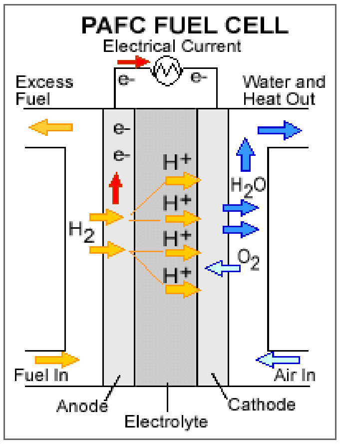
Polymer Electrolyte Membrane Fuel Cells (PEMFCs) are being considered for applications that require faster start-up times and frequent starts and stops such as automotive applications, material handling equipment and backup power. For PEMFCs, continuing advancements are needed to minimize precious metal loading, improve component durability, and manage water transport within the cell. Membranes that are capable of operation at up to 120°C for automotive applications and above 120°C for stationary applications are needed for better thermal management. For this purpose, the development of polybenzimidazole-type (PBI-type) PEMFCs operating above 130°C has benefits. R&D is required to reduce cost and increase MEA durability of PBI-type PEMFCs. R&D is also required to reduce cost and improve durability of system BOP components, such as humidifiers and compressors.

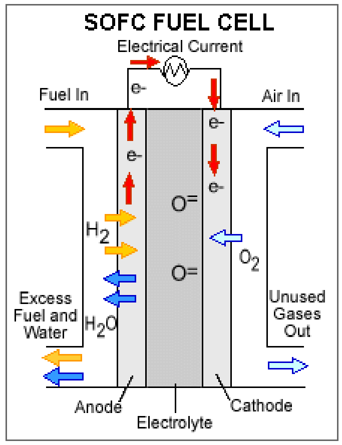
Direct Methanol Fuel Cells (DMFCs) are well suited for portable power applications in consumer electronic devices where the power requirements are low and the cost targets and infrastructure requirements are not as stringent as for transportation applications. A higher energy density alternative to existing technologies is required to fill the increasing gap between energy demand and energy storage capacity in these applications. Challenges for DMFCs include reducing methanol crossover to increase efficiency and simplifying the BOP, to increase energy and power density, improve reliability, and reduce cost.

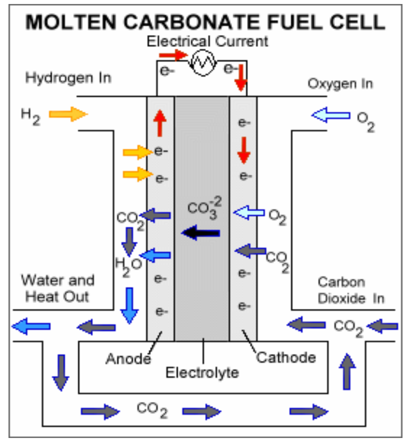


Alkaline Fuel Cells (AFCs) have long been used in space applications where pure hydrogen and oxygen are available. The advantage of AFCs to enable non-precious metal catalysis has been outweighed by the increased system complexity and difficulties of working with a liquid electrolyte, as well as issues with carbonate formation for most terrestrial applications. Alkaline membrane fuel cells (AMFCs) avoid or mitigate the shortcomings of traditional liquid AFCs and are being considered for applications in the W to kW scale. Challenges for AMFCs include tolerance to carbon dioxide, membrane conductivity and durability, higher temperature operation, water management, power density, and anode electrocatalysis.

Medium temperature (Phosphoric Acid) and high temperature (Solid Oxide and Molten Carbonate) fuel cells are more applicable where systems may run for extended periods without frequent start and stop cycles. These systems also have benefits in combined heat and power (CHP) generation, and offer simplified operation on fossil and renewable fuels. R&D needs for phosphoric acid-based fuel cells include methods to decrease or eliminate anion adsorption on the cathode, lower cost materials for the cell stack and BOP components, and durable electrode catalysts and support materials. For high-temperature Molten Carbonate Fuel Cell (MCFC) systems, R&D is needed to limit electrolyte loss and prevent microstructural changes in the electrolyte support that lead to early stack failure, and to develop more robust cathode materials. For Solid Oxide Fuel Cells (SOFCs), challenges include stack survivability during repeated thermal cycling, decreasing long start up times, and potential mechanical and chemical compatibility/reactivity issues between the various stack and cell components due to high temperature operation. For all these systems, improved fuel processing and cleanup, especially for fuel-flexible operation and operation on biofuels, are needed to improve durability and reduce system costs. Table 3.4.1 describes the different fuel cell types.







To meet the efficiency, durability and cost requirements for fuel cells, R&D will focus on identifying new materials and novel design and fabrication methods for electrolytes and electrolyte supports, catalysts and supports, gas diffusion media, cell hardware (including bipolar plates, interconnects and seals) and balance-of-plant components (e.g., compressors, radiators, humidifiers, fuel processors, etc.). Testing of new materials, designs, and fabrication methods will be carried out by industry, national laboratories, and universities. New R&D efforts will include demonstration in single cells or membrane electrode assemblies (MEAs), in stacks, and at the sub-system and system level. The Technology Validation sub-program (see Section 3.6), provides fuel cell vehicle and stationary power data under real-world conditions and, in turn, supplies valuable results to help refine and direct future activities for fuel cell R&D.

Table 3.4.1 Fuel Cell Types

Fuel Cell Type	Temperature / Electrolyte / Charge Carrier	Applications
Phosphoric Acid (PAFC) and Polymer / Phosphoric Acid	150–200° C H_3PO_4, Polymer/H_3PO_4 / H^+	Distributed power Transportation
Polymer Electrolyte Membrane (PEMFC)	50–100° C Perfluorosulfonic acid / H^+	Distributed power Portable power Transportation
Direct Methanol (DMFC)	50–100° C Perfluorosulfonic acid / H^+	Portable Power
Alkaline (AFC)	25–75° C, 100–250° C Alkaline polymer, KOH / OH^-	Portable Power Backup Power
Molten Carbonate (MCFC)	600–700° C $(Li,K,Na)_2CO_3$ / CO_3^{2-}	Distributed power
Solid Oxide (SOFC)	500–1000° C Yttria–Stabilized Zirconia ($Zr_{.92}Y_{.08}O_2$) / O^{2-}	Electric utility Distributed power APUs

3.4.3 Programmatic Status

Current Activities

Table 3.4.2 summarizes the FY 2011 activities in the Fuel Cells sub-program. Activities targeted toward polymer electrolytes include the identification and development of ionomers with increased conductivity (especially under conditions of low relative humidity and high temperature), increased mechanical and chemical durability, and reduced material costs. Failure mechanisms in fuel cells are being explored both experimentally and via modeling. Scalable fabrication processes for production of membranes, electrodes, MEAs, and bipolar plates are being designed. Catalysts with reduced precious metal loading, increased activity and durability, and lower cost (including non-precious metal catalysts), are under development. Bipolar plates with lower weight and volume and with negligible corrosion are being developed. To enable early-market entry of fuel cells, R&D on stationary and other applications such as material handling equipment, portable power and auxiliary power units is pursued. To gauge the status of the technology, the cost and performance of fuel cell components are benchmarked and evaluated.

Table 3.4.2 Current Fuel Cell Activities

Task	Approach	Activities
Electrolytes	• Develop / identify electrolytes and membranes/matrices (polymer, phosphoric/solid acid, anion-exchange, solid oxide, molten carbonate) with improved conductivity over the entire temperature and humidity range, increased mechanical, chemical, and thermal stability, with reduced/eliminated fuel cross-over • Fabricate membranes from ionomers with scalable fabrication processes, increased mechanical, chemical, and thermal stability and reduced cost • Perform membrane testing and characterization to improve durability	• **3M**: Membranes and MEA's for Dry, Hot Operating Conditions. • **Case Western Reserve University**: Rigid Rod Polyelectrolytes: Effect on Physical Properties: Frozen-in Free Volume: High Conductivity at Low RH • **Colorado School of Mines**: Novel Approaches to Immobilized Heteropoly Acid (HPA) Systems for High Temperature, Low Relative Humidity Polymer-Type Membranes • **Fuel Cell Energy, Inc.**: High Temperature Membrane with Humidification-Independent Cluster Structure • **Giner Electrochemical Systems**: Dimensionally Stable Membranes • **Los Alamos National Laboratory**: Resonance-Stabilized Anion Exchange Polymer Electrolytes • **University of Central Florida**: Lead Research and Development Activity for DOE's High Temperature, Low Relative Humidity Membrane Program • **Vanderbilt University**: Nano Capillary Network Proton Conducting Membranes for High Temperature Hydrogen/Air Fuel Cells

Table 3.4.2 Current Fuel Cell Activities		
Task	**Approach**	**Activities**
Catalysts/ Electrodes	• Develop electro catalysts with reduced precious metal loading, increased activity, improved durability / stability, and increased tolerance to air, fuel and system-derived impurities • Develop supports with reduced corrosion, lower cost, and increased non-PGM catalyst loading • Optimize electrode design and assembly • Develop anodes for fuel cells operating on non-hydrogen fuels	• **3M**: Advanced Cathode Catalysts and Supports for PEM Fuel Cells • **3M**: Durable Catalysts for Fuel Cell Protection During Transient Conditions • **Argonne National Laboratory**: Polymer Electrolyte Fuel Cell Lifetime Limitations: The Role of Electro catalyst Degradation • **Argonne National Laboratory**: Nanosegregated Cathode Catalysts with Ultra-Low Platinum Loading • **Brookhaven National Laboratory**: Contiguous Platinum Monolayer Oxygen Reduction Electro catalysts on High-Stability-Low-Cost Supports • **GM**: High-Activity Dealloyed Catalysts • **Illinois Institute of Technology**: Synthesis and Characterization of Mixed-Conducting Corrosion Resistant Oxide Supports • **Los Alamos National Laboratory**: The Science and Engineering of Durable Ultralow PGM Catalysts • **Los Alamos National Laboratory**: Engineered Nano-scale Ceramic Supports for PEM Fuel Cells. • **Lawrence Berkeley National Laboratory**: Molecular-scale, Three-dimensional Non-Platinum Group Metal Electrodes for Catalysis of Fuel Cell Reactions • **Northeastern University**: Development of Novel Non Pt Group Metal Electro catalysts for Proton Exchange Membrane Fuel Cell Applications • **National Renewable Energy Laboratory**: Extended, Continuous Pt Nanostructures in Thick, Dispersed Electrodes • **National Renewable Energy Laboratory**: WO_3 and HPA Based System for Ultra-High Activity and Stability of Pt Catalysts in PEMFC Cathodes • **Pacific Northwest National Laboratory**: Alternative and Durable High Performance Cathode Supports for PEM Fuel Cells • **University of South Carolina**: Development of Ultra-Low Platinum Alloy Cathode Catalyst for PEM Fuel Cells • **UTC Power**: Power Highly Dispersed Alloy Catalyst for Durability

Table 3.4.2 Current Fuel Cell Activities		
Task	**Approach**	**Activities**
Membrane Electrode Assemblies, Gas Diffusion Media, and Cells	• Integrate membrane/electrolytes and electrodes • Expand MEA operating range addressing temperature and humidity range, improving stability, and mitigating effects of impurities. • Test, analyze, and characterize MEAs • Improve GDL/MPL performance and durability.	• **DuPont**: Analysis of Durability of MEAs in Automotive PEMFC Applications. • **Giner Electrochemical Systems, LLC**: Transport in PEMFC Stacks • **GM**: Investigation of Micro- and Macro-Scale Transport Processes for Improved Fuel Cell Performance • **Ion Power**: Corrugated Membrane Fuel Cell Structures • **CFD Research Corp.**: Water Transport in PEM Fuel Cells: Advanced Modeling, Material Selection, Testing, and Design Optimization • **Sandia National Laboratories**: Development and Validation of a Two-phase, Three-dimensional Model for PEM Fuel Cells • **Nuvera Fuel Cells**: Transport Studies Enabling Efficiency Optimization of Cost-Competitive Fuel Cell Stacks
Seals, Bipolar Plates, and Interconnects	• Optimize balance-of-stack components • Improve performance and durability of bipolar plates • Decrease cost of bipolar plates	• **Argonne National Laboratory**: Metallic Bipolar Plates with Composite Coatings • **Treadstone Technologies**: Low Cost PEM Fuel Cell Metal Bipolar Plates
Stack and Component Operation and Performance	• Improve technical understanding and characterization	• **Lawrence Berkeley National Laboratory**: Fuel-Cell Fundamentals at Low and Subzero Temperatures • **Plug Power, Inc.**: Air Cooled Stack Freeze Tolerance
Systems Operation and Performance	• Improve technical understanding and characterization	• No current activities
Systems BOP Components	• Develop chemical and temperature sensors for stationary applications • Develop air management technologies for stationary applications • Develop humidifiers • Develop thermal management technologies for fuel cell systems	• **Honeywell**: Development of Thermal and Water Management System for PEM Fuel Cell • **W.L. Gore**: Materials and Modules for Low-Cost, High Performance Fuel Cell Humidifiers

Table 3.4.2 Current Fuel Cell Activities		
Task	**Approach**	**Activities**
Fuel Processors	• Develop fuel-flexible fuel processors capable of generating a hydrogen-rich gas stream • Improve durability and tolerance to impurities • Integrate fuel processor subsystems eliminating reactor hardware, piping	• No current activities
Fuel Cell Systems	• Develop stationary fuel cell systems for Distributed Generation • Develop auxiliary power units • Develop portable power technologies	• **Arkema**: Novel Materials for High Efficiency Direct Methanol Fuel Cells • **Los Alamos National Laboratory**: Advanced Materials and Concepts for Portable Power Fuel Cells • **National Renewable Energy Laboratory**: Direct Methanol Fuel Cell Anode Catalysts • **University of North Florida**: New MEA Materials for Improved DMFC Performance, Durability, and Cost • **Acumentrics**: Development of a Low Cost 3-10kW Tubular SOFC Power System
Testing and Technical Assessment	• Perform cost analysis • Annually update technology status • Conduct tradeoff analysis • Develop protocols for testing • Experimentally determine long-term stack failure mechanisms • Experimentally determine system emissions • Perform independent testing to characterize component and stack properties	• **Argonne National Laboratory**: Fuel Cell Systems Analysis • **Ballard**: Development of Micro-Structural Mitigation Strategies for PEM Fuel Cells: Morphological Simulations and Experimental Approaches • **Directed Technologies, Inc.**: Mass-Production Cost Estimation for Automotive Applications • **Hawaii Natural Energy Institute**: The Effect of Airborne Contaminants on Fuel Cell Performance and Durability • **Los Alamos National Laboratory**: Durability Improvements through Degradation Mechanism Studies • **National Renewable Energy Laboratory**: Effect of System and Air Contaminants on PEMFC Performance and Durability • **NIST**: Neutron Imaging Study of Water Transport in Operating Fuel Cells • **University of Connecticut**: Effects of Impurities on Fuel Cell Performance and Durability • **Nuvera Fuel Cells**: Durability of Low Pt Fuel Cells Operating at High Power Density • **Argonne National Laboratory**: Fuel Cell Test

Table 3.4.2 Current Fuel Cell Activities		
Task	**Approach**	**Activities**
		Facility • **Los Alamos National Laboratory**: Accelerated Testing Validation • **Los Alamos National Laboratory**: Technical Assistance to Developers • **Oak Ridge National Laboratory**: Characterization of Fuel Cell Materials • **UTC Power**: Improved Accelerated Stress Tests Based on Fuel Cell Electric Vehicle Data

3.4.4 Technical Challenges

Cost and durability are the major challenges to fuel cell commercialization. Size and weight are approaching targets but further reductions are needed to meet packaging requirements for some commercial systems. Understanding of the effects of air, fuel, and system-derived impurities (including from the fuel storage system) needs to be improved, and mitigation strategies need to be identified and demonstrated. Cost, efficiency, and packaging of fuel cell balance-of-plant components are also barriers to the commercialization of fuel cells. For transportation applications, fuel cell technologies face more stringent cost and durability requirements. In stationary power applications, raising the operating temperature of PEMs to increase fuel cell performance will also improve heat and power cogeneration and overall system efficiency. Development of low-cost fuel processing and gas cleanup is required to enable fuel flexibility and enable the use of renewable fuels, such as biogas. Improving the durability at lower cost of high temperature fuel cell systems is also required. Fuel cell systems for portable power applications must have increased durability and reduced costs to compete with batteries. Likewise, fuel cells for auxiliary power must have longer durability and reduced costs to penetrate the market.

Transportation Systems

Light Duty Vehicles

The cost of fuel cell power systems must be reduced before they can be competitive with gasoline internal combustion engines (ICEs). Conventional automotive ICE power plants currently cost about $25-$35 / kW (August 2011); a fuel cell system ultimately needs to cost less than $30/kW for the technology to be competitive. A significant fraction of the cost of a PEM fuel cell comes from precious-metal catalysts that are currently used on the anode and cathode for the electrochemical reactions. Other key cost factors include the membrane, cell hardware, and balance-of-plant components.

The durability of fuel cell systems operating under automotive conditions is being evaluated under the Technology Validation Learning Demonstration Program. Results indicate a projected durability of up to 2,500 hours[3]. Fuel cell power systems will be required to be as durable and reliable as current automotive engines (i.e., 5,000 hour lifespan [150,000 miles equivalent] with less than 10% loss of performance by the end of life) and able to function over the full range of external environmental conditions (-40° to +40°C). Membranes are critical components of the fuel cell stack and must be able to perform over the full range of system operating temperatures and humidity. Current commercial membranes need humidification. External humidification adds cost and complexity to the system. The durability of catalysts is also an issue and can be compromised by platinum sintering and dissolution, especially under conditions of load-cycling and high electrode potentials. Carbon support corrosion is another challenge at high electrode potentials and can worsen under load cycling and high-temperature operation.

Fuel cell and stack hardware (bipolar plates, gas diffusion layers and seals) also need further development. Bipolar plates represent a significant fraction of stack weight, which must be reduced. Seal materials must be durable over the lifetime of a fuel cell and yield acceptable leak rates.

Air management for fuel cell systems is a challenge because today's compressor technologies are not suitable for automotive fuel cell applications. In addition, thermal and water management for fuel cells are issues. Fuel cell operation at lower temperatures creates a small differential between the operating and ambient temperatures necessitating large heat exchangers and humidifiers. These components increase the cost and complexity of the system and use some of the power that is produced, reducing overall system efficiency.

Buses

Transit bus applications represent a promising early-to-mid-term market for fuel cell technology. Central fueling of transit bus fleets facilitates introduction of hydrogen fuel in this market, and less stringent cost, weight, and volume criteria make implementation of fuel cell propulsion systems less challenging in transit buses than in other transportation applications.

Fuel cell buses have been undergoing research, development, and deployment for decades.[4] PAFC and PEMFC have been the primary fuel cell technologies considered in pure and battery or ICE hybrid systems operating on hydrogen, methanol, and natural gas.

A recent fuel-cell bus demonstration has achieved >10,000 operating hours in real-world-service with the original cell stacks and no cell replacement.[5] Fuel cell bus power plants are offered with a 12,000-hour or 5-year warranty, including air, fuel, and water management systems. Remaining fuel cell durability issues are difficult to identify and understand through field data. Development and implementation of accelerated stress tests (ASTs) are needed to shorten the time required to address durability issues for all drive cycles and hybridization strategies.

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[3] K. Wipke, *et al.*, *Controlled Hydrogen Fleet and Infrastructure Analysis*, http://www.hydrogen.energy.gov/pdfs/review11/tv001_wipke_2011_o.pdf

[4] L. Eudy *et al.*, *Fuel Cell Buses in U.S. Transit Fleets: Summary of Experiences and Current Status*, http://www.nrel.gov/hydrogen/pdfs/41967.pdf

[5] UTC Power Press Release, dated August 10, 2011, http://www.utcpower.com/pressroom/pressreleases/utc-power-fuel-cell-system-sets-world-record-achieving-10000-hr-durability

Because balance-of-plant components, power electronics, and power plant integration issues cause more forced shutdowns than the fuel cell system does, development of fuel cell powered buses should be done at the overall system level. Of course, hybridization strategy has a major effect on system design and technical requirements.

Although fuel cell durability increases have been realized and costs have been reduced, efficiency, durability, and cost targets (manufacturing, capital, operations, and maintenance) have not been met. Initial capital cost is particularly important.

Stationary Power Systems

Stationary fuel cells can be used in a broad range of commercial, industrial, and residential applications and can supplement or even replace power from the electrical grid. These fuel cells can be multi-megawatt systems for large centralized power generation, small units (e.g. 1 kW) for backup power, or 1 kW–3 MW systems for homes, buildings, and distributed generation applications, including CHP systems. Because fuel cells can be grid-independent and offer both high reliability and low emissions, they are attractive for critical load applications.

The advantages of fuel cells for distributed power generation include: elimination of transmission and distribution losses, low emissions, increased reliability, and reduction in bottlenecks and peak demand on the electric grid. Fuel cells can also provide the very high efficiencies inherent in CHP installations, with the potential to use more than 80% of the fuel energy, compared to the 45% to 50% combined overall efficiency of using electricity from coal or natural gas plants and thermal energy from on-site natural-gas combustion. Other benefits include their nearly silent and vibration-free operation, ability to use the existing natural gas fuel supply as well as biogas sources such as wastewater treatment plants and landfill gas facilities, low operation and maintenance requirements, and excellent transient response and load following capability.

Even though the specific performance requirements differ from transportation applications, some of the technical challenges for stationary fuel cell systems are the same. For example, the overall cost of these fuel cell power systems must be competitive with conventional/incumbent technologies or offer enhanced capabilities. However, stationary and other fuel cell systems have an acceptable price point considerably higher than transportation systems.

Performance of fuel cells for stationary applications for more than 80,000 hours has been demonstrated in PAFC installations, but other fuel cell technologies require durability improvements to achieve 80,000 hours of reliable operation over the full range of external environmental conditions (-40° to 40°C).

The low operating temperature of PEM fuel cells limits the amount of waste heat that can be effectively used in CHP applications. Technologies need to be developed that will allow higher operating temperatures and/or more effective heat recovery systems. Improved system designs that will enable higher CHP efficiencies are also needed. In addition, technologies that allow the thermal energy rejected from stationary fuel cell systems to be utilized in heating and cooling systems need to be evaluated. Fuel flexible processing systems are needed that take advantage of opportunity fuels from waste processing or bio-derived fuels.

Medium-scale CHP / Distributed Generation (100 kW–3 MW modular)

Phosphoric acid (PAFC) and molten carbonate fuel cells (MCFC) are being commercialized because of their modularity, the quality of waste heat, and their demonstrated durability (PAFC >80,000 and MCFC >40,000 hours). As the technology further matures, SOFCs are also making headway in this application.

The initial cost for PAFCs (capital equipment, manufacturing processes, installation, and warranty) needs to be reduced. Challenges to reducing these costs include increasing catalyst performance by reducing or eliminating anion adsorption and developing more durable and stable catalysts and catalyst support materials that enable stable operation over the extended life of the PAFC and PBI-type fuel cells. Development of lower cost materials for the cell stack (replacement of Teflon in the cell stack) and BOP is also a challenge.

Durability of MCFCs needs to be increased. More robust cathode materials must be developed to decrease the rate of cathode dissolution. Development of new electrolyte compositions to limit electrolyte loss, as well as new electrolyte supports with more durable microstructure, is needed to prevent early stack failure. Common technical challenges for MCFC and PAFC are reducing the system conditioning time and developing low-cost manufacturing methods.

SOFC stacks have demonstrated durability in excess of 25,000 hours. The high operating temperature can lead to compatibility and reactivity issues among the various cell and stack components, especially over extended operating times. The ability of the stack to survive repeated thermal cycling and the relatively long start up times are additional technical challenges. Lowering the operating temperature of SOFCs further will help resolve these challenges. R&D work funded by the Office of Fossil Energy is being leveraged to develop SOFCs for medium-scaled applications.

Micro Combined Heat and Power (1–10 kW)

High-temperature fuel cells, including (but not limited to) solid oxide and PBI-type fuel cells, are a key focus area of DOE's R&D activities for small scale stationary power generation because of their fuel flexibility, high efficiency, and potential for use in CHP applications. It is anticipated that residential CHP fuel cells will use primarily natural gas fuel to provide electrical power, heating, and hot water. Challenges for micro CHP applications include decreasing cost and increasing durability and cell component stability. The technical issues for PBI-type fuel cells and SOFC systems for micro CHP applications are similar to those described in the Medium-scale CHP/Distributed Generation section above.

Fuel Processing

Stationary/distributed generation systems often include a fuel processing sub-system to convert the raw fuel to clean hydrogen or synthesis gas for fuel cell consumption. Raw fuels include natural gas, LPG, and renewable fuels such as digester gas, landfill gas, biodiesel, alcohols, etc. These fuels need varying degrees of treatment depending on the initial composition and heating value and the type of fuel cell used. Military logistic fuels such as JP8 are not included here, but are covered by Department of Defense funding. The impurities cover a very broad range of deleterious compounds which vary depending on the raw fuel source type and geographical origin and include various sulfur-containing compounds, siloxanes, ammonia, and others.

The fuel processing sub-system can include but is not limited to the following components or process steps: raw fuel pre-treatment (e.g., desulfurization); reactors to convert the raw fuel into a hydrogen-rich stream (e.g., reformers); reactors to reduce carbon monoxide and increase hydrogen content (e.g., water-gas-shift); and separators and/or polishers to enrich and further clean the hydrogen stream (e.g., pressure-swing adsorption (PSA) and preferential oxidation (PROX)). Higher temperature fuel cells require less processing and therefore fewer components than listed above.

Significant issues for the fuel processing system are: fuel flexibility, durability, cost, fuel clean-up, impurity tolerance, thermal and physical integration, and cold start-up time. Current fuel processing systems need improved efficiency and reduced costs. Fuel processors can be improved by thermally and/or physically integrating the functions of the fuel processing sub-systems and by developing multi-functional catalysts to facilitate multiple reactions in the same reactor. Thermal and/or physical integration of the reactors can reduce cost and increase efficiency by eliminating reactor hardware, piping, and possibly sensors and controls. Multi-functional catalysts also increase efficiency and reduce cost by system simplification and component elimination. DOE will investigate combining sub-system functions into single reactors or closely integrating the thermal loads of the sub-systems.

A broad spectrum of deleterious compounds is found in the raw fuels (e.g., sulfur-containing compounds, siloxanes, and ammonia). These compounds may have adverse effects not only on the fuel cell but also on the fuel processing system. Specifically, but not exclusively, even the low levels of sulfur in natural gas could potentially have a poisoning effect on certain fuel processor catalysts and adversely affect system durability. Sulfur tolerance requirements are dependent on the type and quantity of sulfur species (e.g., hydrogen sulfide, mercaptans, or substituted dibenzothiophenes) in the fuel and the fuel processing sub-system under consideration, (e.g., steam reforming catalyst, autothermal reforming catalyst, and water gas shift catalyst). Therefore, some degree of clean-up may be required upstream of the fuel processor as well as immediately before the fuel cell and possibly between fuel processor sub-systems.

DOE will investigate broad-spectrum clean-up technologies to remove the impurities regardless of raw fuel composition and purity. Technologies are not restricted to sulfur and may be for upstream or intermediate impurity removal provided that the assumed composition and condition of the fuel stream entering the sub-system is realistic and supported by data.

DOE will investigate development of catalysts and hardware capable of generating fuel cell-grade hydrogen or reformate from a variety of renewable fuel sources (e.g., digester gas, landfill gas, biodiesel, and alcohols). In addition, research will be performed to develop an entire fuel processor system capable of taking in raw fuel at its inlet and delivering fuel cell quality hydrogen or reformate at the fuel processor outlet (the fuel cell inlet) that contains $\geq$ 1 g/min hydrogen.

Reversible Fuel/Flow Cells

Reversible fuel/flow cells, sometimes referred to as flow batteries, are of interest for energy storage applications, and hold promise as an enabler for implementation of intermittent renewable energy technologies. This technology allows for storage of excess energy during periods of low electricity demand which can then be used during times of peak demand. Some types of fuel/flow cells, such as hydrogen/halogen cells, are closely related to conventional fuel cells. Reversible fuel cells are capable of operating in both power production (fuel cell) and energy storage (electrolysis) modes. Advantages of reversible fuel/flow cell technology include high round-trip efficiency (60-90%), decoupled power and energy capacity, long cycle life, low self-discharge rate, and reliable and stable performance. Cost and durability are barriers to implementation of reversible fuel/flow cells, but leveraging of fuel cell R&D in the areas of membranes, electro catalysts, electrode architectures, bipolar plates, and diffusion media would result in cost reduction and durability improvements.

Auxiliary Power Units

Fuel cells can provide clean, efficient auxiliary power for trucks, recreational vehicles, marine vessels (yachts, commercial ships), airplanes, locomotives, and similar applications that have significant auxiliary power demands. In many of these applications, the primary motive-power engines are often kept running solely for auxiliary loads. This practice is inefficient, resulting in significant additional fuel consumption and emissions. Fuel cell APUs are being considered for terrestrial, aviation, and maritime applications. This section addresses only long-haul truck hotel applications. APUs for heavy duty vehicles represent a potential early market opportunity for fuel cell deployment. Significant fuel savings, as well as reduction in CO_2 and criteria pollutant emissions, may be achieved through more efficient fuel conversion and reduction in engine idling time. For the approximately 500,000 long-haul Class 7 and Class 8 trucks in the United States, emissions during overnight idling have been estimated to be 10.9 million tons of CO_2 and 190,000 tons of NO_X annually.[6] The use of auxiliary power units (APUs) for Class 7–8 heavy trucks to avoid overnight idling of diesel engines could save up to 280 million gallons of fuel per year and avoid more than 92,000 tons of NO_X emissions.[7] Further, emissions from idling and auxiliary power are likely to be the subject of increasing regulations in the future. Idling restrictions for heavy-duty highway vehicles have already been enacted in 28 states.[8] In 2008, the EPA adopted new requirements for limiting idling emissions from locomotives.

The main challenges for this application are the cost and the combination of the transient operation of the APU, the need to utilize the fuel onboard the vehicle (diesel) without adding additional requirements (i.e. no additional water for reforming), and the harsh environment (shock and vibrations on the vehicle). In addition, the APU unit must fit in the available space and not add unnecessary weight to the vehicle. Fuel cells for auxiliary power unit (APU) applications need to

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[6] Nicholas Lutsey, Christie-Joy Brodrick & Timothy Lipman, "Analysis of Potential Fuel Consumption and Emissions Reduction from Fuel Cell Auxiliary Power Units (APUs) in Long Haul Trucks," Elsevier Science Direct, Energy 32, September 2005. http://www.sciencedirect.com/science/article/pii/S0360544207001016

[7] Preferences Survey, American Transportation Research Institute (prepared for New York State Energy Research and Development Authority), February 2006. → http://www.atri-online.org/research/results/Idle%20Survey%20One%20Page%20Summary.pdf

[8] ATRI Compendium of Idling Regulations, http://www.atri-online.org/research/idling/ATRI_Idling_Compendium.pdf

have increased specific power and power density to meet packaging requirements for heavy-duty trucks.

Portable Power Systems

Fuel cell systems with higher energy density, power density, and specific power than existing technologies for applications less than 250 W are one focus area of DOE's R&D activities. It is anticipated that portable power applications, including battery chargers, consumer electronics, handheld terminals, unattended security devices, notebook PCs, and emergency response mobile communications, will provide an early market for fuel cell technologies. A high-energy density alternative to existing technologies is required to fill the increasing gap between energy demand and energy supply for these applications. Challenges for fuel cells for portable power include reducing cost (mainly by reducing catalyst loading), increasing efficiency (by reducing fuel crossover and increasing catalyst selectivity), and reducing the size of the system BOP.

Portable power R&D needs include development of electrodes with higher activity and selectivity, reduction of methanol crossover, and decrease in system volume and weight. Total life cycle efficiency improvement would have a positive impact on emissions reduction during operation and disposal. Flexible fuel capability (e.g., ethanol, butane), based on renewable fuels is attractive.

Backup Power and Material Handling Equipment

Backup power installations are recognized as one of the leading applications for fuel cells. Therefore, the Market Transformation Team is leading the DOE support of this application and no specific issues are being addressed in this section. It is assumed that fuel cell and system advances in the other applications will have a positive impact on back-up power fuel cell technology. Performance targets for these applications are being reached, including from demonstration projects supported by the American Recovery and Reinvestment Act of 2009.

Material handling equipment, including forklifts and yard dogs (tractor trailer type trucks used for moving freight trailers within a facility), are a leading application for fuel cells. Therefore, the Market Transformation Team is leading the DOE support of this application through deployments, and no specific issues are being addressed in this section. Fuel cell and system advances in the other applications will have a positive impact on material handling fuel cell technology.

Technical Targets

Tables 3.4.3 and 3.4.4 list the DOE technical targets specifically for integrated PEM fuel cell power systems and fuel cell stacks operating on direct hydrogen for transportation applications. These targets have been developed with input from the U.S. DRIVE Partnership, which includes automotive and energy companies, specifically the Fuel Cell Technical Team. Tables 3.4.5 through 3.4.6 list the DOE technical targets for stationary applications. These targets have been developed with input from developers of stationary fuel cell power systems.

Tables 3.4.7 and 3.4.8 list the DOE technical targets for portable power and auxiliary power applications, respectively. Tables 3.4.9 through 3.4.11 list DOE technical targets for automotive and stationary fuel cell systems humidifiers and automotive compressor/expander units. Tables 3.4.12

through 3.4.15 list DOE technical targets for PEM fuel cell components: membranes, electrodes / catalysts, membrane electrode assemblies and bipolar plates. These tables assist component developers in evaluating progress without testing full systems.

All targets must be achieved simultaneously; however, the status values are not necessarily from a single system.

Table 3.4.3 Technical Targets for Automotive Applications: 80-kW$_e$ (net) Integrated Transportation Fuel Cell Power Systems Operating on Direct Hydrogen [a, k]

Characteristic	Units	2011 Status	2020 Targets
Energy efficiency[b] @ 25% of rated power	%	59	60
Power density	W / L	400[c]	850
Specific power	W / kg	400[c]	650
Cost[d]	\$ / kW$_e$	49[e]	40
Cold start-up time to 50% of rated power			
@–20°C ambient temp	seconds	20[f]	30
@+20°C ambient temp	seconds	<10	5
Start up and shut down energy[g]			
from -20°C ambient temp	MJ	7.5	5
from +20°C ambient temp	MJ	-	1
Durability in automotive drive cycle	hours	2,500[h]	5,000[i]
Assisted start from low temperatures[j]	°C	–	-40
Unassisted start from low temperatures[j]	°C	-20[f]	-30

a Targets exclude hydrogen storage, power electronics and electric drive.

b Ratio of DC output energy to the lower heating value of the input fuel (hydrogen). Peak efficiency occurs at about 25% rated power.

c Based on input from the Technology Validation activity.

d Cost projected to high-volume production (500,000 systems per year).

e The projected cost status is from a 2011 DTI study and will be periodically updated. The status is based on an analysis of state-of-the-art components that have been developed and demonstrated primarily through the DOE Program at the laboratory scale. Additional efforts would be needed for integration of components into a complete automotive system that meets durability requirements in real-world conditions.

f Based on average of status values reported at 2010 SAE World Congress. These systems do not necessarily meet other system-level targets.

g H_2 fuel energy (Lower Heating Value) to include the fuel energy required to account for the electrical energy consumed from cold start.

h Projected time to 10% voltage degradation from the Technology Validation activity.

i Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/guest/view_team.php?teams_id=17), Table 6, <10% drop in rated power after test.

j 8-hour soak at stated temperature must not impact subsequent achievement of targets.

k Details in this table are being revised to match recent changes in the high level cost target.

Table 3.4.4 Technical Targets: 80-kW$_e$ (net) Transportation Fuel Cell Stacks Operating on Direct Hydrogen[a, j]

Characteristic	Units	2011 Status	2020 Targets
Stack power density[b]	W / L	2,200[c]	2,500
Stack specific power	W / kg	1,200[c]	2,000
Stack efficiency[d] @ 25% of rated power	%	65	65
Cost[e]	$ / kW$_e$	22[f]	15
Durability with cycling	hours	2,500[g]	5,000[h]
$Q/\Delta T_i$[i]	kW/ºC	–	1.45

a Excludes hydrogen storage, power electronics, electric drive and fuel cell ancillaries: thermal, water and air management systems.

b Power refers to net power (i.e., stack power minus auxiliary power). Volume is "box" volume, including dead space.

c Average of data from selected proprietary and public sources.

d Ratio of output DC energy to lower heating value of hydrogen fuel stream. Peak efficiency occurs at about 25% rated power.

e Cost projected to high-volume production (500,000 stacks per year).

f Status is from 2011 DTI study and will be periodically updated.

g Projected time to 10% voltage degradation from the Technology Validation activity.

h Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/commands/files_download.php?files_id=267), Table 6, <10% drop in rated power after test.

i $Q/\Delta T_i$ = [Stack power (90kW) x (1.25V - Voltage at Rated Power) / (Voltage at Rated Power)] / [(Stack Coolant out temp (°C) - Ambient temp (40°C)] Target assumes 90kW stack gross power required for 80 kW net power, and is to be measured using the polarization curve protocol in Table 5 of the U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/commands/files_download.php?files_id=267).

j Details in this table are being revised to match recent changes in the high level cost target.

Table 3.4.5 Technical Targets: 1–10 kW_e Residential Combined Heat and Power and Distributed Generation Fuel Cell Systems Operating on Natural Gas[a]			
Characteristic	**2011 Status**	**2015 Targets**	**2020 Targets**
Electrical efficiency at rated power[b]	34-40%	42.5%	>45% [c]
CHP energy efficiency[d]	80-90%	87.5%	90%
Equipment cost[e], 2-kW_{avg}[f] system	NA	$1,200/$kW_{avg}$	$1,000/$kW_{avg}$
Equipment cost[e], 5-kW_{avg} system	$2,300 - $4,000/kW[g]	$1,700/$kW_{avg}$	$1,500/$kW_{avg}$
Equipment cost[e], 10-kW_{avg} system	NA	$1,900/$kW_{avg}$	$1,700/$kW_{avg}$
Transient response (10 - 90% rated power)	5 min	3 min	2 min
Start-up time from 20°C ambient temperature	<30 min	30 min	20 min
Degradation with cycling[h]	<2%/1,000 h	0.5%/1,000 h	0.3%/1,000 h
Operating lifetime[i]	12,000 h	40,000 h	60,000 h
System availability[j]	97%	98%	99%

a Pipeline natural gas delivered at typical residential distribution line pressures.
b Regulated AC net/LHV of fuel.
c Higher electrical efficiencies (e.g. 60% using SOFC) are preferred for non-CHP applications.
d Ratio of regulated AC net output energy plus recovered thermal energy to the LHV of the input fuel. For inclusion in CHP energy efficiency calculation, heat must be available at a temperature sufficiently high to be useful in space and water heating applications. Provision of heat at 80°C or higher is recommended.
e Complete system, including all necessary components to convert natural gas to electricity suitable for grid connection, and heat exchangers and other equipment for heat rejection to conventional water heater, and/or hydronic or forced air heating system. Includes all applicable tax and markup. Based on projection to high-volume production (50,000 units per year).
f kW_{avg} is the average output (AC) electric power delivered over the life of system while unit is running.
g Strategic Analysis, Inc. preliminary 2011 cost assessment of stationary PEM system, range represents manufacturing volumes of 100 to 50,000 units per year.
h Durability testing should include effects of transient operation, startup, and shutdown.
i Time until >20% net power degradation.
j Percentage of time the system is available for operation under realistic operating conditions and load profile. Unavailable time includes time for scheduled maintenance.

Table 3.4.6 Technical Targets[a]: 100 kW–3 MW Combined Heat and Power and Distributed Generation Fuel Cell Systems Operating on Natural Gas[b]

Characteristic	2011 Status[c]	2015 Targets	2020 Targets
Electrical efficiency at rated power[d]	42-47%	45%	>50%[e]
CHP energy efficiency[f]	70-90%	87.5%	90%
Equipment cost, natural gas	\$2,500-\$4,500/kW[g]	\$2,300/kW[h]	\$1,000/kW[h]
Installed cost, natural gas	\$3,500-\$5,500/kW[g]	\$3,000/kW[h]	\$1,500/kW[h]
Equipment cost, biogas	\$4,500-\$6,500/kW[g]	\$3,200/kW[h]	\$1,400/kW[h]
Installed cost, biogas	\$6,000-\$8,000/kW[g]	\$4,100/kW[h]	\$2,100/kW[h]
Number of planned/forced outages over lifetime	50	50	40
Operating lifetime[i]	40,000–80,000 h	50,000 h	80,000 h
System availability[j]	95%	98%	99%

a Includes fuel processor, stack and ancillaries.

b Pipeline natural gas delivered at typical residential distribution line pressures.

c Status varies by technology.

d Ratio of regulated AC net output energy to the lower heating value (LHV) of the input fuel.

e Higher electrical efficiencies (e.g. 60% using SOFC) are preferred for non-CHP applications.

f Ratio of regulated AC net output energy plus recovered thermal energy to the LHV of the input fuel. For inclusion in CHP energy efficiency calculation, heat must be available at a temperature sufficiently high to be useful in space and water heating applications. Provision of heat at 80°C or higher is recommended.

g Current production volume (~30 MW per year).

h Includes projected cost advantage of high-volume production (totaling 100 MW per year).

i Time until >10% net power degradation.

j Percentage of time the system is available for operation under realistic operating conditions and load profile. Unavailable time includes time for scheduled maintenance.

Table 3.4.7.a Technical Targets: Portable Power Fuel Cell Systems (<2 Watt)[a]				
Characteristic	Units	2011 Status	2013 Targets	2015 Targets
Specific power[b]	W/kg	5	8	10
Power density[b]	W/L	7	10	13
Specific energy[b,c]	Wh/kg	110	200	230
Energy density[b,c]	Wh/L	150	250	300
Cost[d]	$/system	150	130	70
Durability[e,f]	hours	1,500	3,000	5,000
Mean time between failures[f,g]	hours	500	1,500	5,000

Table 3.4.7.b Technical Targets: Portable Power Fuel Cell Systems (10-50 Watts)[a]				
Characteristic	Units	2011 Status	2013 Targets	2015 Targets
Specific power[b]	W/kg	15	30	45
Power density[b]	W/L	20	35	55
Specific energy[b,c]	Wh/kg	150	430	650
Energy density[b,c]	Wh/L	200	500	800
Cost[d]	$/W	15	10	7
Durability[e,f]	hours	1,500	3,000	5,000
Mean time between failures[f,g]	hours	500	1,500	5,000

Table 3.4.7.c Technical Targets: Portable Power Fuel Cell Systems (100-250 Watts)[a]				
Characteristic	Units	2011 Status	2013 Targets	2015 Targets
Specific power[b]	W/kg	25	40	50
Power density[b]	W/L	30	50	70
Specific energy[b,c]	Wh/kg	250	440	640
Energy density[b,c]	Wh/L	300	550	900
Cost[d]	$/W	15	10	5
Durability[e,f]	hours	2,000	3,000	5,000
Mean time between failures[f,g]	hours	500	1,500	5,000

a These targets are technology neutral and make no assumption about the type of fuel cell technology or type of fuel used. In addition to meeting these targets, portable power fuel cells are expected to operate safely, providing power without exposing users to hazardous or unpleasant emissions, high temperatures, or objectionable levels of noise. Portable power fuel cells are also expected to be compatible with the requirements of portable electronic devices, including operation under a range of ambient temperature, humidity, and pressure conditions, and exposure to freezing conditions, vibration, and dust. They should be capable of repeatedly turning off and on, and should have turndown capabilities required to match the dynamic power needs of the device. For widespread adoption, portable power fuel cell systems should minimize lifecycle environmental impact through the use of reusable fuel cartridges, recyclable components, and low-impact manufacturing techniques.

b This is based on rated net power of the total fuel cell system, including fuel tank, fuel, and any hybridization batteries. In the case of fuel cells embedded in other devices, only device components required for power generation, power conditioning, and energy storage are included. Fuel capacity is not specified, but the same quantity of fuel must be used in calculation of specific power, power density, specific energy, and energy density.

c Efficiency of 30% in 2013 and 35% in 2015 is recommended to enable high specific energy and energy density.

d Cost includes material and labor costs required to manufacture the fuel cell system and any required auxiliaries (e.g., refueling devices). Cost is defined at production rates of 50,000, 25,000 and 10,000 units per year for <2, 10–50, and 100–500 W units, respectively.

e Durability is defined as the time until the system rated power degrades by 20%, though for some applications higher or lower levels of power degradation may be acceptable.

f Testing should be performed using an operating cycle that is realistic and appropriate for the target application, including effects from transient operation, startup and shutdown, and off-line degradation.

g Mean Time Between Failures (MTBF) includes failures of any system components that render the system inoperable without maintenance.

Table 3.4.8 Technical Targets: Fuel Cell Auxiliary Power Units (1 to 10 kW_e) Operating on Ultra-low Sulfur Diesel Fuel)

Characteristic	2011 Status	2013 Targets	2015 Targets	2020 Targets
Electrical efficiency at rated power[a]	25%	30%	35%	40%
Power density	17 W/L	30 W/L	35 W/L	40 W/L
Specific power	20 W/kg	35 W/kg	40 W/kg	45 W/kg
Factory cost, stack plus required BOP[b]	$750/kW[c]	$700/kW	$600/kW	$500/kW
Factory cost, system[d]	$2,000/kW	$1,400/kW	$1,200/kW	$1,000/kW
Transient response (10 to 90% rated power)	5 min	4 min	3 min	2 min
Start-up time from:				
20 °C	50 min	45 min	45 min	30 min
Standby conditions[e]	50 min	20 min	10 min	5 min
Degradation with cycling[f]	2.6%/1,000 h	2%/1,000 h	1.3%/1,000 h	1%/1,000 h
Operating lifetime[f, g]	3,000 h	10,000 h	15,000 h	20,000 h
System availability[h]	97%	97.5%	98%	99%

a Regulated DC net/LHV of fuel.

b Cost includes materials and labor costs to produce stack, plus any balance of plant necessary for stack operation. Cost defined at 50,000 unit/year production of a 5 kW system. Today's low-volume cost is expected to be higher than quoted status. Allowable cost is expected to be higher than the target for systems with rated power below 5 kW, and lower than the target for systems with rated power above 5 kW.

c Available cost status is that of a fuel cell stack only.

d Cost includes materials and labor costs to produce system. Cost defined at 50,000 unit/year production of a 5 kW system. Today's low-volume cost is expected to be higher than quoted status. Allowable cost is expected to be higher than the target for systems with rated power below 5 kW, and lower than the target for systems with rated power above 5 kW.

e Standby conditions may be at or above ambient temperature depending on operating protocol.

f Durability testing should include, at minimum, daily cycles to stand-by condition, and weekly cycles to full off condition (ambient temperature). The system should be able to meet durability criteria during and after exposure to vibration associated with transportation and highway operation, and during operation in a range of ambient temperature from -40 to 50 °C, a range of ambient relative humidity from 5% to 100%, and in dust levels up to 2 mg/m^3.

g Time until >20% net power degradation.

h Percentage of time the system is available for operation under realistic operating conditions and load profile. Scheduled maintenance does not count against system availability.

Table 3.4.9 Technical Targets: Cathode Humidification System for 80-kW$_e$ Transportation Fuel Cell Systems Operating on Direct Hydrogen[d]

Characteristic	Units	2020 Targets
Maximum operating temperature	°C	>95
Maximum pressure differential between wet and dry sides	kPa	75
Maximum pressure drop at full flow (each side)	kPa	3.5
Water transfer at full flow[a]	$g\ s^{-1}$	5
Durability[b]	h	5,000
Maximum air leakage at full flow	%	0.5
Volume	L	5
Weight	kg	5
Cost[c]	$	100

a Dry air in: 3000 SLPM dry gas flow, 183 kPa (absolute), 80°C, 0% RH. Wet air in: 2600 SLPM dry gas flow, 160 kPa (absolute), 80°C, 85% RH.

b Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/guest/view_team.php?teams_id=17), <10% drop in water transfer at full flow.

c Cost projected to high-volume production (500,000 systems per year).

d Details in this table are being revised to match recent changes in the high level cost target.

Table 3.4.10 Technical Targets: Cathode Humidifier Membrane for 80-kW$_e$ Transportation Fuel Cell Systems Operating on Direct Hydrogen[d]

Characteristic	Units	2020 Targets
Maximum operating temperature	°C	>95
Maximum pressure differential between wet and dry sides	kPa	75
Water transfer flux at full flow[a]	$g\ min^{-1} cm^{-2}$	0.025
Durability[b]	h	5,000
Cost[c]	$\$/m^2$	10

a Dry air in: 0.23 SLPM/cm^2 dry gas flow, 183 kPa (absolute), 80°C, 0% RH. Wet air in: 0.20 SLPM/cm^2 dry gas flow, 160 kPa (absolute), 80°C, 85% RH.

b Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/guest/view_team.php?teams_id=17), <10% drop in water transfer at full flow.

c Cost projected to high-volume production (500,000 systems per year).

d Details in this table are being revised to match recent changes in the high level cost target.

Table 3.4.11 Technical Targets: Air Compression System for 80-kW_e Transportation Fuel Cell Systems Operating on Direct Hydrogen[h]			
Characteristic	**Units**	**2011 Status**	**2020 Targets**
Input power[a] at full flow[b] (with / without expander)	kW_e	11.0 / 17.3	8 / 14
Combined motor and motor controller efficiency at full flow[b]	%	80	90
Compressor / expander efficiency at full flow[b]	%	71 / 73	75 / 80
Input power at 25% flow[c] (with / without expander)	kW_e	2.3 / 3.3	1.0 / 2.0
Combined motor / motor controller efficiency at 25% flow[c]	%	57	80
Compressor / expander efficiency at 25% flow[c]	%	62 / 64	65 / 70
Input power at idle[d] (with / without expander)	W_e	600 / 765	200 / 200
Combined motor / motor controller efficiency at idle[d]	%	35	70
Compressor / expander efficiency at idle[d]	%	61 / 59	60 / 60
Durability	h	–	5,000
Number of startup and shutdown cycles		–	250,000
Turndown ratio (max/min flow rate)		20	20
Noise at maximum flow	dBA at 1 m	–	65
Transient time for 10-90% of maximum flow	s	1	1
System volume[e]	L	15	15
System weight[e]	kg	22	15
System cost[f]	$	960[g]	500

[a] Electrical input power to motor controller when bench testing fully integrated system. Fully integrated system includes control system electronics, air filter, and any additional air flow that may be used for cooling.

[b] Compressor: 92 g/s flow rate, 2.5 bar (absolute) discharge pressure; 40°C, 25% RH inlet conditions. Expander: 88 g/s flow rate, 2.2 bar (absolute) inlet pressure, 70°C, 100% RH inlet conditions.

[c] Compressor: 23 g/s flow rate, minimum 1.5 bar (absolute) discharge pressure; 40°C, 25% RH inlet conditions. Expander: 23 g/s flow rate, 1.4 bar (absolute) inlet pressure, 70°C, 100% RH inlet conditions.

[d] Compressor: 4.6 g/s flow rate, minimum 1.2 bar (absolute) discharge pressure; 40°C, 25% RH inlet conditions. Expander: 4.6 g/s flow rate, < compressor discharge pressure, 70°C, 20% RH inlet conditions.

[e] Weight and volume include the motor, motor controller.

[f] Cost target based on a manufacturing volume of 500,000 units per year.

[g] DTI cost model of the Honeywell 100,000 rpm machine, 2.5 bar (absolute), 92 g/s, dry air, 40°C: $960 including markup. TIAX 2009 estimate of Honeywell technology (compressor, expander, motor, motor controller) presented at 2010 Annual Merit Review and Peer Evaluation: $790 including 15% markup.

[h] Details in this table are being revised to match recent changes in the high level cost target.

Table 3.4.12 Technical Targets: Membranes for Transportation Applications[e]			
Characteristic	**Units**	**2011 Status** [a]	**2020 Targets**
Maximum oxygen cross-over[b]	mA / cm^2	<1	2
Maximum hydrogen cross-over[b]	mA / cm^2	<1.8	2
Area specific proton resistance at:			
Maximum operating temperature and water partial pressures from 40-80 kPa	Ohm cm^2	0.023 (40kPa) 0.012 (80kPa)	0.02
80°C and water partial pressures from 25-45 kPa	Ohm cm^2	0.017 (25kPa) 0.006 (44kPa)	0.02
30°C and water partial pressures up to 4 kPa	Ohm cm^2	0.02 (3.8 kPa)	0.03
-20°C	Ohm cm^2	0.1	0.2
Operating temperature	°C	<120	≤120
Minimum electrical resistance	Ohm cm^2	–	1,000
Cost[c]	$ / m^2	–	20
Durability[d]			
Mechanical	Cycles with <10 sccm crossover	>20,000	20,000
Chemical	hours	>2,300	>500

a Status represents 3M PFIA membrane (S. Hamrock, U.S. Department of Energy Hydrogen and Fuel Cells Program 2011 Annual Progress Report, (http://www.hydrogen.energy.gov/pdfs/progress11/v_c_1_hamrock_2011.pdf).

b Tested in MEA at 1 atm O_2 or H_2 at nominal stack operating temperature, humidified gases at 0.5 V DC.

c Costs projected to high-volume production (500,000 stacks per year).

d Protocol for mechanical stability is to cycle a 25-50 cm^2 MEA at 80°C and ambient pressure between 0% RH (2 min) and 90°C dew point (2 min) with air flow of 2 SLPM on both sides. Protocol for chemical stability test is to hold a 25-50 cm^2 MEA at OCV, 90°C, with H_2/air stoichs of 10/10 at 0.2 A/cm^2 equivalent flow, inlet pressure 150 kPa, and relative humidity of 30% on both anode and cathode. Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/commands/files_download.php?files_id=267), MEA Chemical Stability and Metrics (Table 3) and Membrane Mechanical Cycle and Metrics (Table 4).

e Details in this table are being revised to match recent changes in the high level cost target.

Table 3.4.13 Technical Targets: Electrocatalysts for Transportation Applications[h]			
Characteristic	**Units**	**2011 Status**	**2020 Targets**
Platinum group metal total content (both electrodes)[a]	g / kW (rated)	0.19[b]	0.125
Platinum group metal (pgm) total loading[a]	mg PGM / cm^2 electrode area	0.15[b]	0.125
Loss in initial catalytic activity[c]	% mass activity loss	48[b]	<40
Electro catalyst support stability[d]	% mass activity loss	<10[b]	<10
Mass activity[e]	A / mg Pt @ 900 $mV_{iR\text{-}free}$	0.24[b]	0.44
Non-Pt catalyst activity per volume of supported catalyst[e, f]	A / cm^3 @ 800 $mV_{IR\text{-}free}$	60 (measured at 0.8 V)[g] 165 (extrapolated from >0.85 V)[g]	300

a PGM content and loading targets may have to be lower to achieve system cost targets.

b M. Debe, U.S. Department of Energy Hydrogen and Fuel Cells Program 2011 Annual Merit Review Proceedings, May, 2011, (http://www.hydrogen.energy.gov/pdfs/review11/fc001_debe_2011_o.pdf)

c Durability measured in a 25-50 cm^2 MEA during triangle sweep cycles at 50 mV/s between 0.6 V and 1.0 V at 80°C, atmospheric pressure, 100% relative humidity, H_2 at 200 sccm and N_2 at 75 sccm for a 50 cm^2 cell. Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/commands/files_download.php?files_id=267), Electrocatalyst Cycle and Metrics (Table 1). Activity loss is based on loss of mass activity, using initial catalyst mass, at end of test.

d Durability measured in a 25-50 cm^2 MEA during a hold at 1.2 V in H_2/N_2 at 80°C, 150 kPa absolute, 100% relative humidity. Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/commands/files_download.php?files_id=267), Catalyst Support Cycle and Metrics (Table 2). Activity loss is based on loss of mass activity, using initial catalyst mass, at end of test.

e Test at 80°C H_2/O_2 in MEA; fully humidified with total outlet pressure of 150 KPa; anode stoichiometry 2; cathode stoichiometry 9.5 (as per Gasteiger et al. Applied Catalysis B: Environmental, 56 (2005) 9-35).

f Volume = active area * catalyst layer thickness.

g P. Zelenay, H. Chung, C. Johnston, N. Mack, M. Nelson, P. Turner, G. Wu, FY 2011 Progress Report for the DOE Hydrogen Program, p. 816, U.S. Department of Energy, Feb. 2011, DOE/GO-102011-3178.

h Details in this table are being revised to match recent changes in the high level cost target.

Table 3.4.14 Technical Targets: Membrane Electrode Assemblies[i]			
Characteristic	Units	2011 Status [a]	2020 Targets
$Q/\Delta T_i$[b]	kW/°C	–	1.45
Cost[c]	$ / kW	13 (without frame and gasket) 16 (including frame and gasket)[d]	7
Durability with cycling	hours	9,000[e]	5,000[f]
Performance @ 0.8 V[g]	mA / cm^2	160	300
Performance @ rated power	mW / cm^2	845[h]	1,000

a First year for which status was available.

b $Q/\Delta T_i$ = [Stack power (90kW) x (1.25 V - Voltage at Rated Power) / (Voltage at Rated Power)] / [Stack Coolant out temp (°C) - Ambient temp (40°C)]. Target assumes 90kW stack gross power required for 80 kW net power, and is to be measured using the polarization curve protocol in Table 5 of the U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/commands/files_download.php?files_id=267).

c Costs projected to high volume production (500,000 stacks per year).

d From DTI 2011 analysis (http://www.hydrogen.energy.gov/pdfs/review11/fc018_james_2011_o.pdf). Includes projected material and processing cost of membranes, catalysts, and diffusion media.

e From 3M (http://www.hydrogen.energy.gov/pdfs/review11/fc001_debe_2011_o.pdf). Membrane lifetime during 3M MEA cycling test was 9,000 hours, but performance degradation was not measured. Not all targets have been achieved by this MEA, nor were all status numbers reported derived from this MEA.

f Need to meet or exceed at temperatures of 80°C up to peak temperature. Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols, Tables 5 and 6 (http://www.uscar.org/commands/files_download.php?files_id=267, <10% drop in rated power after test.

g 0.8 V represents approximately ¼ rated power.

h Mark Debe, U.S. Department of Energy Hydrogen and Fuel Cells Program 2011 Annual Merit Review Proceedings, May, 2011, http://www.hydrogen.energy.gov/pdfs/review11/fc001_debe_2011_o.pdf.

i Details in this table are being revised to match recent changes in the high level cost target.

Table 3.4.15 Technical Targets: Bipolar Plates[j]			
Characteristic	**Units**	**2011 Status [a]**	**2020 Targets**
Cost[b]	\$ / kW	5-10	3
Plate H_2 permeation coefficient[c]	Std $cm^3/(sec\ cm^2 Pa)$ @ 80°C, 3 atm 100% RH	N/A	$<1.3 \times 10^{-14}$ [d]
Corrosion, anode[e]	$\mu A / cm^2$	<1	<1
Corrosion, cathode[f]	$\mu A / cm^2$	<1	<1
Electrical conductivity	S / cm	>100	>100
Areal specific resistance[g]	$Ohm\text{-}cm^2$	0.03	0.01
Flexural strength[h]	MPa	>34 (carbon plate)	>25
Forming elongation[i]	%	20–40	40

[a] Status is based on information found in 2010 & 2011 Annual Progress Reports – project description write ups of TreadStone Technologies, Inc. and Oak Ridge National Laboratory.

[b] Costs projected to high volume production (500,000 stacks per year), assuming MEA meets performance target of 1000 mW/cm^2.

[c] Per the standard gas transport test (ASTM D1434).

[d] Blunk, *et al*, J. Power Sources 159 (2006) 533-542.

[e] pH 3 0.1ppm HF, 80°C, peak active current $<1 \times 10^{-6}$ A/cm^2 (potentiodynamic test at 0.1 mV/s, -0.4V to +0.6V (Ag/AgCl)), de-aerated with Ar purge.

[f] pH 3 0.1ppm HF, 80°C, passive current $<5 \times 10^{-8}$ A/cm^2 (potentiostatic test at +0.6V (Ag/AgCl) for >24h, aerated solution.

[g] Includes interfacial contact resistance (on as received and after potentiostatic test) measured both sides per Wang, *et al.* J. Power Sources 115 (2003) 243-251 at 200 psi (138 N/cm^2).

[h] ASTM-D 790-10 Standard Test method for flexural properties of unreinforced and reinforced plastics and electrical insulating materials.

[i] Per ASTM E8M-01 Standard Test Methods for Tension Testing of Metallic Materials.

[j] Details in this table are being revised to match recent changes in the high level cost target.

3.4.5 Technical Barriers

Of the many barriers discussed here, cost and durability present two of the most significant challenges to achieving clean, reliable, cost-effective fuel cell systems. While addressing cost and durability, fuel cell performance must meet or exceed that of competing technologies. Ultimately, operation of components and subsystems will be validated within the Technology Validation sub-program (see Section 3.6).

A. Durability

In the most demanding applications, realistic operating conditions include impurities in the fuel and air, starting and stopping, freezing and thawing, and humidity and load cycles that result in stresses on the chemical and mechanical stability of the fuel cell materials, components, and interfaces. Durability of PEMFC stacks, which must include tolerance to impurities and chemical and mechanical integrity, has not been established. Tolerance to air, fuel, and system-derived impurities (including the storage system) needs to be established. Sufficient durability of fuel cell systems operating over automotive drive cycles has not been demonstrated. Operation at low relative humidity (25–45 kPa water vapor at 80°C, or 40–80 kPa water vapor at maximum operating temperature), has not been demonstrated. Component degradation and failure mechanisms are not well understood, which makes development of effective mitigating strategies necessary.

Stationary fuel cells must achieve greater than 60,000 hours durability to compete against other distributed power generation systems and to allow for an acceptable return on investment to the end-user. The operating temperatures required for high temperature fuel cells place stringent durability requirements on materials and components, including the electrolyte, electrolyte support, and electrode. Improved durability under start-up and transient operation is also required for high temperature fuel cells. Durability of PBI-type fuel cells needs to be increased to that of conventional PAFC systems, for which established durability comes at a high cost. Research is also needed to understand failure mechanisms and develop mitigation strategies. Accelerated testing protocols need to be developed to enable projection of durability and to allow for timely iterations and improvements in the technology. State-of-the-art systems must also be benchmarked.

Regardless of application, system BOP component durability needs to be improved. The majority of fuel cell system failures and forced outages (~90% in automotive systems[9] and ~90% in micro CHP systems[10]) are the result of non-fuel cell stack BOP events.

B. Cost

For fuel cells and fuel cell systems to be commercially viable, significant reduction in cost is required. Materials and manufacturing costs for stack components need to be reduced. Low-cost,

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[9] Results from the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, CDP #64, http://www.nrel.gov/hydrogen/docs/cdp/cdp_64.ppt

[10] P. Mocoteguy, International Workshop on Degradation Issues of Fuel Cells, Sept. 19-21, 2007 Hersonessos, Crete, Greece

high-performance membranes, high-performance catalysts enabling ultra-low precious metal loading, and lower cost, lighter, corrosion-resistant bipolar plates are required to make fuel cell stacks competitive. PEMFCs, PBI-type fuel cells, and PAFCs suffer from the necessity of relatively high PGM loading. This is particularly important for stationary power applications, where the need for enhanced durability and reformate tolerance requires the use of high PGM loadings, which in the case of PAFCs accounts for 4 to 6% of the current installed costs of the power plant.[11] Furthermore, for automotive applications, the cost of electrocatalyst is projected to be the largest single component of the cost of a PEMFC system manufactured at high volume.[12] The use of PGM-free catalysts will further reduce the cost of MEAs. For high-temperature fuel cells, such as MCFCs and SOFCs, PGM-free materials are available, but research is required to lower stack component costs, such as for cells and interconnects, as well as for system BOP components required for high-temperature operation. As an example, the strong economic incentive to use traditional, low cost metals (e.g., ferritic stainless steels) for the interconnect is a driving force for the development of lower temperature SOFCs.

Balance-of-plant components and subsystems specifically designed for use in fuel cell systems need development in order to achieve cost targets. For automotive fuel cell systems, system BOP constitutes about half the cost of the system.[11] For stationary primary power applications, the relatively high cost of the fuel processor needs to be addressed. One of the most important issues, and one that is not specific to any fuel cell type, is the development of a cost-effective process and sub-system for removing contaminants, especially those found in renewable fuels, which would considerably reduce overall cost and allow for fuel flexibility. For high temperature fuel cells, some of the BOP components (e.g., heat exchangers) need to operate at elevated temperatures. The temperature limitations on other components (e.g., anode recycle blower) can negatively impact the overall system efficiency.

C. Performance

Fuel cell and fuel cell system performance and efficiency must meet or exceed that of competing technologies to allow for market penetration and the inherent environmental benefits of the technology.

<u>Cell Issues Affect Performance</u>

Improved cell performance is required to ensure lower cost and enhanced durability for the range of fuel cell technologies. For instance, poor cathode kinetics cause overpotentials of 0.4 V or greater in state-of-the-art PEM fuel cells operating under typical conditions. This overpotential represents a loss at the cathode of approximately one-third of the theoretically available energy from a fuel cell. Therefore, cathode R&D is needed to meet efficiency targets simultaneously with other targets. Mitigation of catalyst dissolution/degradation during operation of low-temperature and high-temperature fuel cells drives higher performance and leads to lower cost. Power densities, especially

[11] MCFC and PAFC R&D Workshop Summary report, U.S. Department of Energy, 2010. http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mcfc_pafc_workshop_summary.pdf

[12] Brian James – Directed Technologies, Inc. The 2010 U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting (AMR), Washington, DC."

at the higher voltages required for high-efficiency operation, are currently too low to meet cost and packaging targets. Higher power densities, across the technologies, could be achieved by increasing the ionic conductivity of the electrolyte and decreasing polarization losses of the electrodes. Novel electrolytes could achieve higher conductivities, but materials must meet operation requirements. Membrane performance under the extremes of automotive drive cycles for instance and the steady-state lifetime requirements for stationary applications have not been established. For low temperature fuel cells, conductivity under low humidity conditions needs to increase, and stable membrane performance at higher temperatures for both proton- and anion-conducting polymer electrolyte fuel cells needs to be achieved.

The chemical and electrical interface between the electrode and the electrolyte material can affect performance, with a poor interface resulting in higher electronic resistance and low utilization. Also, new electrolyte materials may require redesign of the electrode structure and interface to maintain performance. Interfacial contact resistance at the electrode/bipolar interface needs to be further reduced.

Stack Water Management Affects Performance

Effective management of the water produced in low-temperature fuel cells is needed to alleviate flooding and/or drying out of the membrane over the full operating temperature range. Ineffective water management leads to liquid-phase water blockage and mass-transport-limited performance or decreased proton conductivity as a result of dehumidification of the ionomer. Transportation and stationary fuel cells must be able to operate in environments where ambient temperatures fall below 0°C, a challenge for low-temperature fuel cells. R&D is needed to improve the designs of the gas diffusion layers, gas flow fields in bipolar plates, catalyst layers and membranes to enable effective water management and operation in subfreezing environments.

System Thermal and Water Management Affects Performance

Thermal and water management processes include heat and water use, cooling and humidification. Improved heat utilization, cooling, and humidification techniques are needed. The low operating temperature of PEM fuel cells results in a relatively small difference between the fuel cell stack operating temperature and ambient air temperature, which is not conducive to conventional heat rejection approaches and limits the use of heat generated by the fuel cell (approximately 50% of the energy supplied by the fuel). More efficient heat recovery systems, improved system designs, advanced heat exchangers and/or higher temperature operation of current systems are needed to utilize the low-grade heat and achieve the most efficient (electrical and thermal) systems, particularly for distributed power generation. The high quality heat generated by high temperature fuel cells leads to higher overall system efficiencies; however, the need to remove heat generated by the high temperature stacks can complicate stack/system design, as well as limit the operating power density and cell size. Improved techniques to manage water during start-up and shutdown at subfreezing temperatures are also needed.

System Air Management Affects Performance

Compressors/expanders specifically designed for low-temperature and high-temperature fuel cell applications are needed to minimize parasitic power consumption, while meeting packaging and cost requirements.

System Start-up and Shut-down Time and Energy/Transient Operation Affects Performance

Automotive fuel cell systems must start rapidly from any ambient condition with minimal fuel consumption. For stationary power applications, and especially for high-temperature fuel cells, rapid start-up and thermal cycling during operation is not anticipated, but transient times need to be minimized and stacks need to be designed to survive thermal upsets. Strategies to address start-up and shut-down time and energy such as the use of hybrid systems and/or stored hydrogen are needed. Fuel cell power plants will also be required to follow load variations, which are dependent on application.

3.4.6 Technical Task Descriptions

Table 3.4.16 describes the technical tasks that are the focus of R&D within the Fuel Cells sub-program. There is a direct correlation between these technical tasks and the current fuel cell activities listed previously in Table 3.4.2.

Table 3.4.16 Technical Task Descriptions		
Task	**Description**	**Barriers**
1	**Electrolytes** Develop / identify electrolytes [polymer electrolyte membrane (80ºC ≤ T ≤ 120ºC), medium temperature electrolytes (phosphoric acid-based, solid acid) (150ºC ≤ T ≤ 500 ºC), liquid-fueled (non-H_2) fuel cell membranes, anion-exchange membranes, high temperature electrolytes/matrixes (e.g., solid oxide fuel cells, molten carbonate fuel cells] • Improve electrolyte conductivity, for both proton- and anion-conducting systems, over the entire temperature and humidity operating range. • Increase the mechanical/chemical/thermal stability of electrolytes over the entire temperature and humidity operating range • Reduce/eliminate fuel cross-over Fabricate Membranes from Ionomers • Design scalable membrane fabrication processes • Increase the mechanical/chemical/thermal stability of the membrane over the entire temperature and humidity operating range (e.g., up to 95 - 120°C for transportation systems, and >120°C for CHP systems) • Reduce the cost of membranes Perform Membrane/Electrolyte Testing and Characterization to Improve Durability • Evaluate the tolerance of the electrolyte material to air, fuel and system-derived impurities • Evaluate the mechanical stability of the membrane with relative humidity (RH) cycling • Identify chemical and mechanical degradation mechanisms • Develop strategies for mitigating degradation in performance and durability	A, B, C

Table 3.4.16 Technical Task Descriptions		
Task	**Description**	**Barriers**
2	**Catalysts / Electrodes** Develop Improved Catalysts • Reduce/eliminate precious metal loading of catalysts for medium and high temperature fuel cells (T ≥ 150°C) • Reduce/eliminate precious metal loading of catalysts for low temperature fuel cells (60°C ≤ T ≤ 120°C) • Increase the specific and mass activities of catalysts • Increase the durability/stability of catalysts with potential cycling • Increase the tolerance of catalysts to air, fuel, and system-derived impurities • Test and characterize catalysts • Develop non-PGM catalysts for polymer electrolyte membrane fuel cells (oxygen reduction reaction) • Develop non-PGM catalysts for anion-exchange membrane fuel cells (hydrogen oxidation reaction and oxygen reduction reaction) • Increase catalyst utilization • Develop electrodes for high temperature fuel cells with enhanced activity and durability Develop Improved Catalyst Supports • Reduce corrosion of catalyst supports • Develop lower cost catalyst support materials and structures • Develop viable supports that allow increased loading and/or thickness of non-PGM catalyst layer Optimize Electrode Design and Assembly • Optimize catalyst/support interactions and microstructure • Develop anodes for fuel cells operating on non-hydrogen fuels	A, B, C

Table 3.4.16 Technical Task Descriptions		
Task	**Description**	**Barriers**
3	**Membrane Electrode Assemblies, Gas Diffusion Media, and Cells** Integrate Membrane/Electrolytes and Electrodes • Optimize mechanical and chemical interactions of the catalyst, support, ionomer, and membrane • Minimize interfacial resistance • Integrate catalysts with membranes and GDLs into MEAs • Integrate catalysts with supports and electrolytes into robust high-temperature fuel cells Expand MEA/Cell Operating Range • Address freeze/thaw issues • Expand temperature and humidity range • Improve MEA/cell stability under voltage and humidity cycling • Develop techniques to mitigate effects of air, fuel, and system-derived impurities Test, Analyze, and Characterize MEAs • Characterize MEAs/cells before, during, and after fabrication and operation • Test cells, MEAs and short stacks Improve GDL/MPL Performance and Durability • Optimize GDL pore structure, morphology, and physical properties • Optimize GDL coatings to improve water management and stable operation • Develop materials and structures with reduced area-specific resistance • Understand corrosion and aging effects on GDL/MPL	A, B, C
4	**Seals, Bipolar Plates, and Interconnects** Optimize Balance-of-Stack Components • Develop high temperature stack interconnects • Develop high temperature stack seals • Develop electrolyte reservoir plates for PAFCs Improve Performance of Bipolar Plates • Decrease weight and volume • Develop coatings to eliminate plate corrosion Decrease Cost of Bipolar Plates • Evaluate the use of different materials and coatings Improve Durability of Bipolar Plates • Identify degradation mechanisms • Develop strategies/technologies for mitigating degradation	A, B, C

Table 3.4.16 Technical Task Descriptions		
Task	**Description**	**Barriers**
5	**Stack and Component Operation and Performance** Improve Technical Understanding/Characterization • Develop, validate, and use models to address impurity effects • Develop, validate, and use models to address durability/degradation • Develop, validate, and use models of freeze/thaw effects on fuel cell operation • Develop and validate component performance models using most recent data • Identify long term stack failure mechanisms through experimentation • Develop models describing mass transport with experimental validation • Optimize MEA and stack water management, including freeze/thaw issues	A, B, C
6	**Systems Operation and Performance** Improve Technical Understanding/Characterization • Develop, validate, and use models to address impurity effects • Develop, validate, and use models to address durability/degradation • Mitigate system issues • Develop methods to minimize electrolyte losses from PAFC matrix • Develop methods to minimize CO_2 migration in alkaline fuel cells • Develop methods to ensure robust and fast start up times for high-temperature fuel cells (SOFC, MCFC)	A, C
7	**System BOP Components** Develop Chemical and Temperature Sensors for Stationary Applications (500-1100°C) • Decrease costs • Improve durability and reliability of fuel cell sensors Develop Air Management Technologies (Blowers) for Stationary Applications (500-1100°C) • Meet performance, packaging, and cost requirements • Minimize parasitic power • Reduce noise level Develop Air Management Technologies (Blowers, Compressors/Expanders) for Transportation Applications • Meet performance, packaging, and cost requirements • Minimize parasitic power Develop Humidifiers for Transportation applications • Increase efficiency, durability, and reliability • Develop humidification materials and concepts • Minimize parasitic power • Develop lightweight, low cost materials to enable compact humidifiers Develop Thermal Management Technologies for Fuel Cell Systems • Develop coolants that are non-toxic and have low electrical conductivity	A, B, C

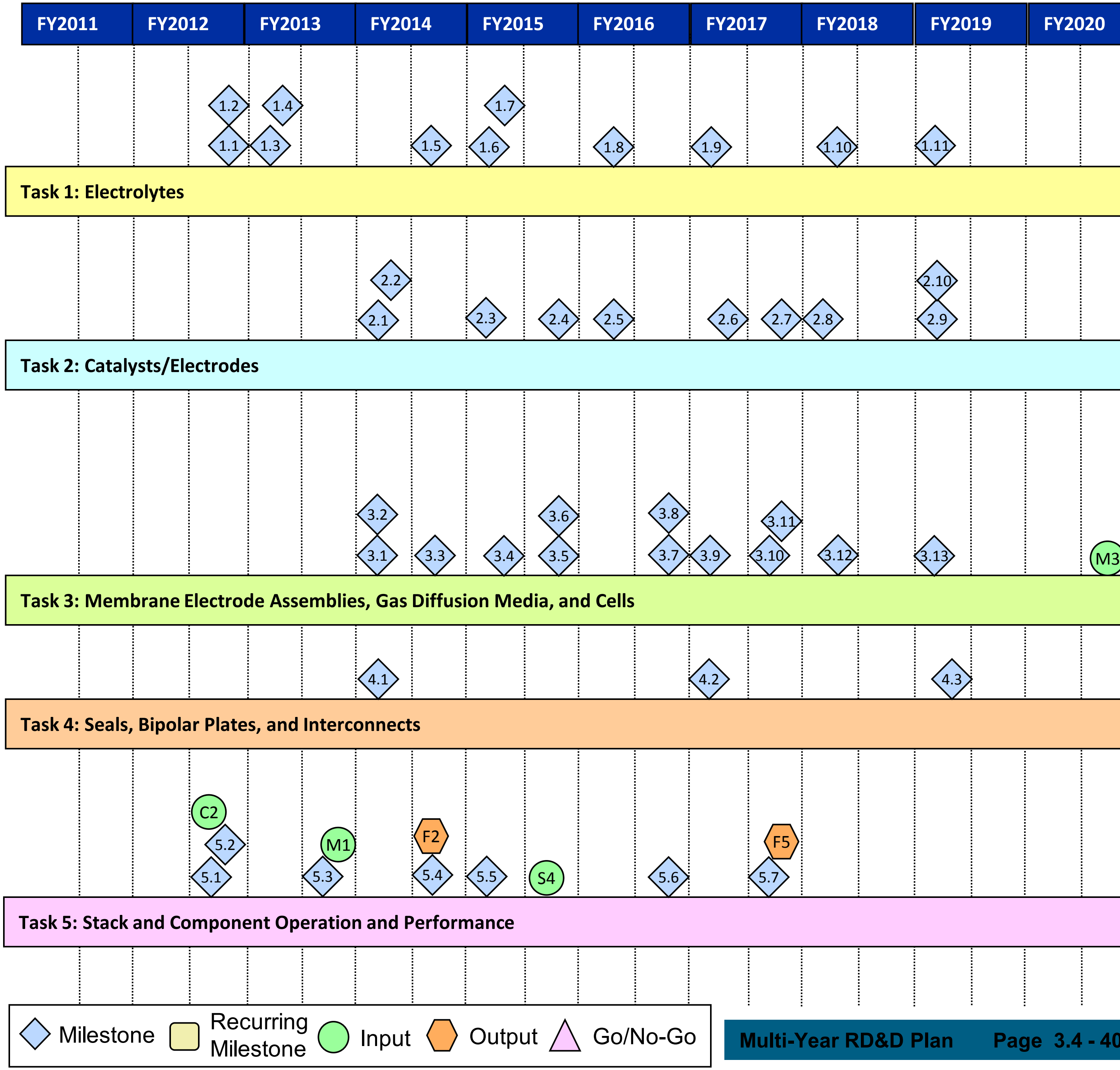
Table 3.4.16 Technical Task Descriptions		
Task	**Description**	**Barriers**
8	**Fuel Processors** Develop Fuel-Flexible Fuel Processors • Develop catalysts and hardware capable of generating hydrogen-rich gas stream • Meet cost requirements Improve Durability and Tolerance to Impurities • Develop low-cost gas clean-up subsystems Integrate Fuel Processor Subsystems • Eliminate reactor hardware, piping, and possibly sensors and controls • Integrate thermal loads of the subsystems	A, B, C
9	**Fuel Cell Systems** Develop Stationary Fuel Cell Systems for Distributed Generation (DG) including CHP • Improve system durability • Improve stack performance with reformate • Increase system electrical and thermal efficiency • Reduce cost Develop Auxiliary Power Units • Develop fuel cell system that operates on reformate • Design, build and test APUs under real-world conditions • Reduce cost Develop Portable Power Technologies • Develop membranes with minimal methanol crossover • Design, build, and test portable power systems under real-world conditions • Reduce cost	A, B, C

Table 3.4.16 Technical Task Descriptions		
Task	**Description**	**Barriers**
10	**Testing and Technical Assessments** Perform Cost Analysis of Stationary, Portable, and Transportation Applications • Perform cost analyses for automotive and bus applications • Perform cost analyses for stationary power and emerging market applications including APUs, back-up power and material handling (forklifts) Annually Update Technology Status Conduct Tradeoff Analysis • Rated power design points vs. performance and efficiency • Start-up energy and start-up time • Hydrogen quality level vs. durability and performance Develop Protocols for Testing • Develop accelerated testing to project durability for stationary fuel cell applications Experimentally Determine Long-Term Stack Failure Mechanisms Experimentally Determine System Emissions Perform Independent Testing to Characterize Component and Stack Properties Before, During, and After Operation	A, B, C

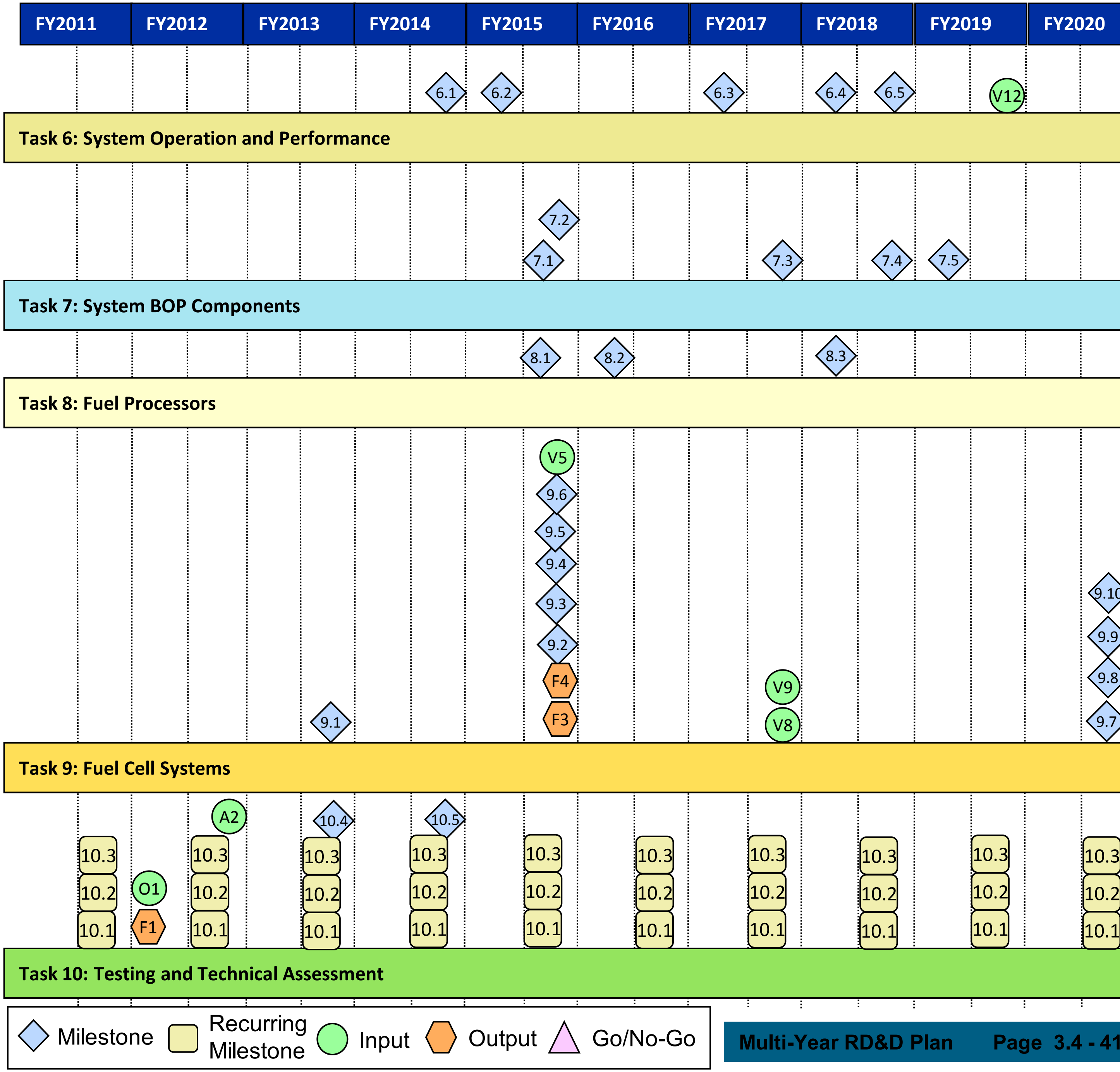
3.4.7 Milestones

The following chart shows the interrelationship of milestones, tasks, supporting inputs and technology program outputs for the Fuel Cell sub-program from FY 2011 through FY 2020. This information is also summarized in Appendix B: Input/Output Matrix.

Fuel Cells Sub-program Milestone Chart



Fuel Cells Sub-program Milestone Chart



Task 1: Electrolytes	
1.1	Demonstrate multiple freeze/thaw cycles. (4Q, 2012)
1.2	Evaluate membrane tolerance to impurities (fuel, air, and system derived) and compare to membrane target. (4Q, 2012)
1.3	Develop membranes that have methanol permeability of less than $5x10^{-8}$ cm^2/sec. (1Q, 2013)
1.4	Demonstrate an anion-exchange membrane that retains 99% of original ion exchange capacity for 1000 hours in hydroxide form at T > 80^oC. (2Q 2013)
1.5	Develop PEM membrane for transportation that meets area specific resistance ≤ 0.02 Ω-cm^2 at 120°C and 40 kPa water partial pressure. (3Q, 2014)
1.6	Develop membranes that have methanol permeability of less than $1x10^{-8}$$cm^2$/sec. (1Q, 2015)
1.7	Evaluate membrane technologies for >5,000 hour durability operating at >80°C. (2Q, 2015)
1.8	Develop an alternative electrolyte for PAFCs that does not poison anodes, has vapor pressure lower than that of phosphoric acid, and has ionic conductivity >0.65 S/cm. (2Q, 2016)
1.9	Develop a PEM membrane for transportation with area specific resistance ≤ 0.02 Ω-cm^2 at 120°C and 40 kPa water partial pressure, and durable for 20,000 voltage cycles and 500 hours chemical durability testing. (1Q, 2017)
1.10	Develop a membrane for operation at T > 150°C with a projected durability of 60,000 hours. (2Q, 2018)
1.11	Demonstrate electrolytes for high-temperature fuel cells with a projected durability of 80,000 hours. (1Q, 2019)

Task 2: Catalysts/Electrodes	
2.1	Characterize catalysts that have undergone durability testing using the DOE durability protocol. (1Q, 2014)
2.2	Demonstrate catalyst support initial mass loss of less than 10%. (2Q, 2014)
2.3	Develop catalysts with 0.14 g_{PGM}/kW at rated power. (1Q, 2015)
2.4	Develop anode for DMFC applications with an activity of 150 mA/cm^2 at 0.6V, at a loading of <2.7 mg Pt/cm^2 (4Q, 2015)
2.5	Demonstrate electrodes in high-temperature fuel cells that meet 60,000 hour durability. (2Q, 2016)
2.6	Develop a PGM-free catalyst with an activity of 300 A/cm^3 at 800 mV. (2Q, 2017)
2.7	Develop catalysts with 0.125 g_{PGM}/kW at rated power. (4Q, 2017)
2.8	Develop PAFCs with advanced catalysts and catalyst layer deposition methods to enable 50% reduction in PGM loading compared to the baseline of 0.7 mg/cm^2 (anode + cathode). (1Q, 2018)
2.9	Demonstrate electrodes in high-temperature fuel cells that meet 80,000 hour durability. (1Q, 2019)
2.10	Demonstrate durability of 30,000 cycles for PGM-free catalyst with less than 40% loss of initial activity. (1Q, 2019)

Task 3: Membrane Electrode Assemblies, Gas Diffusion Media, and Fuel Cells	
3.1	Develop MEA that will tolerate start-stop transient operation and fuel starvation excursions. (1Q, 2014)
3.2	Develop improved gas diffusion materials to enable time stable operation at high power density >40,000 hours for stationary applications. (1Q, 2014)
3.3	Evaluate methods to mitigate effects of fuel, air and system-derived impurities. (3Q, 2014)
3.4	Develop a membrane electrode assembly that can operate above 150 °C with a projected durability of 40,000 hours. (2Q, 2015)
3.5	Evaluate short stack with improved MEAs against 2020 membrane and MEA targets. (4Q, 2015)
3.6	Evaluate progress toward extending durability to >5000 hours with automotive cycling. (4Q, 2015)
3.7	Demonstrate PAFC with reduced anion poisoning resulting in a 25% increase in a real power density compared to baseline value of 160 mW/cm^2. (4Q, 2016)
3.8	Demonstrate anion-exchange membrane technologies in MEA/single cells with non-PGM catalysts that maintain performance higher than 350 mW/cm^2 for 2000 hours at T > 80°C. (4Q, 2016)
3.9	Demonstrate MEA performance of 1000 mW/cm^2 at rated power at a high-volume projected cost of $9/kW. (1Q, 2017)
3.10	Demonstrate MEA performance of 250 mW/cm^2 at 0.8 V while meeting catalyst loading targets. (3Q, 2017)
3.11	Demonstrate short stack with improved MEAs meeting 2020 membrane and MEA targets. (4Q, 2017)
3.12	Report on status of MEA/cell durability to meet stationary fuel cell target of >60,000 hours. (2Q, 2018)
3.13	Develop a membrane electrode assembly/cell assembly that can operate above 150 °C with a projected durability of 60,000 hours. (1Q, 2019)

Task 4: Seals, Bipolar Plates, and Interconnects	
4.1	Develop PEM bipolar plates with a cost less than or equal to $5/kW while meeting other technical targets. (1Q, 2014)
4.2	Develop PEM bipolar plates with a cost less than or equal to $3/kW while meeting other technical targets. (1Q, 2017)
4.3	Develop interconnect that is durable for 20,000 hours with less than 20% degradation SOFC APU stack performance. (2Q, 2019)

Task 5: Stack and Component Operation and Performance	
5.1	Demonstrate a fuel cell stack for micro-CHP applications with > 40% electrical efficiency and >80% total efficiency. (3Q, 2012)
5.2	Determine durability and performance degradation of cells with novel flow-field architecture and low Pt loading (0.1 mg_{Pt}/cm^2) operated at high current densities (>2.5 A/cm^2) relative to 15 µV/h/cell at 1 A/cm^2. (4Q, 2012)
5.3	Develop model describing mass transport in PEMFCs and experimentally validate within 10%. (3Q, 2013)
5.4	Demonstrate successful mitigation of the impact of major airborne contaminants on stack operation. (3Q, 2014)
5.5	Determine effect of system impurities on stack performance. (1Q, 2015)
5.6	Demonstrate high-temperature (>500 ^{o}C) stack durability of greater than 60,000 hours. (4Q, 2016)
5.7	Demonstrate 120^{o}C MEA in a PEMFC stack – meeting membrane and MEA target. (3Q, 2017)

Task 6: System Operation and Performance	
6.1	Determine effect of system impurities on BOP component performance. (4Q, 2014)
6.2	Evaluate durability of truck APU, determine degradation issues, and assess against durability target of 15,000 hours. (2Q, 2015)
6.3	Evaluate status of automotive fuel cell system durability and assess against target of 5,000 hours. (2Q, 2017).
6.4	Evaluate status of bus fuel cell system durability and assess against target of 18,000 hours. (2Q, 2018)
6.5	Report on status of fuel cell system durability to meet stationary fuel cell target of >60,000 hours. (4Q, 2018)

Task 7: System BOP Components	
7.1	Increase air compression system motor and controller efficiency to 80% at 25% of rated air flow. (3Q, 2015)
7.2	Experimentally validate coolant with 5000 hours durability. (4Q, 2015)
7.3	Develop a humidifier module with projected durability of 5,000 hours during RH cycling, and water transfer rate at 80ºC of 5 grams per second. (4Q, 2017)
7.4	Develop low-cost, high-temperature chemical sensors for high-temperature fuel cell systems (500-1100ºC) with a durability of >60,000 hours. (4Q, 2018)
7.5	Demonstrate anode recirculation blower with durability of 80,000 hours. (2Q, 2019)

Task 8: Fuel Processors	
8.1	Demonstrate sulfur removal to provide fuel cell grade reformate. (3Q, 2015)
8.2	Demonstrate siloxane removal from landfill gas to provide fuel cell grade reformate. (2Q, 2016)
8.3	Demonstrate stationary fuel cell stack operating on LPG, natural gas, landfill gas, and anaerobic digester gas. (2Q, 2018)

Task 9: Fuel Cell Systems	
9.1	Develop truck APU with projected durability of 10,000 hours, at a cost of $1400/kW, operating on standard ultra-low sulfur diesel. (4Q, 2013)
9.2	Develop truck APU with projected durability of 15,000 hours, at a cost of $1200/kW, operating on standard ultra-low sulfur diesel. (4Q, 2015)
9.3	Develop a portable fuel cell system (100-250 W) with a durability of 5,000 hours and an energy density of 900 Wh/L at a cost of $5/W. (4Q, 2015)
9.4	Develop a portable fuel cell system (10-50 W) with a durability of 5,000 hours at a cost of $7/W. (4Q, 2015)
9.5	Demonstrate micro-CHP at 42.5% electrical efficiency, 87.5% CHP efficiency and projected durability of 40,000 hours. (4Q, 2015)
9.6	Demonstrate medium-scale CHP at 45% electrical efficiency, 87.5% CHP efficiency, and projected durability of 50,000 hours. (4Q, 2015)
9.7	Develop a 60% peak-efficient, 5,000 hour durable, direct hydrogen fuel cell power system for transportation at a cost of $40/kW (at high volumes). (4Q, 2020)
9.8	Demonstrate micro-CHP at 45% electrical efficiency, 90% CHP efficiency and projected durability of 60,000 hours. (4Q, 2020)
9.9	Demonstrate medium-scale CHP at 50% electrical efficiency, 90% CHP efficiency, projected durability of 80,000 hours, at a cost of $2,100/kW operating on biogas. (4Q, 2020)
9.10	Develop a fuel cell system for APUs with specific power of 45 W/kg and power density of 40 W/L. (4Q, 2020)

Task 10: Testing and Technical Assessments	
10.1	Test and evaluate fuel cell systems and components such as MEAs, short stacks, bipolar plates, catalysts, membranes, etc. and compare to targets. (3Q, 2011 thru 3Q, 2020)
10.2	Update fuel cell technology cost estimate for 80 kW transportation systems and compare it to targeted values. (3Q, 2011 thru 3Q, 2020)
10.3	Update fuel cell technology cost estimates for material handling, backup power units, primary power, and combined heat and power systems, and compare to target values. (3Q, 2011 thru 3Q, 2020)
10.4	Provide higher frame capabilities from neutron imaging, up to 100 frames per second in response to user needs. (4Q, 2013)
10.5	Develop a 10-fold accelerated test for high-temperature fuel cell durability testing. (4Q, 2014)

Outputs

F1 Output to Systems Integration: Cost of the baseline automotive fuel cell system. (1Q, 2012)

F2 Output to Storage: Report on the effect of impurities from storage materials on fuel cells. (3Q, 2014)

F3 Output to Technology Validation and Systems Integration: Provide micro-combined heat and power system test data from documented sources indicating performance status. (4Q, 2015)

F4 Output to Technology Validation and Systems Integration: Provide auxiliary power unit system test data from documented sources indicating performance status. (4Q, 2015)

F5 Output to Technology Validation and Systems Integration: Provide automotive stack test data from documented sources indicating performance status. (4Q, 2017)

Inputs

A2 Input from Systems Analysis: Cost of competing vehicle powertrain. (4Q, 2012)

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

M1 Input from Manufacturing: Report on high-speed, low-cost fabrication of gas diffusion electrodes for membrane electrode assemblies. (4Q, 2013)

M3 Input from Manufacturing: Report on fabrication and assembly processes for polymer electrolyte membrane fuel cells that meet the transportation fuel cell system cost target of $40/kW. (4Q, 2020)

O1 Input from Vehicle Technologies Program: U.S. DRIVE baseline vehicle system architecture (e.g., hybridization) and fuel economy. (1Q, 2012)

S4 Input from Storage: Update of fuel quality from promising storage materials. (Q3, 2015)

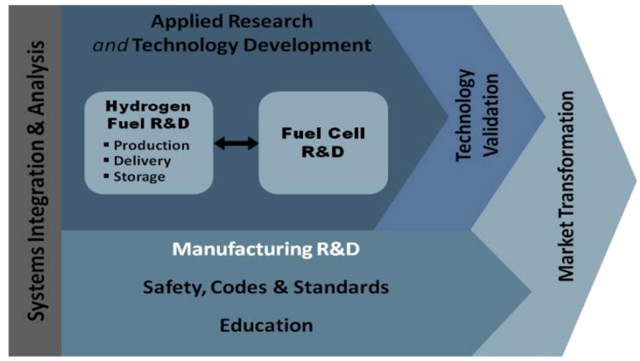
V5 Input from Technology Validation: Report on the validation of residential fuel cell micro combined heat and power systems' efficiency and durability. (4Q, 2015)

V8 Input from Technology Validation: Complete validation of commercial fuel cell combined heat and power systems' efficiency and durability. (4Q, 2017)

V9 Input from Technology Validation: Validate status of truck auxiliary power unit durability. (4Q, 2017)

V12 Input from Technology Validation: Validate light duty fuel cell vehicle durability. (4Q, 2019)

3.5 Manufacturing R&D



More than 15,000 fuel cell systems were shipped in 2010 worldwide,[1] representing more than 80 MW of power. As the market for hydrogen and fuel cells grows, the need for development of automation and manufacturing processes for mass production of these systems grows as well.

To meet the needs of increasing production volumes in the growing hydrogen and fuel cells industries, the Manufacturing R&D sub-program works with industry, universities and national laboratories to research, develop, and demonstrate high-volume manufacturing processes to reduce cost while ensuring high quality products for hydrogen production, delivery and storage, as well as low and high temperature fuel cell systems. This sub-program facilitates the development of a domestic supplier base for hydrogen and fuel cell technologies.

3.5.1 Technical Goal and Objectives

Goal

Research, develop, and demonstrate technologies and processes that reduce the cost of manufacturing hydrogen production, delivery, storage, and fuel cell systems.

Objectives

- Develop manufacturing techniques to reduce the cost of automotive fuel cell stacks at high volume (500,000 units/year) from the 2008 value of $38/kW[2] to $21/kW by 2020.
- Develop fabrication and assembly processes to produce compressed hydrogen storage systems that cost $10/kWh for widespread commercialization of hydrogen fuel cell vehicles across most light duty platforms by 2020.
- Support efforts to reduce the cost of manufacturing components and systems to produce hydrogen at <$4/gge (2007 dollars) (untaxed, delivered, and dispensed) in 2020.

3.5.2 Technical Approach

This sub-program focuses on improving processes and reducing the cost of manufacturing components and systems for hydrogen and fuel cell applications. In addition, cross-cutting technologies (e.g., metrology) and capabilities will be developed, including modeling and simulation tools.

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[1] excluding thousands shipped for toy/educational product applications
[2] http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mass_production_cost_estimation_report.pdf

The Manufacturing R&D sub-program:

- Identifies cost drivers of manufacturing processes
- Modifies manufacturing processes to eliminate process steps
- Reduces cost by implementing process control tools
- Reduces labor costs and improves reproducibility by increasing automation
- Reduces cost by improving manufacturing processes to improve yields and reduce scrap
- Scales-up laboratory fabrication methods to low-cost, high-volume production.
- Develops in-line diagnostics for component quality control and validates in-line
- Develops an understanding of the relationship between process parameters and product properties
- Quantifies the effect of defects in materials on performance and durability to understand the accuracy requirements for diagnostics.

Manufacturing R&D efforts focus on reducing the cycle times of the processes being developed. Research areas include approaches for:

- Significantly reducing the cost of the processes used to manufacture hydrogen and fuel cell components
- Rapidly defining and producing "production quality" tooling or approaches for simplifying and reducing the cost of tooling
- Increasing the uniformity and repeatability of fabrication.

Progress towards attaining the goals of Manufacturing R&D is tracked by assessing: (1) the reduction in cost of hydrogen production, delivery, storage, and fuel cell systems, and (2) the increase of manufacturing rates and annual manufacturing capacity.

These efforts will enable industry to:

- Meet customer requirements for hydrogen and fuel cell systems.
- Develop a competitive domestic supplier base for hydrogen and fuel cell system components.

3.5.3 Programmatic Status

Current Activities

Table 3.5.1 summarizes the FY 2011 activities in the Manufacturing R&D sub-program. Most activities are targeted towards polymer electrolyte membrane (PEM) fuel cells for automotive applications. Future funding opportunities will include all fuel cell types, (i.e., solid oxide, molten carbonate, phosphoric acid, polymer electrolyte, and alkaline) for all applications. Portable power from direct methanol fuel cells is covered primarily by the Department of Defense and is less likely to be a focus of DOE's Manufacturing sub-program activities.

Currently, the Manufacturing R&D sub-program has one project aimed at developing new methods to manufacture Type IV pressure vessels for hydrogen storage. While the Storage sub-program is developing new materials (chemical hydrides, metal hydrides and sorbents) for hydrogen storage, a material-based system will not likely be scaled-up during the near term. As a result, the Storage sub-program is also focusing on high pressure gaseous storage as the path to near-term commercialization. The Manufacturing project on hydrogen storage is developing a new hybrid fabrication process for high pressure storage vessels by optimizing the elements of advanced fiber placement and commercial filament winding.

The Fuel Cell Technologies (FCT) Program does not currently sponsor any efforts focused on reducing the manufacturing cost of components and systems for production and delivery of hydrogen. To explore additional opportunities, NREL hosted a workshop in August 2011 on H_2 & FC Manufacturing R&D in Washington, D.C. with representatives from industry, academia, laboratories, and government. During the workshop, participants identified and prioritized needs and barriers to manufacturing hydrogen and fuel cell components and systems. Key suggestions included:

- **PEM Fuel Cells/Electrolyzers BOP:** Facilitate a manufacturing group for DOE to expand supply chain.
- **Electrodes:** Apply ink directly to membrane; dual direct coating of CCM; membrane dimensional change with deposition of current inks
- **PEM Fuel Cells/Electrolyzers BOP:** Develop low cost manufacturing of natural gas reformers high volume stack assembly processes: reduced labor, improved automation
- **Quality/Inspection/Process Control:** Develop methods of identifying coating defects on a moving web, then rejecting single pieces downstream; defect detection after MEA assembly when defect may no longer be visible; ability to separate materials with defects from rolled goods with minimum production of scrap
- **SOFC:** Multi-layer/component sintering

Presentations and a summary of recommendations can be found in the workshop report at http://www1.eere.energy.gov/hydrogenandfuelcells/wkshp_h2_fc_manufacturing.html. The recommendations will support future funding opportunities.

The current Manufacturing portfolio includes projects focused on PEM fuel cells:

- Developing in-line defect diagnostics for quality control of membrane electrode assemblies (MEAs) and MEA components
- Reducing the fabrication costs of gas diffusion materials
- Developing processes that reduce steps and scrap in the production of MEAs
- Exploiting ultrasonic bonding to reduce the pressing cycle time of MEAs
- Quantifying the effect of variable dimensions in bipolar plates on fuel cell performance.

Some of these projects, such as in-line defect detection, are relevant to fuel cells other than PEM.

Table 3.5.1. Current Manufacturing Activities		
Topic	**Approach**	**Activities**
PEM Fuel Cells		
Fuel Cell MEA Manufacturing R&D	Develop capabilities and knowledge related to in-line quality control that will assist manufacturers of PEM fuel cell MEA components in transitioning to high-volume manufacturing methods.	**National Renewable Energy Laboratory:** Developing diagnostics suitable for in-line quality control for MEAs and components. Investigating the effects of MEA component manufacturing defects on MEA performance and durability. Refining and validating models to predict the effects of local variations in MEA component properties.
Manufacturing of Low-Cost, Durable MEAs Engineered for Rapid Conditioning	Develop a unique, high-volume manufacturing process that will produce low-cost, durable, high-power density 3-layer MEAs that require little or no stack conditioning.	**W.L. Gore & Associates:** Developing a new process to reduce the use of intermediate backer materials, reducing the number and cost of coating passes, improving safety, and reducing process cost by minimizing solvent use and reducing required conditioning time and costs.
Adaptive Process Controls and Ultrasonics for High Temperature PEM MEA Manufacture	Enable cost-effective, high-volume manufacture of high-temperature proton exchange MEAs.	**Rensselaer Polytechnic Institute:** Achieving greater uniformity and performance of MEAs by adaptive process controls combined with *in situ* property sensing to the MEA pressing process and reducing MEA pressing cycle time through the development of novel, robust ultrasonic bonding processes for high-temperature PEM MEAs.
Flow Field Plate Manufacturing Variability and its Impact on Performance	Develop a pre-competitive knowledge base of engineering data relating bipolar plate manufacturing process parameters and dimensional variability to fuel cell performance variation.	**National Institute of Standards and Technology (NIST):** Fabricating cathode-side flow field plates with various well-defined combinations of flow field channel dimensional variations. Quantifying the effects of dimensional variations on single-cell fuel cell performance and correlating the results into required dimensional fabrication tolerance levels.
Non-Contact Sensor Evaluation for Bipolar Plate Manufacturing Process Control	Identify and evaluate the capability and uncertainty of commercially available non-contact, high-speed scanning technologies for applicability to bipolar plate manufacturing process control.	**NIST:** Identifying, developing, integrating, and/or evaluating high-speed non-contact sensors or system of sensors for application in process control of bipolar plates.
Optical Scatterfield Metrology for Online Catalyst Coating Inspection of PEM Soft Goods	Evaluate the suitability of optical scatterfield metrology as a viable measurement tool for *in situ* process control of catalyst coatings.	**NIST:** Engaging MEA manufacturers and industry experts in an effort to identify the critical parameters of the catalyst layer and to obtain samples that vary these parameters to enable conduction of a sensitivity study of the proposed technique.

Table 3.5.1. Current Manufacturing Activities (continued)		
Topic	**Approach**	**Activities**
High-Speed, Low-Cost Fabrication of Gas Diffusion Electrodes for MEAs	Reduce cost in fabricating the gas diffusion electrode (GDE) through the introduction of high-speed coating technology, with a focus on materials used for combined heat and power generation.	**BASF Fuel Cell Inc.:** Identifying key quality GDE metrics that relate directly to ink performance, developing an understanding of the forces behind ink stability, and introducing solution measurement methods that relate ink performance to the quality metrics.
Hydrogen Storage		
Advanced Manufacturing Technologies for Low Cost Hydrogen Storage Vessels	Develop new methods for manufacturing Type IV pressure vessels for hydrogen storage with the objective of lowering the overall product cost.	**Quantum Fuel Systems Technologies Worldwide, Inc.:** Develop new methods for manufacturing Type IV pressure vessels for hydrogen storage with the objective of lowering the overall product cost by optimizing composite usage through combining traditional filament winding and advanced fiber placement techniques and by exploring the usage of alternative fibers on the outer layers of the FW process.

3.5.4 Technical Challenges

Technical challenges in manufacturing hydrogen and fuel cell systems are summarized in this section.

Fuel Cells

The ramp-up to high-volume production of fuel cells will require quality control and measurement technologies consistent with high-volume manufacturing processes. Manufacturers will need process control strategies specific to producing fuel cell components to reduce or eliminate sampling and testing of components, modules, and subsystems.

As fuel cell manufacturing scales up, the relationships among fuel cell system performance, manufacturing process parameters, and variability must be clearly understood. Such understanding will likely play a major role in fuel cell system design, acceptable tolerances and specifications, and it is integral to implementing design for manufacturability. Modeling and simulation; better understanding of generic, cross-cutting manufacturing process technologies; reliable measurements; and standards will advance fuel cell manufacturing.

Manufacturing R&D is needed for:

- MEA production
- Gas diffusion media production
- Fuel cell stack assembly
- Stack conditioning and final testing
- Bipolar plate fabrication
- Quality control

Hydrogen Storage

The high cost of materials, particularly carbon fiber, is the primary issue with composite tank technology. The goal is to achieve a manufacturing process with: lower composite material usage, a lower cost fiber, and higher manufacturing efficiency. Current preliminary factory cost assessments of 350 bar and 700 bar one-tank, Type IV compressed gas systems (with 5.6 kg usable hydrogen) are $29/kWh and $36/kWh, respectively,[3] at a low-volume production rate of 10,000 units/yr. These costs can be reduced through materials and process improvements and moving to higher volume manufacturing processes through advanced manufacturing R&D. Composite storage technology will most likely be employed in the near term for transportation applications and be essential for most materials-based approaches for hydrogen storage. The cycle time needs to be significantly reduced, which will require advances in filament winding processes or in the use of an alternative technology yet to be identified or developed. Reducing the amount of fiber used through fiber placement, and improvements in resin matrix technologies could greatly lower costs.

Hydrogen Production and Delivery

Currently, hydrogen production is capital-intensive. Widespread adoption of hydrogen fuel cells requires consumers to have access to cost-competitive hydrogen. Steam methane reforming of natural gas in centralized production facilities is projected to meet the DOE threshold cost of <$4/gge at high production volumes, but there are opportunities for lowering the manufacturing costs of building hydrogen fueling stations. Moreover, while the technology of storing hydrogen in compressed gas tanks is mature, the cost of manufacturing compressed tanks remains high due in large part to high cost of raw materials. Additionally, reliability issues in manufactured components and systems cause the overall cost of compression to be high.

Manufacturing R&D is needed for:

- Improving the reliability and manufacturability of hydrogen compressors
- Implementation of in-use sensors to alert users of contaminants or impending component failure
- Fabrication of larger diameter hydrogen storage tubes
- Reducing the material cost for fiber-reinforced polymer pipeline

[3] http://www.hydrogen.energy.gov/pdfs/progress11/iv_e_3_law_2011.pdf

- Composite tube trailer vessels that face not only challenges similar to other pressure vessels, but must also meet additional Department of Transportation requirements because of their relatively large size.
- Increasing the reliability and lowering the cost of compressors in dispensing systems. Need to show a pathway to lower cost of advanced compressors, e.g., by scale-up to high volume production

Cross Cutting Activities

Modeling and Simulation

Modeling and simulation can significantly advance the development and optimization of manufacturing processes. Mathematical models and modeling process integration are needed to evaluate the effects of various manufacturing techniques. Information on manufacturing process capabilities can be fed into component performance models to assess the impact of manufacturing variations. This will help to establish manufacturing process requirements (e.g., tolerances and quality assurance requirements), reduce manufacturing costs by relaxing noncritical tolerances, cut development times by generating more robust designs, and facilitate optimal solutions.

Quality Control and Process Control

Control technologies for manufacturing processes are needed to increase the reliability and quality of manufactured products while reducing cost. Low-cost systems are needed for monitoring and controlling manufacturing processes to produce the quantities of products that meet market requirements.

Metrology

Instruments that provide rapid and accurate measurements are needed to apply quality assurance techniques such as statistical process control. Metrology will provide quantitative information about a manufacturing process and its output. The ability to measure various process quantities such as leaks, microstructure defects, surface roughness, coating quality, and dimensional accuracy reliably, will enable cost-effective manufacturing. In-process measurements will allow manufacturers to establish statistical process capabilities and make adjustments to control process and component quality during operation. Current inspection techniques often require off-line measurements, manual inspection techniques, and even destructive tests. These approaches slow the manufacturing process and add cost. Non-destructive testing techniques that eliminate manual and time-consuming test and measurement processes are needed.

3.5.5 Technical Barriers

This section summarizes the technical and economic barriers that must be overcome to meet the Manufacturing R&D objectives.

Low-Temperature Fuel Cells

A. Lack of High-Volume Membrane Electrode Assembly Processes

Currently, some MEAs are prepared using decal transfer of the electrode to the membrane. New manufacturing methods are needed to fabricate MEAs involving direct coating of the electrode on the membrane or gas diffusion layer (GDL) substrate. Continuous lamination processes that do not impact stiffness of GDLs (as a finished MEA) and continuous lamination processes that provide uniform pressure/temperature over area of contact are needed.

B. Lack of High-Speed Bipolar Plate Manufacturing Processes

Both metal and non-metal bipolar plates are used in PEM fuel cells. Non-metal plate materials include expanded graphite and graphite-based composites. New technologies for forming low-cost bipolar plates at low volume are needed; these technologies are needed to produce plates without cracks that form when thin metal foil is stamped. More rapid production processes for graphite and metal plates need to be developed.

C. Lack of High Strength Gas Diffusion Media

Less brittle paper GDLs and stronger woven GDLs are needed. In addition to new approaches to produce stronger gas diffusion media, methods to reduce or eliminate protruding or loose fibers or other materials from the GDL surfaces are needed.

D. Lack of High-Speed Sealing Techniques

High-speed processes need to be developed to integrate MEA components incorporating edge and interfacial seals and gaskets. Merging the MEA sealing assembly process with the bipolar plate sealing in a continuous process could reduce the cost of stack assembly.

E. Lack of Improved Methods of Final Inspection of MEAs

New methods to inspect MEAs for leaks, shorts, membrane pinholes and other defects prior to assembly are needed. Currently a large loss of time and increased overall cost results when a stack is torn down to remove a faulty cell identified during final stack testing.

High-Temperature Fuel Cells

F. High Cost and Complexity of Processing Cell Materials

The processing of high temperature fuel cell materials is costly and can be complicated when materials are prepared in batches rather than by continuous processes, when multiple steps are required for processing, and/or when processes are inefficient and low throughput. Multi-layer/component casting, forming and sintering processes are needed for solid oxide fuel cells (SOFCs while high temperature thermal processing techniques are needed for molten carbonate fuel cells (MCFCs) and SOFCs. Cells are stacked manually for all technologies leading to slow assembly.

(We note that some phosphoric acid fuel cell (PAFC) systems have automated cell and stack production.) Part count in the system is too high.

G. Lack of High-Speed Separator Plate and Current Collector Manufacturing Processes

The plate and current collector material requirements of low and high-temperature fuel cell systems are different so it is unclear if techniques developed to manufacture plates for low-temperature cells can be applied to high-temperature cells. Improved processing of interconnects, coatings, and flow fields are needed.

H. Lack of Processes for Forming Thermal Insulation

Formation of thermal insulation for high temperature fuel cell systems is often a manual, time consuming process. Net shape or other forming processes are needed to reduce cycle time and cost.

Cross-cutting Fuel Cell Barriers

I. Manual Stack Assembly

Development of automated methods to assist cell and stack assembly is needed. Implementation of these methods will reduce cycle time, improve repeatability and quality, and reduce cost. Methods to ensure proper alignment and proper handling of both soft and hard-goods are needed as well as cutting processes that do not damage cell materials.

J. Lack of Rapid, Low Cost Methods for Stack Conditioning and Final Testing

Reduction of the time and cost associated with conditioning and final testing of stacks is needed. Current processes can take hours to days, require expensive equipment, floor space, and gases.

K. Low Levels of Quality Control

Capabilities to monitor the physical and chemical uniformity of electrode and electrolyte layers, as well as to perform final quality testing of full MEAs and cells are needed. Development and validation of measurement techniques for in-line use will assist manufacturers in scale-up of processing to high volumes. Techniques to mark identified defects or regions of unacceptable variability for later removal in ways that minimize loss of surrounding material are needed. Improving the basis of knowledge around the performance and durability effects of variability and defects such that product specifications can be set based on systematic studies are needed. Quality assurance test methods to ensure that engineered powders meet process specifications are also needed.

L. Lack of Standardized Balance-of-Plant Components

Balance-of-plant components are either not designed for fuel cell applications and thus incur performance penalties or if they are, the volumes are so low that costs are excessive. Common specifications for fuel cell balance-of-plant (BOP) components do not exist. Design for Manufacturing and Assembly (DFMA) could be applied during the development of standardized specifications to reduce part count and cost, and improve manufacturability. High-volume manufacturing of balance-of-plant components and rapid assembly into the fuel cell power plant system need to be developed to reduce costs. Specific examples of BOP components needing developing are heat exchangers, liquid flow control and metering devices, blowers, and humidifiers.

We note that addressing the barrier of part standardization will require industry-wide collaboration including the fuel cell manufacturers as well as their MEA and BOP suppliers.

Hydrogen Storage

M. Lack of Low-cost Carbon Fiber

Currently, composite tanks require high-strength carbon fiber that costs from $10-16/lb.[4] Manufacturing R&D is needed to reduce the energy used to process carbon materials and increase the rate of carbonization processes for the carbon fiber, e.g., with microwave or plasma processing. In addition to improved carbonization processes, other steps in the process, such as oxidation and graphitization need to be improved.

N. Lack of Low-Cost Fabrication Techniques for Storage Tanks

New manufacturing methods are needed to reduce the cycle time, that is, the time to fabricate a single tank. Potential advances in manufacturing technologies include faster filament winding (e.g., multiple heads), new filament winding strategies and equipment, and continuous versus batch processing. New manufacturing processes for room temperature curing, wet winding processes, applying the resin matrix, and fiber-imbedded thermoplastics for hot wet winding should also be investigated. New hybrid manufacturing methods for carbon fiber winding and fiber placement manufacturing are needed. A cost model is needed to guide development of high-volume production processes for high-pressure composite tanks employing fiber placement technologies.

Hydrogen Production & Delivery

O. Lack of Reliable Hydrogen Compressors

Hydrogen compressors are unreliable and account for a significant fraction of maintenance events associated with the hydrogen infrastructure for material handling equipment and light-duty vehicles. Redundancy is employed to mitigate the unreliability but that increases lifecycle costs.

P. Lack of In-Use sensors

Integration of sensor systems to provide in-use indications of the needs for preventative maintenance or of the onset of known failure mechanisms is needed.

Q. Lack of Processes to Fabricate Large-Diameter, Low-cost Tubes for Compressed Hydrogen Storage

Processes to fabricate larger diameter tubes for compressed hydrogen storage need to be developed. The costs of plumbing and assembly are too high and space is poorly utilized. Throughput needs to be increased; winding, cure, and assembly are too slow.

[4] Ibid.

3.5.6 Technical Task Descriptions

The technical task descriptions and the barriers associated with each task are presented in Table 3.5.2. Concerns regarding safety and environmental effects will be addressed within each task in coordination with the appropriate sub-program.

Table 3.5.2 Technical Task Descriptions

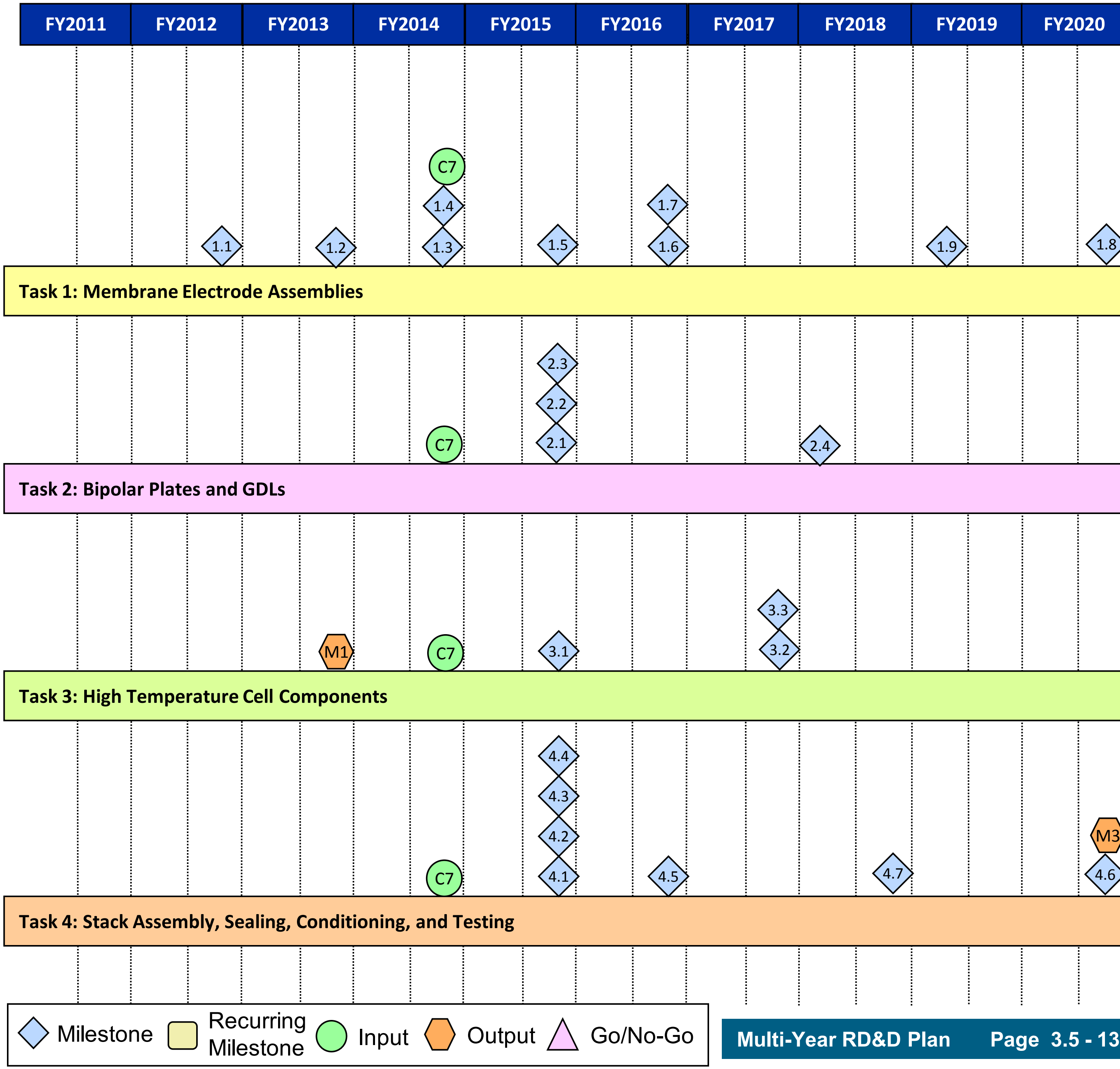
Task	Description	Barriers
Low-Temperature Fuel Cells		
1	**Membrane Electrode Assemblies** • Develop and demonstrate processes for direct coating of electrodes on membranes or gas diffusion media • Develop and demonstrate highly uniform continuous lamination of MEA components • Develop cell manufacturing processes that increase throughput and efficiency and decrease complexity and waste	A
2	**Bipolar Plates and GDLs** • Develop high-volume, low-cost processes for manufacturing graphite/resin and metal bipolar plates • Develop low-cost bipolar plate fabrication processes that are applicable to low-rate production • Develop rapid prototyping and flexible tooling specifically for the manufacture of bipolar plates • Develop GDL fabrication and handling processes, especially to improve strength, decrease brittleness, and reduce or eliminate loose or protruding fibers from the surfaces	B,C
High-Temperature Fuel Cells		
3	**Cell Components** • Develop cell fabrication processes, including casting, forming, sintering, and other thermal processing, to increase throughput and efficiency and to decrease complexity and waste • Develop separator/bipolar/flow-field plate and current collector fabrication processes • Develop net shape or other improved forming processes for thermal insulation	F, G, H
Cross-Cutting Tasks		
4	**Stack Assembly and Sealing** • Develop techniques to seal components rapidly and reliably • Develop equipment capable of high-rate assembly of cell stacks using automated methods • Develop processes and methods to assure proper alignment and handling of hard and soft goods during stack assembly • Develop quality control instruments to assure specified compression on cell stack • Develop methods and processes to decrease the amount of time and equipment intensity currently required for stack testing and conditioning	D, I,J

Table 3.5.2 Technical Task Descriptions (continued)		
Task	**Description**	**Barriers**
5	**Balance-of-Plant** • Support activities that lead to standardized specifications for BOP equipment • Apply DFMA analysis to standard designs to reduce part count and cost, and improve manufacturability ▪ Support exploration and implementation of automation in the assembly of BOP components	L
6	**Quality Control and Modeling** • Develop automated and/or continuous in-line measurement of material properties and defects during cell and cell sub-assembly fabrication • Develop methods to inspect full MEAs and cells for leaks, shorts, and membrane pinholes after pressing/lamination, prior to assembly into a stack • Develop techniques to mark identified defect regions for later removal • Develop correlations between manufacturing parameters/defects and performance/durability/life of MEAs • Establish, validate and extend models that predict the effect of manufacturing variations on MEA performance	E,K
Hydrogen Storage		
7	**High-Pressure Composite Tanks** • Produce a cost model for high-pressure tank manufacture • Develop new manufacturing methods for high-pressure composite tanks using hybrid tank design with lower cost carbon fibers on exterior • Develop high-speed filament winding processes • Develop fiber placement processes that reduce the amount of carbon fiber required • Develop fabrication processes for larger diameter compressed gas tubes	M, Q
Hydrogen Production & Delivery		
8	**Components** • Develop manufacturing processes that improve the reliability of hydrogen compressors • Integrate in-use sensors to detect contaminants or detect failures early • Develop fabrication processes for large compressed gas tubes for tube trailers	N, O, P

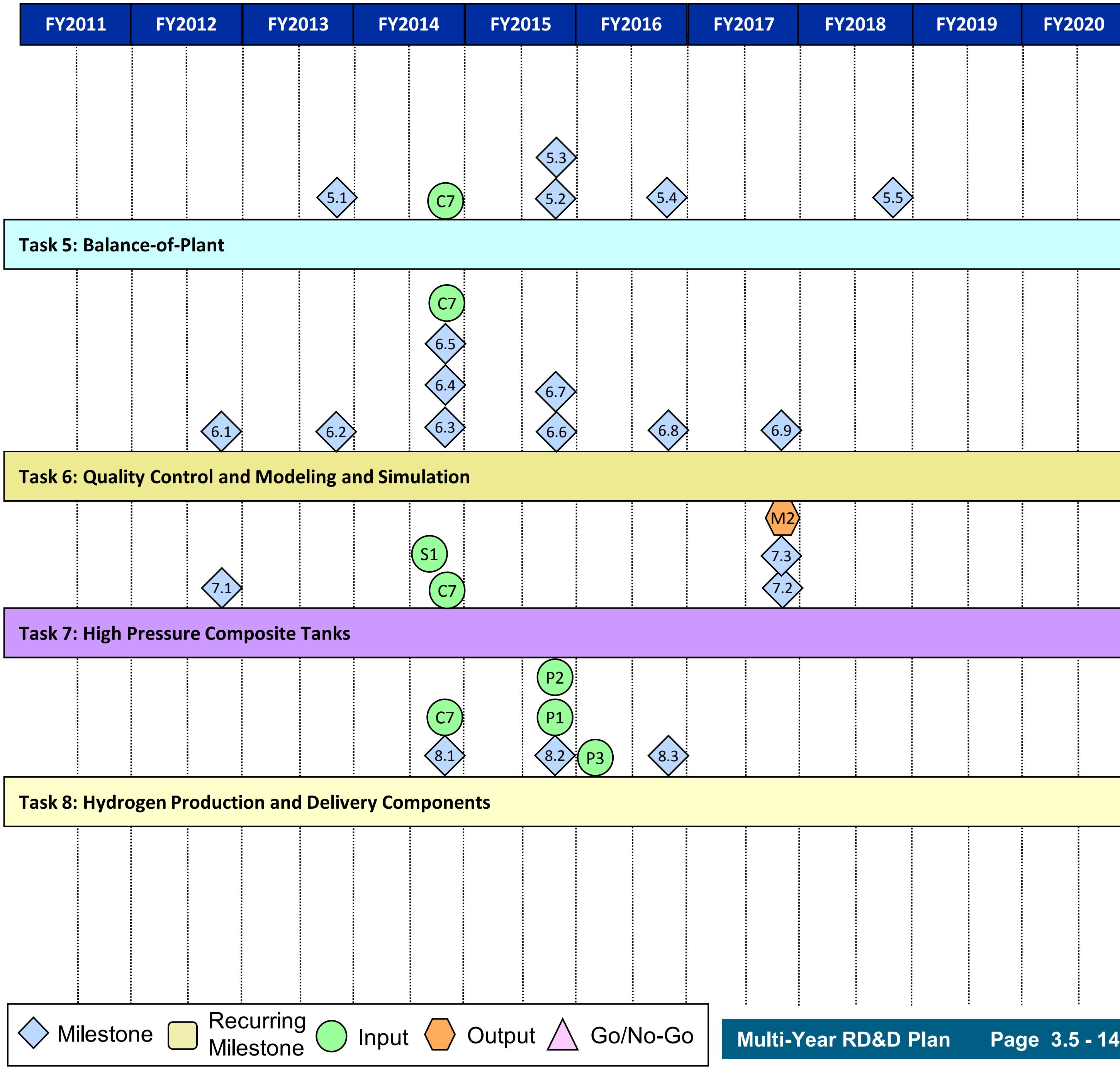
3.5.7 Milestones

The following chart shows the interrelationship of milestones, tasks, and supporting inputs from (and outputs to) other sub-programs to (from) the Manufacturing R&D sub-program.

Manufacturing Milestone Chart



Manufacturing Milestone Chart



Fuel Cells

Task 1: Membrane Electrode Assemblies	
1.1	Develop continuous in-line measurement for MEA fabrication. (4Q, 2012)
1.2	Reduce the cost of manufacturing MEAs by 25%, relative to 2008 baseline of $126/kW (at 1,000 units/year). (4Q, 2013)
1.3	Develop processes for direct coating of electrodes on membranes or gas diffusion media (4Q, 2014)
1.4	Develop processes for highly uniform continuous lamination of MEA components (4Q, 2014)
1.5	Develop cell manufacturing processes that increase throughput and efficiency and decrease complexity and waste (4Q, 2015)
1.6	Demonstrate processes for direct coating of electrodes on membranes or gas diffusion media (4Q, 2016)
1.7	Demonstrate processes for highly uniform continuous lamination of MEA components (4Q, 2016)
1.8	Develop fabrication and assembly processes for PEM fuel cell MEA components leading to an automotive fuel cell system that cost $40/kW. (4Q, 2020)
1.9	Develop fabrication and assembly processes for membranes that operate at T > 150°C with a projected durability of 60,000 hours. (2Q, 2019)
Task 2: Bipolar Plates and GDLs	
2.1	Demonstrate pilot scale processes for manufacturing bipolar plates that reduce cost at both low and high volume. (4Q, 2015)
2.2	Develop rapid prototyping and flexible tooling specifically for the manufacture of bipolar plates. (4Q, 2015)
2.3	Develop GDL fabrication and handling processes, especially to improve strength, decrease brittleness, and reduce or eliminate loose or protruding fibers from the surfaces (4Q, 2015)
2.4	Develop manufacturing processes for PEM bipolar plates that cost <$3/kW while meeting other technical targets. (1Q, 2018)

Task 3: High Temperature Cell Components	
3.1	Develop and demonstrate cell fabrication processes to increase throughput and efficiency and to decrease complexity and waste (4Q, 2015)
3.2	Develop fabrication processes for separator, bipolar, and flow-field plates and current collectors (4Q, 2017)
3.3	Develop net shape or other improved forming processes for thermal insulation (4Q, 2017)
Task 4: Stack Assembly, Sealing, Conditioning and Testing	
4.1	Develop pilot scale processes for manufacturing of end plates and manifolds. (4Q, 2015)
4.2	Demonstrate pilot scale processes for assembling and sealing stacks. (4Q, 2015)
4.3	Develop processes and methods to assure proper alignment and handling of hard and soft goods during stack assembly (4Q, 2015)
4.4	Reduce the cost of PEM fuel cell stack assembly and testing by 50%, relative to 2008 baseline of $1.68/kW (at 1,000 units/year). (4Q, 2015)
4.5	Develop processes and methods to decrease the amount of time and equipment intensity currently required for stack testing and conditioning (4Q, 2016)
4.6	Develop fabrication and assembly processes for PEM automotive fuel cell stacks that meet cost of $40/kW. (4Q, 2020)
4.7	Develop fabrication and assembly processes for stacks with MEAs that operate at 120°C and meet membrane and MEA targets. (4Q, 2018)
Task 5: Balance-of-Plant	
5.1	Establish a plan, with industry input and guidance, to support activities leading to standardization of specifications and application of DFMA to BOP components (4Q, 2013)
5.2	Develop manufacturing methods to automate the production and assembly of BOP components (4Q, 2015)
5.3	Establish a public/private working group (or groups) for the standardization of BOP component specifications (4Q, 2015)
5.4	Develop manufacturing processes for air compression systems that have 80% efficiency at 25% of rated air flow. (4Q, 2016)
5.5	Develop manufacturing processes for humidifier modules with projected durability of 5,000 hours during RH cycling. (4Q, 2018)

Task 6: Quality Control and Modeling and Simulation	
6.1	Develop continuous in-line measurement for PEM MEA fabrication. (4Q, 2012)
6.2	Develop defect detection techniques in pilot scale applications for manufacturing MEAs and MEA components. (4Q, 2013)
6.3	Establish models to predict the effect of manufacturing variations on MEA performance. (4Q, 2014)
6.4	Demonstrate methods to inspect full MEAs and cells prior to assembly into stacks (4Q, 2014)
6.5	Validate and extend models to predict the effect of manufacturing variations on MEA performance. (4Q, 2014)
6.6	Demonstrate continuous in-line measurement for MEA and MEA component fabrication. (4Q, 2015)
6.7	Develop methods to mark identified defects for later removal (4Q, 2015)
6.8	Develop and demonstrate techniques and diagnostics for automated or continuous in-line measurement of high temperature cells and sub-assemblies during fabrication. (4Q, 2016)
6.9	Develop correlations between manufacturing parameters and manufacturing variability, and performance and durability of MEAs (4Q, 2017)

Hydrogen Storage

Task 7: High-Pressure Composite Tanks	
7.1	Produce manufacturing cost model for high pressure tanks (4Q, 2012)
7.2	Develop fabrication and assembly processes for high pressure hydrogen storage technologies that cost $15/kWh for Type IV, 700 bar tanks. (4Q, 2017)
7.3	Develop fabrication processes for larger diameter compressed gas tubes (4Q, 2017)

Hydrogen Production & Delivery

Task 8: Components	
8.1	Develop manufacturing processes that improve the reliability of hydrogen compressors (4Q, 2014)
8.2	Demonstrate in-use sensors integrated with production and delivery systems (4Q, 2015)
8.3	Develop fabrication processes for large compressed gas tubes for tube trailers (4Q, 2016)

Outputs

M1 Output to Fuel Cells: Report on high-speed, low-cost fabrication of gas diffusion electrodes for membrane electrode assemblies. (4Q, 2013)

M2 Output to Storage: Report on fabrication and assembly processes for high pressure hydrogen storage tanks that cost $15/kWh for Type IV, 700 bar tanks. (4Q, 2017)

M3 Output to Fuel Cells: Report on fabrication and assembly processes for polymer electrolyte membrane fuel cells that meet the transportation fuel cell system cost target of $40/kW. (4Q, 2020)

Inputs

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

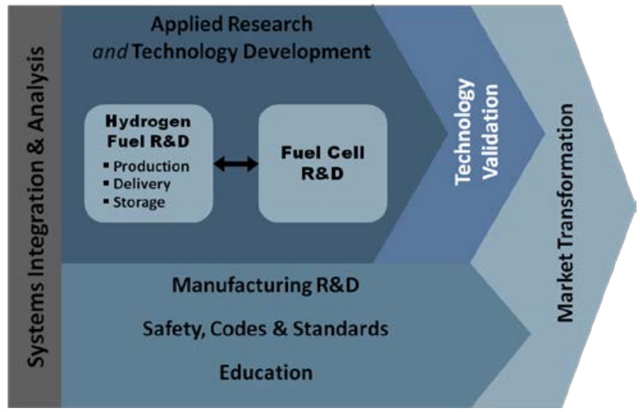
P1 Input from Production: Hydrogen production system based on centralized biomass gasification technology producing hydrogen at a projected cost of $2.10/kg at the plant gate. (4Q, 2015)

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)

S1 Input from Storage: Update status of composite tank costs. (3Q, 2014)

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.

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[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.

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[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

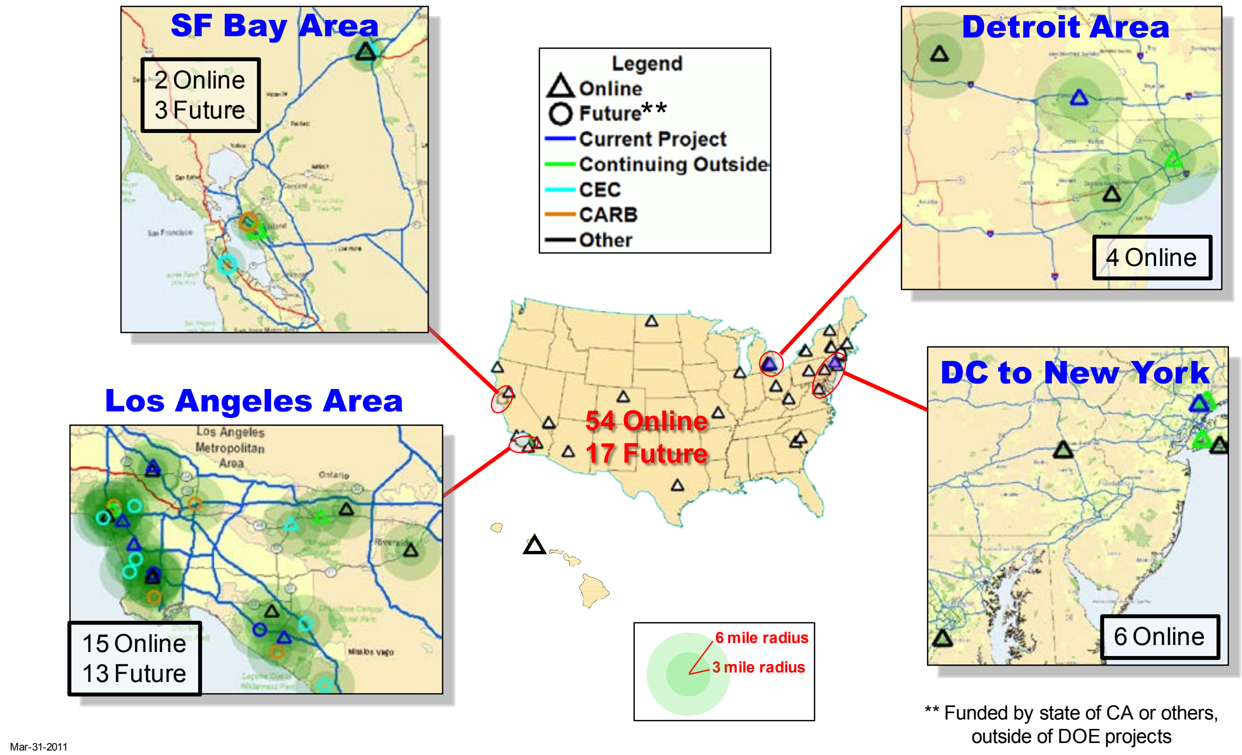


Figure 3.6.1 Current Hydrogen Infrastructure – Online and Planned Hydrogen Fueling Stations in the United States.

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.

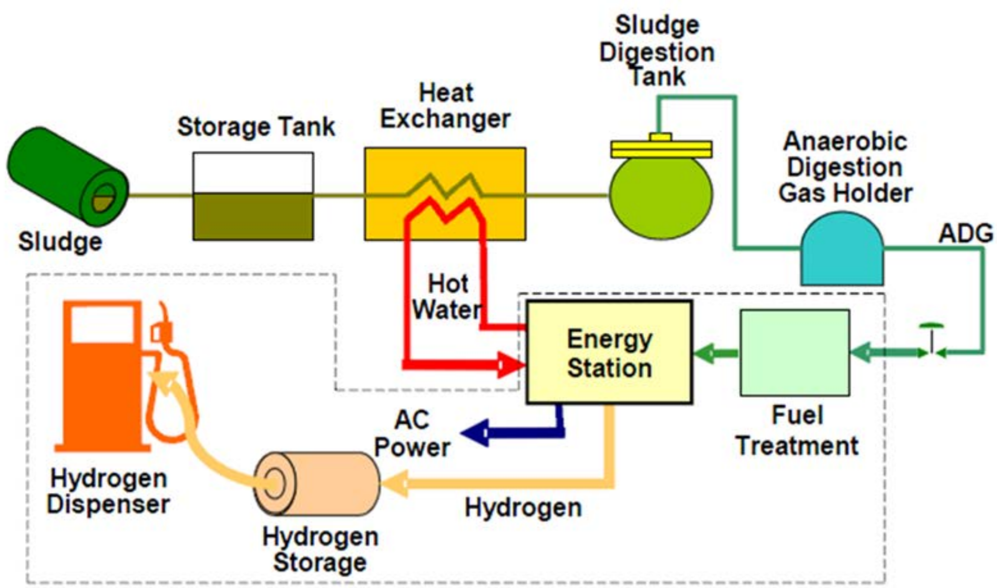


Figure 3.6.2 Hydrogen Energy Station - The Energy Station using thermo chemical processes for continuous hydrogen generation as well as heat and electrical power (figure credit: Air Products)

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.

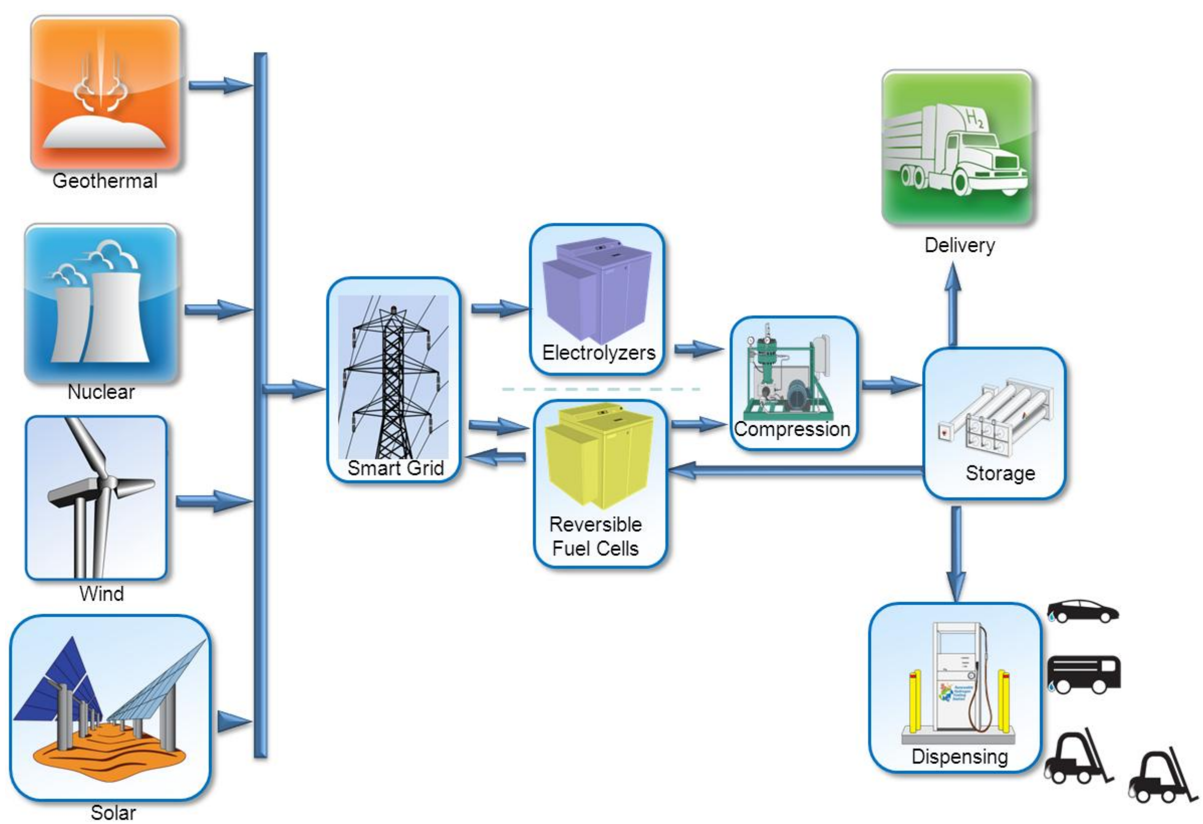


Figure 3.6.3 Electrolyzers and reversible fuel cells provide expanded market for base load and surplus renewable and zero-GHG power.

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]

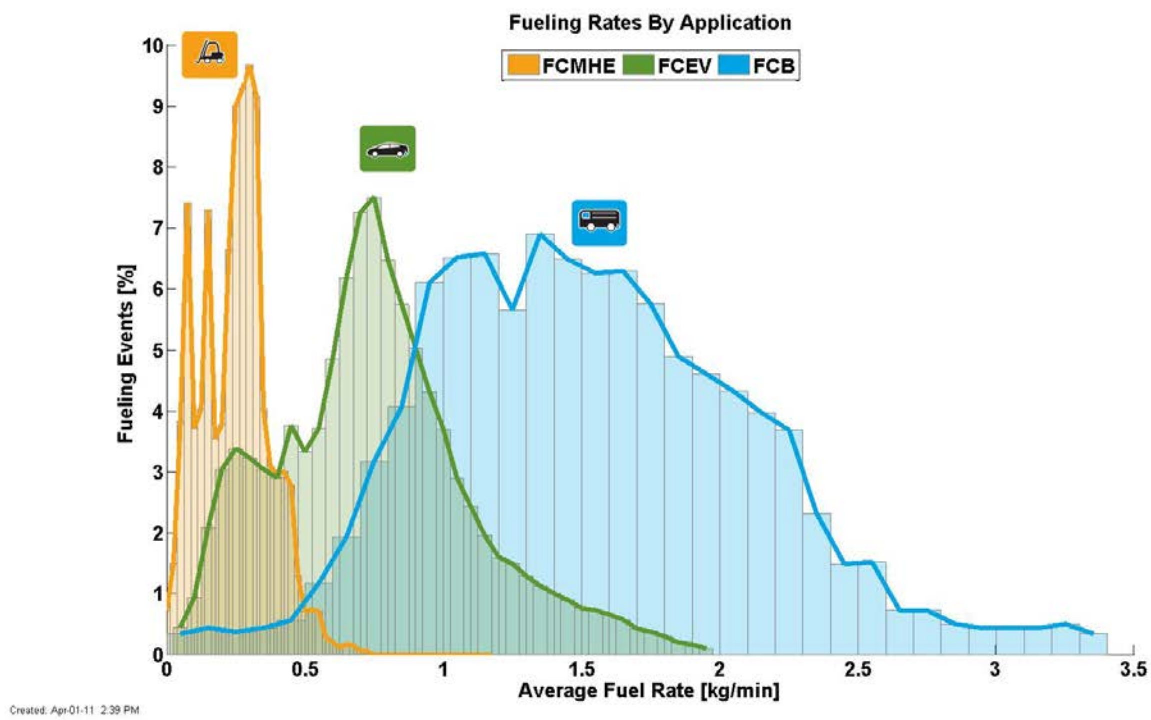


Figure 3.6.5 An example of a cross-application CDP, comparing fueling rates for fuel cell cars, buses, and forklifts.

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.

[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.

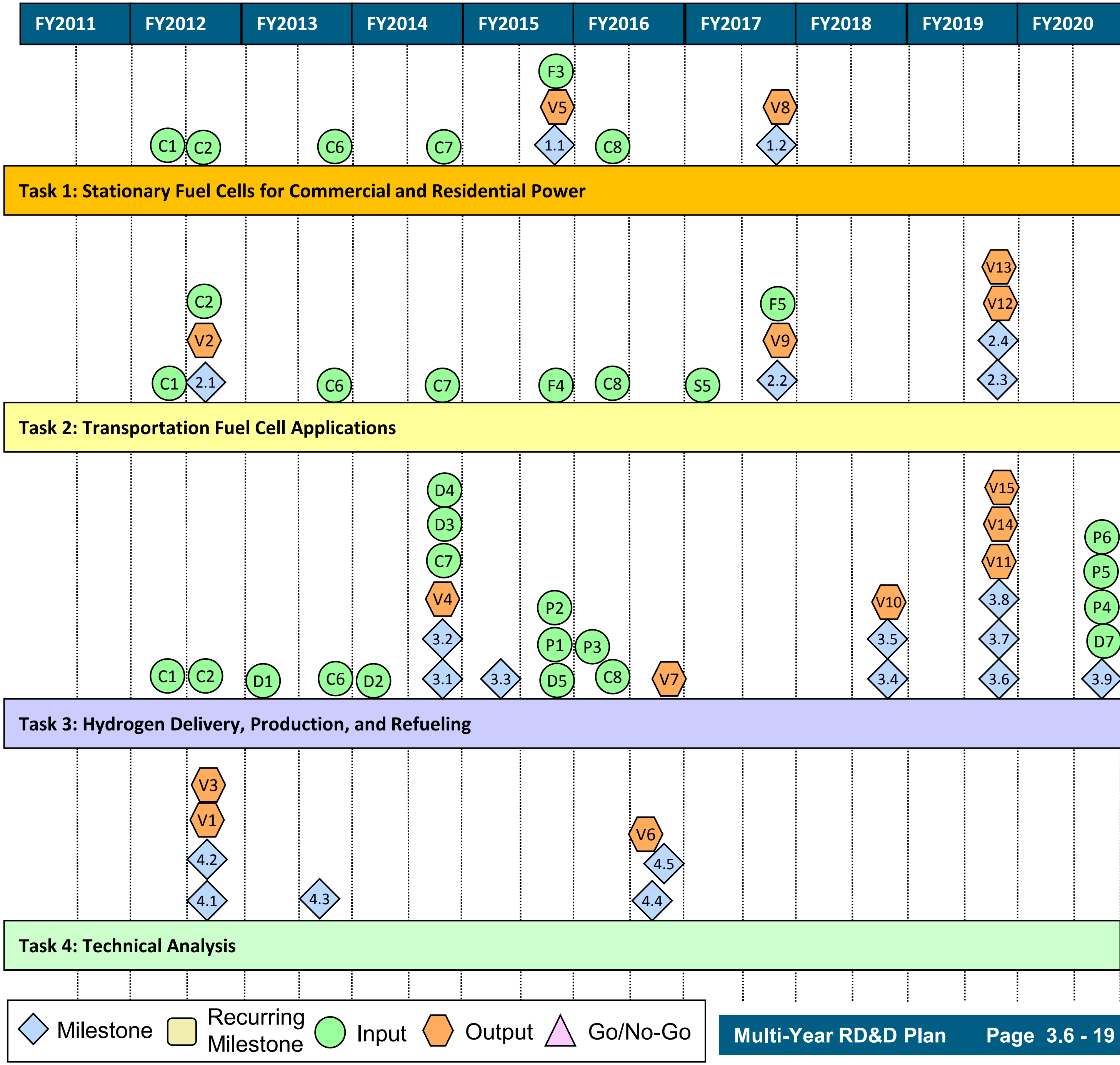
Table 3.6.7 Technical Task Descriptions

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)

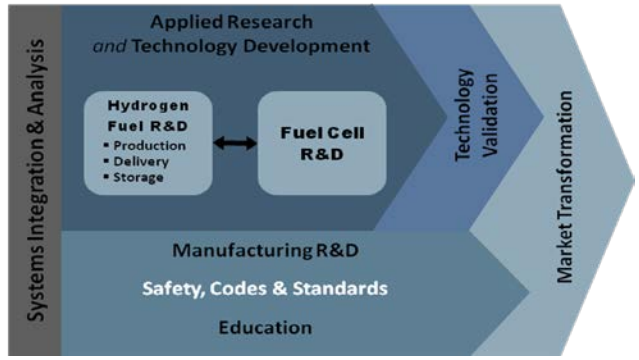
P4 Input from Production: Solar hydrogen production system based on centralized high-temperature thermochemical conversion technology producing hydrogen at a projected cost of $3.10/kg at the plant gate. (4Q, 2020)

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)

3.7 Hydrogen Safety, Codes and Standards



The United States and many other countries have established laws and regulations that require commercial products and infrastructure to meet all applicable codes and standards to demonstrate that they are safe, perform as designed and are compatible with the systems in which they are used. Hydrogen and fuel cell technologies have a history of safe use with market deployment and commercialization underway.

The Safety, Codes and Standards sub-program (SCS) facilitates deployment and commercialization of fuel cell and hydrogen technologies by developing information resources for their safe use. SCS relies on extensive input from automobile manufacturers, energy companies, fuel cell providers, subject matter experts from a variety of sectors, first responders and other stakeholders to develop and update these resources. The resources include lessons learned from safety events and best practices and training to ensure safety in the operation, handling, and use of hydrogen and fuel cell technologies for all funded projects in the U.S. Department of Energy (DOE) Fuel Cell Technologies Program (FCT).

To enable the widespread deployment and commercialization of hydrogen and fuel cell technologies, SCS supports research and development (R&D) that provide experimentally validated fundamental understanding of the relevant physics, critical data, and safety information needed to define requirements for technically sound and defensible codes and standards. SCS identifies and evaluates risk management measures that can be incorporated into codes and standards to reduce the risk and mitigate the consequences of potential incidents that could hinder the widespread commercialization of these technologies. SCS promotes collaborative efforts among government, industry, standards development organizations (SDOs), model code development organizations, universities, and national laboratories to harmonize domestic and international regulations, codes, and standards (RCS).

SCS helps to ensure that safety practices incorporating a wealth of historical experience as well as new knowledge and insights gained from R&D and stakeholder inputs are in place, enabling continuous and priority attention to safety in all aspects of hydrogen and fuel cell technologies: R&D, design and manufacture, deployment, operation, and maintenance. In addition, SCS aims to ensure that RCS for the safe deployment of hydrogen and fuel cell technologies, based on sound and traceable technical and scientific data and analysis, are in place, enabling full market entry of these technologies in the United States. The RCS must be harmonized, to the extent possible, with global technical regulations and codes and standards in major international markets. Scientific research and testing, developed through consensus of all major stakeholders, contribute to the refinement of RCS on an ongoing basis.

3.7.1 Goal and Objectives

Goal

Develop and implement practices and procedures for the safe conduct of DOE-funded hydrogen and fuel cell projects. Provide the scientific and technical basis for requirements in critical RCS to enable full deployment of hydrogen and fuel cell technologies in all market sectors.

Objectives

- Develop and validate test measurement protocols and methods to support and facilitate international harmonization of codes and standards for high pressure tanks by 2013.
- Conduct materials R&D to provide the technical underpinning to enable fault tolerant system designs for use with hydrogen infrastructure rollout by 2015.
- Conduct a quantitative risk assessment study to address indoor refueling requirements to be adopted by code developing organizations, e.g., National Fire Protection Association (NFPA) and International Code Council, by 2015.
- Support and facilitate development and promulgation of essential codes and standards by 2015 to enable widespread deployment and market entry of hydrogen and fuel cell technologies and completion of all essential domestic and international RCS by 2020.
- Ensure that best safety practices underlie research, technology development, and market deployment activities supported through DOE-funded projects.
- Conduct R&D to provide critical data and information needed to define requirements in developing codes and standards.
- Develop and enable widespread sharing of safety-related information resources and lessons learned with first responders, authorities having jurisdiction (AHJs), and other key stakeholders.

3.7.2 Technical Approach

To attain its goals and objectives, the SCS sub-program has adopted a technical approach that focuses on five areas: 1. safety management, 2. R&D, 3. test measurement protocols, 4. RCS development, and 5. dissemination of data, safety knowledge, and information. This section provides a brief overview of those focus areas followed by in-depth details on the technical approach to each one.

- **Comprehensive safety management** to ensure that all DOE funded projects are conducted with no sacrifice of safety
  - Utilize the Hydrogen Safety Panel, other expert knowledge, and results of R&D and testing for the safe operation, handling, and use of hydrogen and fuel cell technologies in all projects supported by the DOE
  - Understand and mitigate risk to facilitate the safe use of hydrogen and fuel cell technologies and the insurability of utilized assets.

- **Comprehensive R&D** to establish a scientific basis for sound safety practices and for the development and incorporation of requirements that enable the safe deployment of hydrogen and fuel cell technologies.
  - Facilitate development of safe, high-performance materials for hydrogen service.
  - Develop appropriate test methodologies for measuring hydrogen effects in materials, including but not limited to, material composition, pressure, temperature-time histories (i.e., static and cycling effects), and component testing for certification and coordination with established testing facilities.
  - Provide critical assessments of indoor and outdoor hydrogen installations and operations, and recommend relevant code modifications.
  - Provide validated understanding of hydrogen behavior in premixed environments (for example: ignition, combustion, and flame acceleration leading to detonation) to enable the design and implementation of risk mitigating strategies.

- **Development and validation of test measurement protocols and methods** to facilitate qualification and listing of hydrogen and fuel cell systems and components essential for full market deployment.
  - Work with the Regulations, Codes and Standards Working Group (RCSWG) of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) to establish a detailed test measurement protocol that will help ensure global uniformity of qualification test results for Type IV composite pressure vessels.
  - Facilitate development and validation of appropriate test methodologies to certify hydrogen and fuel cell systems and components in collaboration with established testing organizations.

- **Coordinated development and refinement of essential codes and standards** to enable safe and widespread deployment of hydrogen and fuel cell technologies and **international harmonization** of requirements and test procedures to qualify hydrogen and fuel cell components and systems in all major market applications
  - Support and facilitate completion of the Global Technical Regulation (GTR) for hydrogen-fueled vehicle systems under the United Nations Economic Commission for Europe, World Forum for Harmonization of Vehicle Regulations and Working Party on Passive Safety Program (UNECE-WP29).
  - Work directly in the codes and standards development processes to ensure that DOE research is utilized in codes and standards development as appropriate.

- **Timely and accurate dissemination of relevant information** to enable the timely development of harmonized codes and standards.
  - Share current safety information and knowledge with the hydrogen community.
  - Provide improved and focused knowledge tools and training for key constituents of the hydrogen safety community.

Safety Management

Comprehensive safety management utilizes expert knowledge that incorporates results from R&D and testing, as well as issues arising from RCS development, for the safe operation, handling, and use of hydrogen and fuel cell technologies in all projects supported by the DOE. Systematic application of safety assessment methodologies reduces the likelihood that a potential risk may be overlooked and allows for a consistent measure of safety across all DOE projects. Safety plans for DOE-funded projects as well as lessons learned from R&D, testing, and demonstration and deployment, play an important role in developing safe practices for hydrogen and fuel cell commercialization.

SCS established the Hydrogen Safety Panel (HSP) to capture relevant experience from automotive and fuel cell original equipment manufacturers (OEMs), energy providers, and other industrial and government stakeholders and to provide a focal point and venue for comprehensive safety management. Members are appointed to the HSP not only for technical expertise on hydrogen safety but also for experience in practicing safety in areas such as industrial hydrogen production and use, fuel cell system development and deployment, laboratory R&D and field testing under private and government programs, industrial liability and facility insurance, risk analysis and mitigation, environmental protection, and fire safety regulation and enforcement. At its regularly scheduled meetings, the HSP provides a unique public forum to discuss critical hydrogen safety issues and serves two principal purposes:

- Help integrate safety planning into DOE funded projects to ensure that all projects address and incorporate best available safety practices
- Provide expert assessment to DOE and assist with identifying safety-related technical data gaps, best practices, and lessons learned.

The HSP reviews all required project safety plans and maintains the DOE safety guidance document (*Safety Planning Guidance for Hydrogen and Fuel Cell Projects, April 2010*).[1] The HSP conducts safety evaluations of projects either through site visits or telephone interviews and provides reports to DOE concerning safety issues and actions that can be taken to mitigate such issues. The HSP also prepares white papers on critical safety issues for consideration by DOE and provides an ongoing gap analysis on hydrogen safety and hazard mitigation.

Research and Development

A primary role of SCS is to support R&D to establish a scientific basis for sound safety practices and for the development and incorporation of requirements in RCS for hydrogen and fuel cell technologies. The R&D is focused on hydrogen behavior, risk assessment and mitigation, and database development and application to support safety best practices and RCS development. The comprehensive R&D and testing effort supported by the SCS is discussed in detail in the R&D

[1] Available at http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/safety_guidance.pdf

Roadmap[2] and is considered an integral part of the Multi Year Research Development and Demonstration Plan.

R&D of hydrogen behavior address challenges for full deployment of hydrogen and fuel cell technologies, particularly the lack of supporting safety data. For example, the classification of hydrogen throughout the world is inconsistent. Some countries, including the U.S., classify hydrogen as a hazardous material that unnecessarily encumbers its safe use as a fuel. SCS is developing the scientific basis to enable the adoption of RCS for hydrogen to be used as a fuel, with a level of safety at least equal to that of gasoline.

Research in hydrogen behavior and effects is necessary to provide the foundation for defensible science-based requirements incorporated in RCS. On the most fundamental level, the physical mechanisms of hydrogen dispersion and ignition at applicable and relevant conditions must be understood to enable the development of engineering models. Experiments must be performed to understand the rate of dispersion and air entrainment, ignition probability, flame propagation, and the effects of the fluid dynamics on these parameters for hydrogen systems under anticipated commercial applications. For example, validated models for fluid dynamics, including the temperature field of the fluid and the tank during refueling, must be developed to provide the basis for refueling protocols. The resulting validated engineering models are applied to help specify requirements in the context of the hydrogen system (e.g., refueler, vehicle, auxiliary power unit being addressed under the RCS development process.

The behavior of hydrogen in materials is also a key R&D focus. Phenomena, such as accelerated embrittlement and fatigue due to hydrogen effects in materials, must be better understood to enable the development of fault-tolerant component and system design standards. The effects of hydrogen on metals, polymers, and composites must be understood so that appropriate test protocols can be developed. Data are needed for the behavior of materials and components in a hydrogen environment commensurate with the commercial applications in mind. Understanding physical mechanisms provides the foundation for specifying operational and cycle-life requirements and the development of safe and effective materials for hydrogen service. Materials of specific interest include stainless steels, low-alloy steels, composite materials, and aluminum alloys. Effects of welds, manufacturing processes, and defects on fatigue and cycle life are poorly understood. Interactions between hydrogen with polymers and composites at temperature and pressure are also poorly understood. Publicly accessible databases and technical reference documents must be developed and maintained to provide technology developers with consistent and defensible data for new systems and components.

Risk assessment methodologies for hydrogen installations must also be established and executed to develop the technical basis for requirements. Risk assessments incorporate two components, consequence modeling and probability data. Consequence models are developed using validated hydrogen behavior models and applied to the relevant environment to determine the consequence of unintended hydrogen releases. Mitigation features such as barriers, pressure relief systems, and

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[2] Codes and Standards RD&D Roadmap 2008 *(Update in progress),* available at http://www.eere.energy.gov/vehiclesandfuels/pdfs/program/cstt_roadmap.pdf

sensors must be analyzed from a risk perspective. Risk data, including frequency and characteristics, are needed from existing installations and past experience. The resulting risk assessment is put in the context of acceptable risk criteria that are provided by technical committees of an appropriate SDO, such as the NFPA, SAE International, International Code Council, and Canadian Standards Organization (CSA).

Although safety-by-design and passive mitigation systems are preferred, it will still be necessary to develop cost effective technologies to detect hydrogen releases and system failures. Low cost, high performance safety sensors are an integral component of deployed hydrogen and fuel cell systems. Advanced sensor development is needed for hydrogen gas detection and component monitoring. The SCS sub-program will develop hydrogen sensors with the appropriate response time, sensitivity, and accuracy for use in safety applications to reduce risk and help establish public confidence (see Table 3.7.6).

In summary, the R&D effort supported by SCS establishes a substantial and verified database of scientific information on the properties and behavior of hydrogen and the performance characteristics of hydrogen and fuel cell technology applications. This information, including quantitative risk assessments of hydrogen installations, is made available to appropriate SDOs, AHJs, and industry to facilitate the development of safe, performance-based technical codes and standards that will accommodate technology innovation and minimize the need to develop new RCS as hydrogen and fuel cell technologies evolve.

Test Measurement Protocols and Methods

Another major focus of SCS is the development and validation of test measurement protocols and methods to address an emerging need for better harmonization of testing and certification of hydrogen and fuel cell materials, components, subsystems, and systems. Test methods must be developed and validated so that the performance of components, subsystems, and systems under real-world operational and environmental conditions can be replicated and understood to ensure their safe and effective deployment.

Qualification of new materials for hydrogen service is costly, time-consuming, and resource-limited. Research must be performed to optimize test protocols in order to streamline and accelerate material and component qualification. Similarly, accelerated system qualification processes must be developed based on technically sound principles and optimized to facilitate the safe and effective deployment of fuel cell technologies. Development of test protocols and testing supported by the SCS will be coordinated with and linked to other R&D efforts funded by DOE as well as other organizations, both domestic and international.

As new near-term applications of hydrogen and fuel cell technologies emerge, so do needs for additional R&D, test data, and consensus testing and certification procedures. An example of an emerging new application is forklifts for warehouses and distribution centers in the industrial, commercial, and military sectors. The SCS has responded to these additional needs by addressing R&D, testing, and RCS development for forklift components, subsystems, and systems.

Development and Harmonization of Regulations, Codes and Standards

For the past decade, SCS has supported and facilitated the coordinated national development and refinement of essential RCS to enable safe and widespread deployment of hydrogen and fuel cell technologies. SCS works with domestic and international SDOs to facilitate development of performance-based standards. These standards are then referenced in building and other codes to expedite regulatory approval of the installation and deployment of hydrogen and fuel cell technologies and facilities. This approach ensures that U.S. consumers can purchase products that are safe and reliable, regardless of their country of origin, and that U.S. companies can compete in international markets. Along with the domestic effort, SCS has engaged key international bodies and forums to harmonize requirements and test procedures used to qualify hydrogen and fuel cell components and systems in all major market applications.

A key to the success of the national hydrogen and fuel cell RCS development efforts was the creation and implementation of "national templates" through which DOE, other federal agencies, national laboratories, industry, the major SDOs, and other key stakeholders coordinate the preparation of critical RCS for hydrogen and fuel cell technologies. The national templates have been accepted by the major SDOs in the U.S., key industry associations, and many state and local governments as the guideposts for a "national agenda" for hydrogen and fuel cell RCS development.

The national templates by consensus:

- establish lead SDOs to develop codes and standards for major components, subsystems, and systems and the organizations that will work collaboratively with the lead SDOs;
- minimize duplication of effort;
- harmonize requirements across RCS; and
- identify RCS development needs and gaps and the organizations that should have responsibility for addressing the gaps.

The structure provided by the templates is implemented through the National Hydrogen and Fuel Cells Codes and Standards Coordinating Committee (Coordinating Committee) formed by the SCS sub-program in collaboration with the above-mentioned stakeholders. The Coordinating Committee provides a single national forum for the hydrogen and fuel cell community to coordinate the continuous refinement and implementation of a national agenda for codes and standards.

SCS recognizes that domestic and international RCS must be coordinated and established to enable the widespread commercialization and safe deployment of hydrogen and fuel cell technologies. The lack of harmonized RCS applicable to hydrogen and fuel cell technologies is a major institutional barrier to deploying these technologies domestically and globally. A key need that has emerged is improved harmonization of requirements in RCS not only in the traditional markets of the European Union and Japan, but also in emerging economies such as China, India, and Brazil. SCS will evaluate specific needs for R&D while monitoring and assessing international efforts. Where possible, SCS will structure its R&D projects to coordinate and to leverage projects undertaken internationally. By working with organizations such as the IPHE, the European Community's Fuel Cell and Hydrogen Joint Undertaking, the International Energy Agency, the International Organization for Standardization (ISO), and the International Electrotechnical Commission (IEC), SCS will facilitate international harmonization of RCS and help further collective global efforts in RCS. Data and analysis needs of such international organizations will be considered to facilitate alignment of R&D projects where mutually beneficial.

Dissemination of Data, Safety Knowledge, and Information

The widespread availability and communication of safety-related information are crucial to ensure the safe operation of future hydrogen and fuel cell technology systems. For example, the HSP holds two meetings per year to conduct and assess its work, engage SCS and DOE program staff in topical discussions, and review safety-related aspects of their project portfolios. At its meetings, the HSP maintains open communication with other experts, organizations, and partnerships of relevance to SCS.

An appropriately prepared emergency response workforce trained in hydrogen safety is critical for a transition to a hydrogen infrastructure and the broad application of fuel cell technologies. A National Research Council review of the DOE Hydrogen Program identified such training as crucial.[3] In response, SCS developed a comprehensive training program on hydrogen safety for emergency responders. The Pacific Northwest National Laboratory (PNNL) teamed with personnel from the California Fuel Cell Partnership, the Volpentest Hazardous Materials Management and Emergency Response Training and Education Center, and the Hanford Fire Department and utilized the HSP and other experts and organizations to develop and deliver a training program for both awareness and operations.

The entire hydrogen community benefits if hydrogen safety-related knowledge is openly and broadly shared. SCS developed and maintains a set of knowledge tools for hydrogen safety as a resource for the community and to help meet its objectives. In FY 2006, SCS launched a website on hydrogen safety incidents and lessons learned (H2Incidents.org) to collect and review records of hydrogen safety events systematically and to ensure the full capture and categorization of knowledge about the events. The database includes information describing hydrogen incidents, near misses, and non-events (such as failed safety inspections), the severity and consequences of the incidents, the primary causes and contributing factors, the setting and equipment, and the lessons learned. All organizational and staff identification information is kept confidential and excluded from the publicly available database. As of summer 2011, the website contains over 200 safety event records, and new records will continue to be added as an ongoing activity. Collecting and sharing this kind of information is intended to help prevent recurrence of similar events in other locations.

In FY 2010, PNNL created a new quarterly feature on H2Incidents.org, "The Lessons Learned Corner," to analyze and share content on selected hydrogen safety themes, illustrated with specific safety event records in the database. Four quarterly editions were published and posted in FY 2011,

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[3] National Research Council and National Academy of Engineering, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, 2004, available at http://www.nap.edu/openbook.php?isbn=0309091632

and new themes will be added in FY 2012. For those working or beginning to work with hydrogen and related systems, PNNL launched a public website (H2BestPractices.org) in FY 2008 on hydrogen safety best practices. This online manual captures a vast base of knowledge and experience to provide guidance on safe practices for working with hydrogen as well as links to more detailed reference materials (e.g., documents, safety manuals, codes and standards, websites) to complement rather than duplicate other available resources.

As with other sub-programs in the Office of Fuel Cell Technologies, SCS participates in the DOE's Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review (AMR) where all of its projects are peer-reviewed. The AMR provides a public forum for all stakeholders to review current projects, ask questions of principal investigators, and provide input to DOE on the scientific and technical quality of projects as well as on improving program direction. Researchers supported by SCS also participates in key conferences and other venues to remain current in their technical fields, present research results, and help disseminate information and knowledge about R&D conducted under SCS.

The timely and accurate dissemination of relevant information is essential for SCS to maintain a consensus among all major stakeholders on the key issues, needs, and priorities for hydrogen and fuel cell RCS. Information about current codes and standards issues is provided through an online newsletter, "Hydrogen and Fuel Cell Safety," published monthly by the U.S. Fuel Cells and Hydrogen Energy Association and available at (www.hydrogensafety.info). The newsletter also tracks activities in codes and standards and provides a convenient site for information such as the minutes of the monthly teleconference meetings of the Coordinating Committee.

3.7.3 Programmatic Status

Current Activities

The current activities for the Hydrogen Safety, Codes and Standards sub-program's five focus areas are described below.

Safety Management

The use of hydrogen in industry is extensive, and energy suppliers and industrial gas companies have established an exemplary safety record in the production, distribution, storage, and use of hydrogen. In contrast, hydrogen and fuel cell technologies have a safe, but relatively short history of commercial use. Deployment of hydrogen and fuel cell technologies on a commercially viable scale introduces safety issues that must be addressed. The early phase of commercialization of new technologies is usually accompanied by rapid innovation and requires all stakeholders to share knowledge of risks and to promote safety of these technologies.

The HSP strives to raise safety consciousness most directly at the project level. Under SCS, safety begins at the project level by establishing safety culture as a priority under organizational policies and procedures. Project safety plans are reviewed in order to encourage thorough and continuous attention to safety aspects of the specific work being conducted. Through June 2011, the HSP reviewed 295 safety plans to help implement and improve safety culture in all DOE-funded projects. Project safety reviews conducted by the HSP help resolve safety issues associated with the use of hydrogen and hydrogen-related systems. These reviews focus on engagement, learning, knowledge-sharing, and active discussion of safety practices and lessons learned rather than as audits or regulatory exercises.

To date, safety review site visits and telephone interviews have been conducted for more than 45 projects. In FY 2010, the HSP first established a follow-up protocol to interview project teams in order to identify actions, findings and conclusions regarding safety review recommendations. Action on report recommendations represents a rich resource of safety knowledge that can have broader benefits to others. The HSP concluded that all interviewees have improved the safety aspects of their work. Overall, over 90% of the recommendations have been implemented in some manner or are in progress for the eleven follow-up interviews conducted.

HSP white papers on safety and hazard mitigation topics continue to provide expert insights and recommendations to DOE. Recent topics covered include (1) secondary protection for 70 MPa fueling, (2) potential fire suppression agents for metal hydride fires, and (3) hydrogen safety event reporting for incidents and near misses.

Research and Development

A major focus of SCS is to support R&D to establish a scientific basis for the development and incorporation of requirements in critical RCS for hydrogen and fuel cell technologies. The R&D component of SCS for hydrogen vehicles and fuel infrastructure is described in detail in the *Codes and Standards RD&D Roadmap 2010* (*Roadmap*) prepared under the Codes and Standards Tech Team (CSTT) of the U.S. DRIVE Partnership, a non-binding and voluntary government-industry partnership focused on advanced automotive and related infrastructure technology R&D. The Partnership provides a forum for pre-competitive technical information exchange to discuss R&D needs, develop joint goals and technology roadmaps, and evaluate R&D progress for a broad range of technical areas. The CSTT provides a forum for frequent and regular interaction among technical experts in hydrogen and fuel cell RCS. The *Roadmap*, in turn, provides a framework to accelerate technical progress in establishing a scientific basis and technical foundation for RCS by identifying pre-competitive R&D needs and challenges, defining possible solutions, and evaluating progress toward achieving technical goals and objectives.

The objective of the *Roadmap* is to identify and coordinate R&D to improve the scientific and technical foundation for RCS essential to enable full market deployment of hydrogen and fuel cell technologies by 2020. The *Roadmap* outline for R&D is shown in Table 3.7.1.

Table 3.7.1 Hydrogen Safety, Codes and Standards Current R&D Activities	
Focus Area	**Activities**

Hydrogen Behavior and Effects – Understanding, Validation, Mitigation	• Unintended release behavior (modeling and validation)
	  ○ Dispersion, diffusion, entrainment
	• Ignition and flammability
	  ○ Mechanisms and probability
	  ○ Flame propagation
	  ○ Global ignition model development
	• Fueling dynamics (modeling and validation)
	• Materials compatibility
	  ○ Quantification of hydrogen effects in metals
	  ○ Mechanisms of embrittlement and effects
	  ○ Hydrogen in non-metals
	• Hydrogen detection
	  ○ Sensor development

Materials Qualification Experimental Protocols	• Method optimization • Accelerated testing

Applied R&D – Data, Analysis, and Implementation: Analysis and Database Development	• Handbooks and resources
	  ○ Hydrogen Compatibility of Materials Technical Reference
	  ○ Material Qualification Handbook
	• Risk assessments
	  ○ Quantitative risk data
	  ○ Scenario analysis (modeling, confinement)
	  ○ Insurability (property and physical assets)
	• Mitigation
	  ○ Passive (barriers)
	  ○ Active (e.g. sensors, ventilation)
	• RCS development
	• International collaboration

For hydrogen behavior and effects, SCS has experimentally evaluated potential hydrogen auto-ignition mechanisms to quantify ignition probability for various unintended hydrogen release scenarios. Previously postulated ignition sources include Joule-Thomson heating, electrostatic discharge, catalytic surface effects, and diffusion ignition, most of which have not been reliably reproduced in a laboratory or have already been discounted[4]. Recently, transient shock processes associated with a rapid pressure boundary failure (e.g., a sudden release from a rupture disk) was identified as an ignition source and can be reliably reproduced over a wide range of pipe system geometries and supply pressures. SCS also investigated auto-ignition caused by entrainment of particles from within piping or tanks during release events. It was determined that entrainment of particles can lead to static discharge ignition when the hydrogen jet impinges on an ungrounded plate. These results contribute to the goal of developing a global engineering ignition model.

[4] For example: The temperature rise from ambient conditions due to the Joule-Thomson effect is insufficient to result in an ignition.

A set of models has been developed to describe the dispersion of hydrogen originating from a variety of storage systems, including high-pressure gas and liquid hydrogen (LH_2). The models have been leveraged to develop separation distances in NFPA 52[5] and NFPA 2[6] for high-pressure storage systems. Methodologies for specifying separation distances have been harmonized with those under consideration by ISO TC197 Working Group 11[7]. A draft separation distance table for LH_2 has been developed, although additional validation is necessary. Several critical release scenarios have been investigated, including that involving indoor refueling and vehicular tunnels. Results of these investigations have impacted requirements in NFPA 2 and NFPA 502[8].

The *Technical Reference for Hydrogen Compatibility of Materials* (*Technical Reference*)[9] was prepared and posted in response to stakeholder requests for data on the mechanical properties of structural materials exposed to hydrogen gas. Each chapter in the *Technical Reference* pertains to a specific material or material class that is relevant to hydrogen containment applications. The Technical *Reference* is a "living document" that is updated as new data become available from materials testing activities. Creation of the *Technical Reference* exposed gaps in the database for mechanical properties of materials in hydrogen gas, prompting the need for new materials testing programs. The effectiveness of efforts to generate new data depends on the materials testing methods. The effectiveness of efforts to generate new data depends on the materials testing methods. Emphasis on enhancing materials test methods has led to more reliable and efficient measurements of properties such as the sustained-load cracking threshold and fatigue crack propagation rates in hydrogen gas. These properties are essential for implementing new codes and standards applied to hydrogen containment components, such as the American Society of Mechanical Engineers (ASME) Article KD-10. In addition to improving test methods, advanced test capabilities are needed to replicate the demanding service environments representative of hydrogen containment components. State-of-the-art testing capabilities have been developed that allow reliable measurement of material properties under relevant service conditions, e.g., cyclic stress, high-pressure gas, low temperature.

Test Measurement Protocols and Methods

SCS is addressing a critical need of the fuel cell and hydrogen industries to facilitate development and validation of consensus test methods to qualify critical components and systems for commercial deployment. For example, the ideal situation from an automotive company's perspective would be that pressure vessels certified in one country would be allowed in other countries, which, in turn, would enable supplier-based development of pressure vessels on a global basis. SCS has outlined the following effort as part of the *Roadmap* in addressing test measurement protocols.

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[5] National Fire Protection Association 52 (NFPA 52): Vehicular Gaseous Fuel Systems Code, web site: http://www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=52

[6] National Fire Protection Association 2 (NFPA 2): Hydrogen Technologies Code, web site: http://www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=2

[7] International Organization for Standardization (ISO) Technical Committee Hydrogen Technologies (TC 197)/Working Group 11 Gaseous Hydrogen – Fueling Stations, web site: http://www.iso.org/iso/iso_technical_committee?commid=54560

[8] National Fire Protection Association 502 (NFPA 502): Standard for Road Tunnels, Bridges, and other Limited Access Highways, web site: http://www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=502

[9] The *Technical Reference* currently consists of 22 chapters that are available from the public website http://www.sandia.gov/matlsTechRef/.

- Test Methods and Component/System Performance
    - Test methods/protocols and validation
        - Materials qualification
            - Experimental method and protocol development
            - Accelerated testing methodologies
        - Component qualification
            - Materials-based qualification methods
            - Life-cycle performance testing
            - Pressure vessels
            - Pressure relief devices
        - System qualification
            - Fuel systems
            - Fuel cell assemblies
            - Dispensers and critical infrastructure systems
- Certification processes and methodologies
- Performance monitoring
    - Service life tracking and regulations
- Non-destructive evaluation (NDE)
    - Failure modes for composite pressure vessels in vehicular applications
- Fuel quality
    - Polymer Electrolyte Membrane (PEM) fuel cells for road vehicles
    - PEM fuel cells for stationary applications

Based on input gathered at several international workshops and from interaction with stakeholders, SCS is focusing on harmonization of requirements and test procedures for qualification of Type IV (fully wrapped composite cylinders with plastic, non-load bearing liners) pressure vessels for hydrogen vehicles. SCS supported development of technical requirements for and validation[10] of SAE J2579 (*Fuel Systems in Fuel Cell and other Hydrogen Vehicles*). SCS is also supporting the integration of verification tests for performance durability and on-road performance as set out in SAE J2579 in Phase 1 of the GTR for hydrogen vehicle systems. This integration will provide a notable example of harmonizing global vehicle regulations through incorporation of performance-based requirements developed under a domestic R&D, testing, and validation effort supported by SCS.

In concert with the development of harmonized requirements for Type IV pressure vessels described above, SCS is working through the Regulations, Codes and Standards Working Group (RCSWG) of the IPHE to prepare and validate a detailed test measurement protocol to enable comparability of results obtained by qualified testing facilities regardless of where the test may be executed. Under Phase 1 of this effort, the RCSWG will focus on developing and validating consensus methods to measure the relevant physics needed to execute the appropriate qualifying test

[10] Powertech Labs, Inc., *SAE J2579 Validation Testing Program: Powertech Final Report*, December, 2010, available at http://www.nrel.gov/docs/fy11osti/49867.pdf..

sequences, such as the pneumatic cycle testing as proposed in the draft GTR. This effort is a critical step in enabling a global supply chain of Type IV pressure vessels for hydrogen vehicles.

SCS through Sandia National Laboratories (SNL) developed and validated a test methodology to assess the performance of Type I (all metal) pressure vessels that undergo a large number of pressure cycles, in applications such as hydrogen powered industrial trucks. SNL performed pressure cycling of Type I pressure vessels with gaseous hydrogen; the pressure vessels were identical to those in service for hydrogen fuel cell forklift applications. Defects were engineered in some pressure vessels to simulate potential manufacturing flaws. Engineering analysis predictions were compared with experimental results from the performance evaluation of full-scale pressure vessels. In this case, test results indicated that engineering analysis provides conservative fatigue crack growth predictions. The testing also illuminated important failure characteristics such as leak size and leak-before-burst.

Traditionally, a deterministic engineering analysis is utilized for quantifying the progression of fatigue cracks as provided in the ASME Boiler and Pressure Vessel Code (Section VIII, Division 3, Article KD-4) and extended to the specific case of high-pressure gaseous hydrogen in Article KD-10. This framework provides a method for conservatively estimating the fatigue cycle life of pressure vessels based on assessment of existing flaws in the pressure vessel. An alternate method is based on the measured performance of manufactured pressure vessels subjected to pressure cycling coupled with statistical assessment of the quality of the pressure vessels and desired cycle life. SNL compared both of these cycle life determination methods for the hydrogen powered industrial truck application.

The qualification and listing of hydrogen and fuel cell systems and components are essential for their widespread market deployment. SCS is addressing pre-competitive needs that can lead to more rapid and less costly certification and listing of certain critical components and subsystems. Key needs identified include:

- Define what constitutes a hydrogen resistant material
- Develop a database of hydrogen resistant materials
- Provide additional data and guidance on materials compatibility, e.g., hydrogen embrittlement
- Assess and correlate existing standard approaches[11] and test protocols to determine resistance to hydrogen embrittlement
- Provide additional data on degradation of non-metallic materials induced at low-temperature
- Inform and educate AHJs on the role, function, and process of product certification, approval, and listing and educate them on inspection and enforcement of service life requirements for components

[11] For example, ASME Article KD-10 in Section VIII, Division 3, BPVC (Special Requirements for Vessels in High Pressure Gaseous Hydrogen Transport and Storage Service) is based on an engineering design approach, while ASME B31.12 2008 (Hydrogen Piping and Pipelines) establishes requirements for materials, components, design, fabrication, etc. Also, see discussion above on pressure cycling tests for pressure vessels.

- Include information on the process and purposes of component and system certification and listing in on-line training courses and incorporate such information in workshops for code officials supported by SCS.

The development, validation, and harmonization of hydrogen fuel quality specifications for polymer electrolyte membrane fuel cell (PEMFC) road vehicles has been a priority activity for the SCS as the performance and durability of PEMFCs can be severely affected by the presence of minute quantities of contaminants in hydrogen fuel. SCS is supporting a comprehensive testing effort to determine the effects of various impurities on fuel cell electrodes and membranes so that a sound technical foundation can be established for domestic and international SDOs to specify limitations for specific contaminants.

In collaboration with auto OEMs, fuel cell manufacturers, and energy suppliers, SCS has supported development of consensus test protocols. These test protocols include a round-robin test to validate testing apparatus and procedures, a common format for reporting data so that the data can be exchanged and shared among laboratories, and modeling to facilitate projection of test data to better understand effects of contaminants under different cell (e.g., pressure, temperature, relative humidity, catalyst loading) and operating (e.g., voltage, current density, stop/start) conditions. The testing has been focused on critical contaminants (CO, total sulfur species, NH_3) and their combination at worst-case operating conditions anticipated for PEMFC road vehicles.

SCS is also working with hydrogen fuel providers to understand better fuel quality issues related to hydrogen production methods and, clean-up systems, and to develop practical methods for verifying fuel quality at key points in the distribution and dispensing chain so that hydrogen can enter the mainstream of transportation fuels. SCS is supporting work by ASTM to develop standardized analytical methods and to validate them through inter-laboratory studies. Support by SCS has enabled both ISO and SAE to prepare fuel quality specifications that are nearing completion.[12]

One critical aspect for the safe and efficient deployment of hydrogen is the ability of chemical sensors to meet required performance specifications for the growing hydrogen infrastructure. SCS recently commissioned a Hydrogen Sensor Test Facility (Figure 3.7.3.1) at the National Renewable Energy Laboratory (NREL) to enable quantitative assessment of hydrogen safety sensors under well-defined protocols.

Sensor performance metrics are measured under precisely controlled conditions, including prescribed gas composition and environmental stresses (temperature, pressure, and humidity extremes). The test apparatus can simultaneously test multiple sensors and can handle all common electronic interfaces, including voltage, current, resistance, controller area network, and serial communication. The test facility is set up for around-the-clock operation, and all tests can be run and monitored remotely via the internet. The test facility provides manufacturers access to a state-of-the-art test facility for an independent, unbiased evaluation of their technologies

[12] ISO DIS 14687-2, *Hydrogen Fuel--Product Specification—Part 2: Proton Exchange Membrane Fuel Cell Applications for Road Vehicles, available at http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=55083*; SAE J2719, *Hydrogen Fuel Quality for Fuel Cell Vehicles, available at* http://standards.sae.org/j2719_201109.

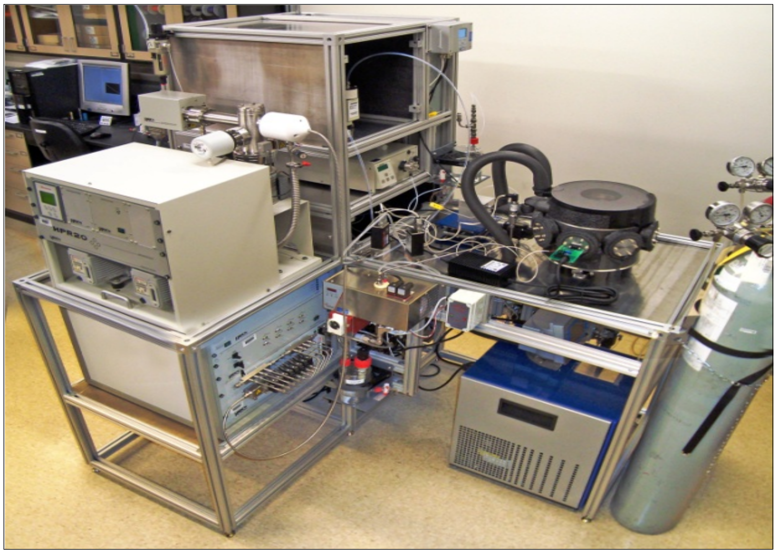


Figure 3.7.3.1 Hydrogen Sensor Test Facility at NREL (http://www.nrel.gov/hydrogen/facilities_hsl.html)

Development and Harmonization of Regulations, Codes and Standards

Traditionally, the role of the federal government has been to serve as a facilitator and developer for standards that cover technologies or applications that are of national interest. Examples include the involvement of the U.S. Coast Guard in standards for marine use; the Department of Transportation (DOT) in regulations governing interstate pipelines, tunnels, railroads, and interstate highways; and DOE for appliance standards, including the voluntary ENERGY STAR Program. The federal government also plays an important role in the adoption process, which involves converting a voluntary standard or model code into a law or regulation. Congress may pass laws governing both residential and commercial building design and construction to ensure public safety. Certain agencies of the federal government may also be granted authority by Congress to adopt and implement regulatory programs. Table 3.7.2 summarizes the various roles that the private sector and the federal government have in the codes and standards development process.

The development of codes and standards in the U.S. relies mainly on the voluntary participation of experts representing interested stakeholders who through a consensus process prepare requirements to help ensure that, within acceptable limits of risk, products are safe, perform as designed, and are compatible with the systems in which they are used. A generic overview of the codes and standards in the U.S. is provided in a recent report prepared for SCS by NREL.[13] The report also provides a comprehensive tabulation of codes and standards applicable to hydrogen fuel (pp. 85ff) and identifies gaps in codes and standards for the expanded use of hydrogen as an alternative fuel. SCS will address these gaps by supporting needs in R&D, testing, codes and standards development, and information dissemination and training identified in the report.

[13] C. Blake, et al., *Vehicle Codes and Standards: Overview and Gap Analysis*, NREL/TP-560-47336, Feb. 2010, pp. 17ff. The report also provides a comprehensive tabulation of codes and standards applicable to hydrogen fuel, pp. 85ff.

Table 3.7.2 Private and Federal Sector Role in Codes and Standards Development				
Private Sector		**Government Sector**		
Standard/Model Code Development Organizations (SDOs)	Other Private Sector Firms	Federal	State	Local
Develop consensus-based codes and standards with open participation of industry and other stakeholders	Develop hydrogen and fuel cell technologies and work with SDOs to develop standards	Perform underlying research to facilitate development of codes and standards, support necessary research and other safety investigations, and communicate relevant information to stakeholders (including state and local government agencies)	Evaluate codes and standards that have been developed and decide whether to adopt in whole, in part, or with changes	Evaluate codes and standards that have been developed and decide whether to adopt in whole, in part, or with changes

In December 2010, the NFPA issued NFPA 2, Hydrogen Technologies Code, a national code for hydrogen technologies that covers critical applications and operations such as hydrogen dispensing, production, and storage. NFPA 2 was created by consolidating NFPA hydrogen related codes and standards requirements into a single document and writing new requirements where there were no existing requirements. This consolidation makes it easier to draft code compliant permit applications and review these applications. This code also serves as a central document for all hydrogen technology reference standards. The current status of the development and harmonization of domestic RCS is summarized in Table 3.7.3.

The development of performance-based and harmonized international RCS is critical to fair and open competition in worldwide markets for hydrogen and fuel cell vehicles. Teaming with the National Highway Transportation Safety Administration (NHTSA) of the DOT, DOE through SCS is an active participant under the UNECE – WP.29 to develop GTRs for hydrogen fuel cell electric vehicles (HFCEV). A comprehensive GTR development process was implemented to address the environmental and safety concerns, including crashworthiness considerations, of HFCEVs. The development of the formal draft Phase 1 GTR resulted in performance-based provisions addressing both in-use and post-crash performance of the vehicle as well as critical components such as compressed gas storage systems and electrical safety. Phase 1 GTR is scheduled for a vote by WP.29 in November 2012. Once approved, Contracting Parties under the 1998 Agreement are obligated to start the adoption of the GTR into their regulations. Phase 2 of the GTR is scheduled to start in 2013, and will address materials compatibility and qualification, crash testing and other outstanding items from Phase 1. The status of international RCS is summarized in Table 3.7.4 and the status of domestic and international RCS for hydrogen and fuel cell vehicles is summarized in Table 3.7.5.

Table 3.7.3 Status of Domestic Hydrogen and Fuel Cell RCS		
Topic	**Status**	**SCS Focus**
Hydrogen Fuel	Fuel quality standard for PEMFC road vehicles (SAE J2719) issued in September, 2011	Support, coordinate single-cell testing, modeling, analysis; support SAE working group
Stationary Fuel Cells	NFPA 853 Standard for the Installation of Stationary Fuel Cell Power Plants, CSA F/C1 in place	Support changes in NFPA 55/2 to definition of bulk storage system that would result in less restrictive separation distances for hydrogen storage required to run stationary fuel cells
Fuel Cell Vehicles	Refer to Table 3.7.5 for details	Validate fuel system and component standards.
Fueling Stations	NFPA 2; International Fire Code Section 2209, Hydrogen Motor Fuel Dispensing and Generation Facilities, in place	Harmonize NFPA2 and IFC -- incorporate by reference or partial text extraction of NFPA 2 into IFC
Hydrogen Transportation	Governed by 49 CFR	Work with DOT on Hazardous Material Response Guidance to address hydrogen behavior

Table 3.7.4 Status of International RCS		
Topic	**Status**	**SCS Focus**
Hydrogen Fuel	Draft fuel quality standard for PEMFC road vehicles (ISO DIS 14687-2) issued by 2012	Support, coordinate single-cell testing, modeling, analysis; ISO working group
Stationary Fuel Cells	Draft fuel quality standard, ISO CD 14687-3, in preparation	Address US industry concerns, clarify rationale/requirements
Fuel Cell Vehicles	GTR Phase 1 issued by 2012 (Refer to Table 3.7.5 for further detail)	Harmonize pressurized fuel system with SAE J2579
Fueling Stations	ISO DIS 20100 under review, Canadian Hydrogen Installation Code in place	Harmonize with NFPA 2, address coordination of key requirements
Hydrogen Transportation	International Civil Aviation Organization (ICAO) *Technical Instructions For The Safe Transport of Dangerous Goods by Air*	Continue to work with ICAO to address air transport of hydrogen and fuel cell technologies

Table 3.7.5 Status of RCS for Hydrogen Fuel Cell Vehicles		
Topic	**Status**	**SCS Focus**
CSA America On-Board Road Vehicle Component Standards	HGV 2 Standard Hydrogen Vehicle Fuel Containers HGV 3.1 Fuel System Components for Hydrogen Gas Powered Vehicles HGV 4.1 Hydrogen Dispensers (Published as Tentative Interim Requirement (TIR) – April 2009) HGV 4.2 Hose and Hose Assemblies for Hydrogen Vehicles and Dispensing Systems (TIR) – April 2009 HGV 4.3 Fueling Parameters for Hydrogen Dispensing System HGV 4.4 Breakaway Devices for Hoses Used in Hydrogen Vehicle Fueling Stations (TIR) – April 2009 HGV 4.5 Priority and Sequencing Equipment for Gaseous Hydrogen Dispensing Systems (TIR) – April 2009 HGV 4.6 Manually Operated Valves Used in Gaseous Hydrogen Vehicle Fueling Stations (TIR) – April 2009 HGV 4.7 Automatic Pressure Operated Valves for Use in Gaseous Hydrogen Vehicle Fueling Stations (TIR) – April 2009 HGV 4.8 Hydrogen Gas Vehicle Fueling Stations Compressor HGV 4.9 Fueling System Guideline (under review) HGV 4.10 Performance of Fittings for Compressed Hydrogen Gas and Hydrogen Rich Gas Mixtures (TIR) December 2008 HPRD 1 Pressure Relief Devices for Hydrogen Gas Vehicle (HGV) Containers	Support completion of standards
CSA America On Board Industrial Truck Standards	HPIT 1 Compressed Hydrogen Powered Industrial Truck Onboard Fuel Storage and Handling Components CSA HPIT 2 Compressed Hydrogen Station and Components for Fueling Powered Industrial Trucks (draft standards)	Complete Type I tank pressure cycling tests

Table 3.7.5 Status of RCS for Hydrogen Fuel Cell Vehicles (continued)		
Topic	**Status**	**SCS Focus**
SAE On board road vehicle system standards	J1766 Recommended Practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing (April 2005) J2572 Recommended Practice for Measuring Fuel Consumption and Range of Fuel Cell and Hybrid Fuel Cell Vehicles Fuelled by Compressed Gaseous Hydrogen (October 2008) J2574 Fuel Cell Vehicle Terminology (September 2011) J2578 Recommended Practice for General Fuel Cell Vehicle Safety (January 2009) J2579 Technical Information Report for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles" (January 2009) J2594 Recommended Practice to Design for Recycling Proton Exchange Membrane (PEM) Fuel Cell Systems J2600 Compressed Hydrogen Surface Vehicle Refueling Connection Devices (March 2002) J2615 Testing Performance of Fuel Cell Systems for Automotive Applications (Stabilized Oct 2011) J2616 Testing Performance of the Fuel Processor Subsystem of an Automotive Fuel Cell System (August 2011) J2719 Hydrogen Fuel Quality for Fuel Cell Vehicles (September 2011) J2760 Pressure Terminology Used in Fuel Cells and Other Hydrogen Vehicle Applications (June 2011)	Validation and harmonization with international standards as appropriate
SAE Road Vehicle Fueling standards	J2601 Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles (TIR status)	Rapid fill model and validation
SAE Industrial truck fueling	J2919 TIR for Compressed Hydrogen Fuel Systems in Fuel Cell Powered Industrial Trucks (under development)	Harmonize with CSA HPIT1 Compressed Hydrogen Powered Industrial Trucks On-board Fuel Storage and Handling Components
Industrial truck performance standards	UL2267 Fuel Cell Power Systems for Installation in Industrial Electric Trucks (Revised January, 2011) NFPA 505 Fire Safety Standard for Powered Industrial Trucks Including Type Designations, Areas of Use, Conversions, Maintenance, and Operations (current edition)	Harmonize with CSA HPIT1 Compressed Hydrogen Powered Industrial Trucks On-board Fuel Storage and Handling Components

Table 3.7.5 Status of RCS for Hydrogen Fuel Cell Vehicles (continued)		
Topic	**Status**	**SCS Focus**
Federal Motor Vehicle Safety Standards (for fuel cell vehicles)	Not promulgated—pending adoption of GTR Phase 1 (Establish a GTR for hydrogen-fueled vehicles based on a component level, subsystems, and whole vehicle crash test approach.	Coordination with DOT/NHTSA
Global Technical Regulations (GTR)	Phase 1 final draft pending review and approval (Dec 2011--Phase I Submitted to the UN ECE WP29 for approval.)	Harmonize with SAE J2579
ISO Standards	13984:1999 Liquid Hydrogen-Land Vehicle Fueling System Interface 13985:2006 Liquid Hydrogen-Land Vehicle Fuel Tanks (Final Document) DIS 14687-2 Hydrogen Fuel -- Product Specification -- Part 2: Proton Exchange Membrane (PEM) Fuel Cell Applications for Road Vehicles (Draft International Standard) 16111:2008 Transportable Gas Storage Devices -- Hydrogen Absorbed in Reversible Metal Hydride (Final Document) 17268:2006 Compressed Hydrogen Surface Vehicle Refueling Connection Devices (Final Document) 15869: Gaseous Hydrogen and Hydrogen Blends -- Land Vehicle Fuel Tanks (June 2009, Currently Under Revision)	Harmonize with domestic standards as appropriate

Dissemination of Data, Safety Knowledge, and Information

SCS provides information, materials, and training facilities that are critical for the commercialization of hydrogen and fuel cell technologies and has published a variety of safety information resource tools to provide publicly available hydrogen safety data.

The *Hydrogen Safety Bibliographic Database* was established in response to a recommendation from the National Research Council and provides a comprehensive source of references to reports, articles, books, and other resources that address hydrogen safety in its production, storage, distribution, and use. The database, which is available at http://www.hydrogen.energy.gov/biblio_database.html, currently contains over 400 entries and is updated annually.

The *Hydrogen Incident Reporting and Lessons Learned Database* is available at http://www.h2incidents.org and provides lessons learned and relevant information gained from hands-on experience with hydrogen. All the safety event records include details of the incidents and are non-attributed to ensure anonymity. A quarterly *Lessons Learned Corner* on a topic of interest focuses discussion on a set of safety event records in the database.

The *Introduction to Hydrogen Safety for First Responders* provides a multimedia tutorial that acquaints first responders with hydrogen, its basic properties, and how it compares with like fuels. The web-based course, available at (http://www.hydrogen.energy.gov/firstresponders.html), has received over 17,000 unique visitors and is averaging 300-500 unique visitors each month from almost every state and many countries.

SCS also provides an operations-level course, *Hydrogen Emergency Response Training for First Responders*, which utilizes a live-fire FCEV prop for hands-on training. Five week-long deployments of the course and prop were held throughout the state of California in 2010 and 2011. Approximately 350 students from 18 states have been trained to date.

The *Hydrogen Safety Best Practices Manual*, available at (http://h2bestpractices.org/), is an online manual that captures a wealth of knowledge and experience for the safe handling and use of hydrogen. The website allows users to share expertise, publicly available documents, and references. The *H2 Safety Snapshot*, available at (http://www.hydrogen.energy.gov/pdfs/h2_snapshot.pdf), is a newsletter promoting safety best practices. The inaugural issue was published in April 2009.

The *Hydrogen Safety Training for Researchers* is an online training course on hydrogen safety for laboratory researchers and technical personnel. The six-module course features supplementary resources, such as a library section, which includes publications, related links, and glossary of terms. The course is available at http://www.h2labsafety.org.

3.7.4 Technical Challenges

The technical challenges must be overcome with solutions that are reliable, safe, and cost-effective. System safety must be convincingly communicated to enablers of fuel cell and hydrogen technologies, including regulatory authorities and the public. The technical challenges to the Hydrogen Safety, Codes, and Standards sub-program's five focus areas are highlighted below:

Safety Management

The key challenge to comprehensive safety management is to achieve 100% compliance with a requirement that all projects supported by the FCT Program submit safety plans for review by the HSP. In turn, SCS will systematically collect, analyze, and report all safety incidents and near misses that take place on FCT projects. In this way, SCS will take up the challenge to achieve zero safety incidents in hydrogen and fuel cell projects funded by FCT.

Comprehensive safety management is also a challenge because best practices for safety developed by industry to comply with regulations and to meet criteria required by insurance providers typically are not publicly available due to proprietary or liability concerns. The scientific and technical basis for best safety practices must then be inferred and validated by R&D and testing.

Research and Development

The most difficult challenge for research and development is the lack of predictive engineering tools that describe hydrogen behavior and data needed to develop and validate scientifically based codes and standards. Specific R&D needs and challenges are described under Technical Approach above. The R&D performed in support of RCS development must also be harmonized internationally to enable deployment of hydrogen technologies in markets worldwide.

A major challenge is to develop and implement methods to perform risk assessments of hydrogen installations and infrastructure. Risk-informed methods are most useful when real operational and safety data are used for analysis inputs, but such data are often proprietary and difficult to obtain. Risk-informed approaches must also allow for analysis of mitigation methods, both active and passive.

Test Measurement Protocols and Methods

The key technical challenge is to perform the first principles work to develop internationally harmonized robust, validated test measurement protocols so that a system qualified for service in one country will be accepted by other countries. Test measurement protocols must be developed for all relevant pressure and temperature environments that materials are subjected to during hydrogen service and must account for relevant manufacturing variables such as welds and other process effects. In addition, measurement protocols and test methods must be optimized to minimize the time and cost of qualification and enhance the timely development and deployment of new materials, components, and systems.

The cost of qualifying hydrogen components and systems can be prohibitive, and if test methods are too time consuming, new technology deployment can be delayed. Accelerated testing methodologies must be developed for materials, components, and system qualification that resolve the relevant physics and adequately emulate operational conditions. These test measurement protocols and methodologies must be documented rigorously such that they can be implemented by standards development and testing organizations.

Development and Harmonization of Regulations, Codes and Standards

The key challenge is to facilitate the development of clear and comprehensive codes and standards to ensure consistency and facilitate deployment of hydrogen and fuel cell technologies. Uniform standards are needed because manufacturers cannot cost-effectively manufacture multiple products that would be required to meet different and inconsistent standards. Availability of applicable standards also facilitates approval by local code officials and safety inspectors.

Another challenge is to reduce competition between individual SDOs and to minimize duplication in domestic codes and standards development. International standards developed by ISO and IEC will have an increasing impact on U.S. hydrogen and fuel cell interests and cooperative and coordinated development of international standards is also a key challenge.

Dissemination of Data, Safety Knowledge, and Information

The key challenge is a general lack of understanding of hydrogen and fuel cell safety needs among local government officials, fire marshals, and the public. For example, local public opposition has prevented or delayed construction and operation of hydrogen fueling stations. In other cases, the local regulatory authority may view one or more hydrogen properties (e.g., flammability at low concentrations) in isolation without considering other characteristics that could mitigate danger (e.g., rapid dispersion when released). Failure to comprehensively consider the properties and behavior of hydrogen may lead to overly restrictive policies that preclude or delay deployment of hydrogen and fuel cell technologies.

Other challenges include establishing mandatory reporting for safety and reliability of hydrogen and fuel cell systems that meet the needs of insurance providers and other stakeholders and training and educating government officials and AHJs.

Targets

Most SCS activities do not have quantifiable technical targets. Specific technical targets for hydrogen safety sensors are defined in Table 3.7.6.

Table 3.7.6 DOE Targets for Hydrogen Safety Sensors
Measurement Range: 0.1% - 10%
Operating Temperature: -30° to 80° C
Response Time: Less than one second
Accuracy: 5% of full scale
Gas Environment: Ambient Air, 10%-98% relative humidity range
Lifetime: 10 years
Interference Resistant (e.g. hydrocarbons)

3.7.5 Barriers

This section summarizes the technical barriers that must be overcome to meet the Hydrogen Safety, Codes, and Standards sub-program's objectives.

A. Safety Data and Information: Limited Access and Availability

Many new hydrogen fuel users and systems manufacturers lack hydrogen experience and have limited accessibility to data and documented experiences related to traditional hydrogen industrial, aerospace, and other applications. Only limited non-proprietary data on the operational and safety aspects of these technologies are easily accessible and data mining and other approaches have not been fully explored.

B. Availability and Affordability of Insurance

Potential liability issues and lack of insurability are serious concerns that could affect market entry and commercialization of hydrogen and fuel cell technologies due to a lack of loss history data.

C. Safety is Not Always Treated as a Continuous Process

Safety planning should be considered as an ongoing process of sufficient priority to achieve safe operation, handling, and use of hydrogen and fuel cell technology technologies. Awareness and adoption of best practices throughout the duration of a project can be a substantial asset toward achieving project goals.

D. Lack of Hydrogen Knowledge by AHJs

Officials responsible for approving the safety of hydrogen and fuel cell technologies, systems, and installations often have insufficient knowledge of hydrogen properties and characteristics. Effective and targeted education and outreach will continue to serve a valuable role.

E. Lack of Hydrogen Training Materials and Facilities for Emergency Responders

A suitably trained emergency response force is essential for preventing the escalation of hydrogen related incidents. Responders can apply their training background to their work but have little experience with hydrogen technologies, in part because applicable training materials specific to hydrogen emergency response are not broadly available.

F. Enabling National and International Markets Requires Consistent RCS

Lack of consistency limits international trade and markets.

G. Insufficient Technical Data to Revise Standards

Research and operational data collection activities are underway to develop science-based codes and standards. New approaches for data generation, collection, and analysis will also be needed to close safety knowledge gaps.

H. Insufficient Synchronization of National Codes and Standards

The codes and standards development and revision cycles established by SDOs vary and are difficult to coordinate or synchronize even under a consensus national agenda.

I. Lack of Consistency in Training of Officials

The training of code officials is not mandated and varies significantly. The large variations in the resources of jurisdictions lead to variation in training and technical capability.

J. Limited Participation of Business in the Code Development Process

Businesses, particularly small businesses, do not have the resources to participate in the codes and standards development process.

K. No Consistent Codification Plan and Process for Synchronization of R&D and Code Development

R&D to obtain data and validate engineering models, for example, are time consuming and difficult to synchronize with code development and revision schedules established by SDOs.

L. Usage and Access Restrictions

Appropriate codes and standards need to be developed for parking structures, tunnels, and other usage areas.

3.7.6 Task Descriptions

Task descriptions for SCS are identified in Table 3.7.7. To complete these tasks, SCS will collect and analyze data from the Production, Delivery, Storage, Fuel Cell, Manufacturing, Technology Validation, Education and Market Transformation sub-programs and coordinate with Systems Analysis on an on-going basis.

Table 3.7.7 Task Descriptions

Task	Description	Barriers
1	**Safety Management** • Address Safety of DOE R&D Projects: ○ Conduct ongoing safety assessments of DOE projects through site visits and safety plan reviews. ○ Develop, update, and maintain guidelines for all DOE-funded projects to include safety planning in all aspects of the project, including safety incident tracking. ○ Coordinate with all FCT sub-programs to communicate relevant safety-related activities and apply lessons learned e.g., include comprehensive safety plan in the annual review process of FCT projects. • Develop a comprehensive communication strategy: ○ Publish communications strategy ○ Compile information from databases and safety assessments. ○ Publish the final Best Practices Handbook for Hydrogen Safety and support the adoption of these practices.	A, B, C, D, E

Table 3.7.7 Task Descriptions (continued)		
Task	**Description**	**Barriers**

2	**Research and Development**
	• Accelerate the implementation of inherently safe installations based on technically defensible RCS:
	  ○ Provide critical data on hydrogen properties and behavior.
	  ○ Coordinate participating organizations to facilitate the adoption of R&D results in hydrogen, building, and fire codes.
	• Explore systems approaches and "holistic" design strategies for development of systems that are inherently safer:
	• Develop leak detection technologies.
	• Establish risk assessment protocol to identify failure modes and mitigate risks to enhance RCS development process:
	  ○ Develop protocols for identifying potential failure modes.
	  ○ Develop and validate risk mitigation approaches.
	  ○ Work with industry experts to review and revise protocol.
	  ○ Release consensus protocol to use in SCS solicitations.
	• Conduct risk assessment and compile key data:
	  ○ Develop a system for classifying accident types.
	  ○ Develop a methodology for estimating accident likelihood.
	  ○ Develop and release a report of the most common accident scenarios.
	• Develop international fuel quality contaminant specifications.
	• Quantify the hydrogen compatibility characteristics of existing and new materials:
	  ○ Understand fundamentals of hydrogen attack.
	  ○ Develop new high-performance materials.
		A, G, K, L

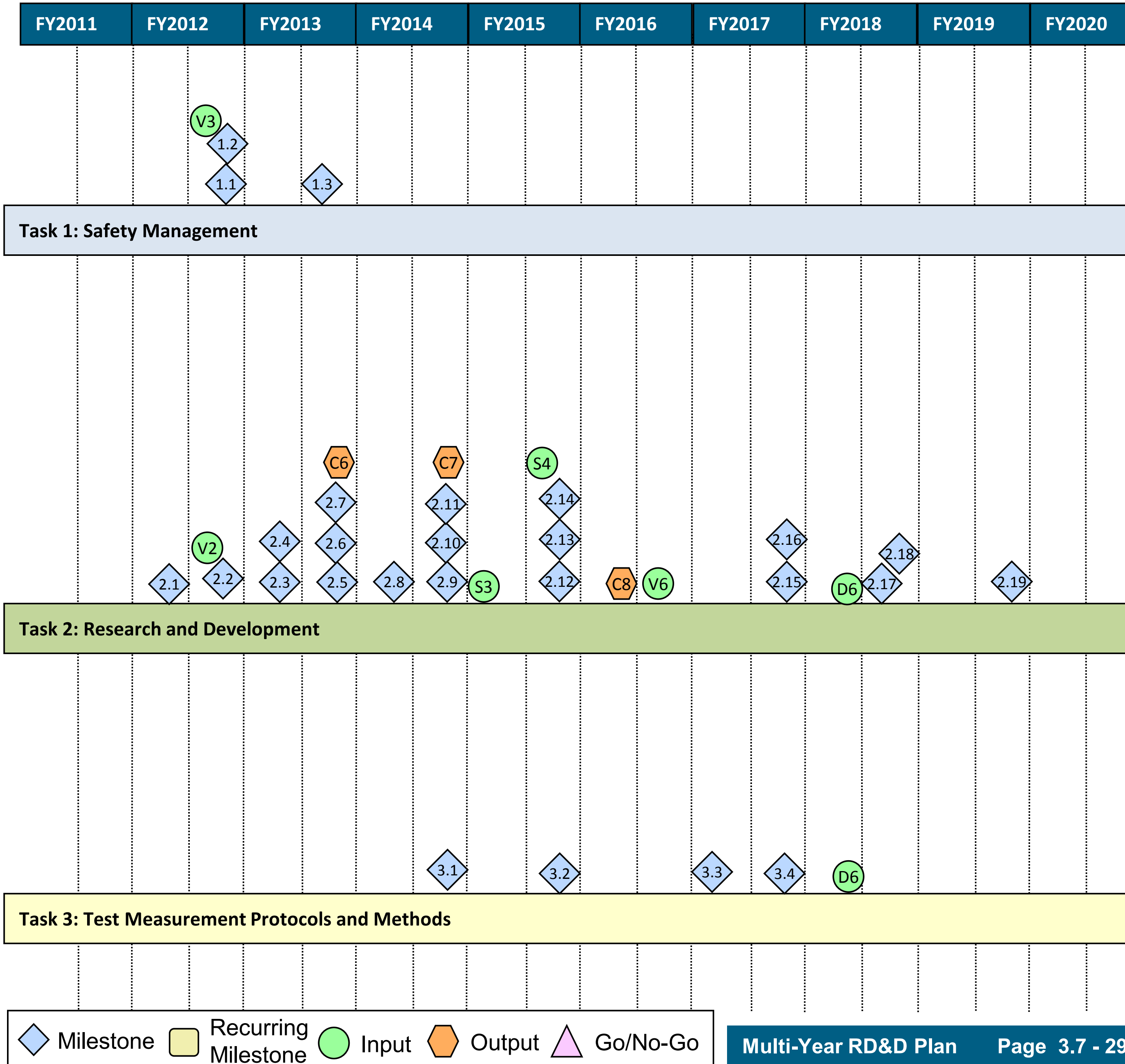
3	**Test Measurement Protocols and Methods** • Develop, validate, and harmonize test measurement protocols and methods for materials, components, and systems to accelerate the qualification process. • Perform hydrogen quality R&D and develop testing protocols and parameters required for the harmonization of hydrogen fuel quality standards.	F, G, H, K

Table 3.7.7 Task Descriptions (continued)		
Task	**Description**	**Barriers**
4	**Development and Harmonization of RCS** • Facilitate the development and promulgation of critical RCS needed to enable full deployment of FC vehicles and hydrogen infrastructure: ○ Identify and evaluate failure modes to establish critical research and validation needs. ○ Develop supporting research programs to provide critical data and technologies. ○ Determine safe refueling protocols for high pressure systems. ○ Perform risk mitigation analysis for advanced transportation infrastructure systems. (i.e., storage technologies, active control on dispensing systems, etc.). • Support harmonization of domestic standards: ○ Implement the National Codes and Standards Chronological Development Plan. ○ Develop a fueling station codes and standards template. ○ Develop and validate requirements for components and systems. • Coordinate the harmonization of international standards: ○ Facilitate the development of U.S. consensus for international standards. ○ Facilitate a unified approach to standards development among key countries in Europe and Asia.	A, D, F, G, H, J, K
5	**Dissemination of Data, Safety Knowledge, and Information** • Develop comprehensive information resources on hydrogen and fuel cell safety and incidents: ○ Develop and maintain a comprehensive repository for hydrogen and fuel cell safety data and information. ○ Publish safety bibliography and incidents databases. • Develop appropriate hydrogen safety props and deliver classroom curriculum for emergency response training. • Implement a mechanism to provide standardized training and improve access to information concerning standards and model codes related to hydrogen technologies. • Assemble and maintain information databases for hydrogen behavior and materials interaction characteristics: ○ Materials compatibility information. ○ Technical references.	A, C, D, E, G, I, K,

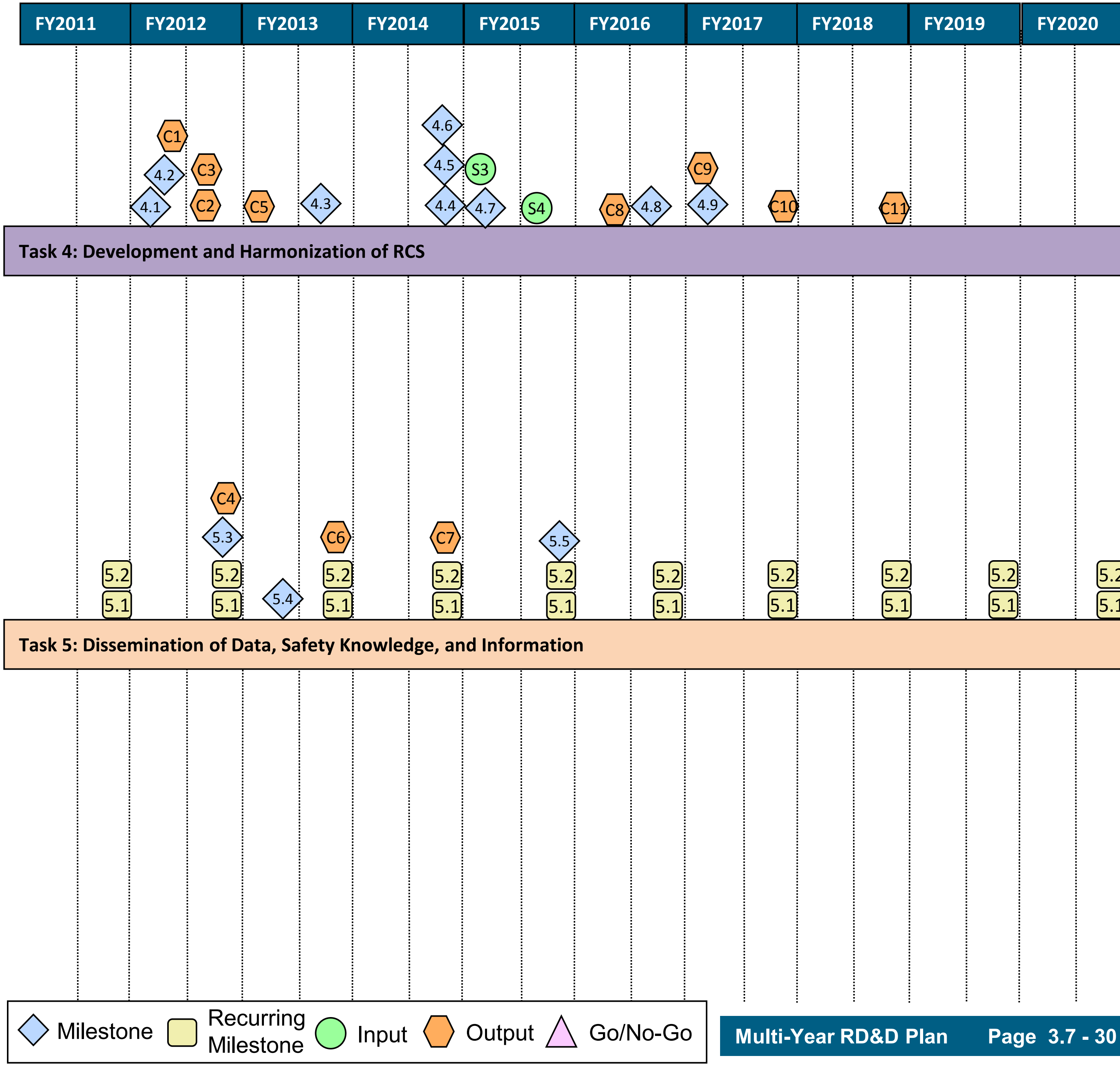
3.7.7 Milestones

The following chart shows the interrelationship of milestones, tasks, supporting inputs from other sub-programs, and technology program outputs for the Hydrogen Safety, Codes, and Standards sub-program. The inputs/outputs are also summarized in Appendix B.

Safety, Codes and Standards Milestone Chart



Safety, Codes and Standards Milestone Chart



Task 1: Safety Management	
1.1	Revise guidelines for all DOE funded projects. (4Q, 2012)
1.2	Publish communication strategy for safety related activities. (4Q, 2012)
1.3	Publish final Best Practices Manual for Hydrogen Safety. (3Q, 2013)

Task 2: Research and Development	
2.1	Publish a system for classifying accident types. (2Q, 2012)
2.2	Publish a draft international hydrogen fuel specification standard (4Q, 2012)
2.3	Publish protocols for identifying potential failure modes. (2Q, 2013)
2.4	Publish a methodology for estimating accident likelihood. (2Q, 2013)
2.5	Release a report of the most common accident scenarios. (4Q, 2013)
2.6	Develop sensors meeting technical targets. (4Q, 2013)
2.7	Provide critical understanding of hydrogen behavior relevant to unintended releases in enclosures. (4Q, 2013)
2.8	Publish risk mitigation approaches. (2Q, 2014)
2.9	Publish technical basis for optimized design methodologies of hydrogen containment vessels to account appropriately for hydrogen attack. (Q4, 2014)
2.10	Understand flame acceleration leading to transition to detonation. (4Q, 2014)
2.11	Publish draft protocol for identifying potential failure modes and risk mitigation. (4Q, 2014)
2.12	Develop leak detection devices for pipelines. (4Q, 2015)
2.13	Develop and validate simplified predictive engineering models of hydrogen dispersion and ignition. (4Q, 2015)
2.14	Publish national indoor hydrogen fueling standard. (4Q, 2015)
2.15	Develop holistic design strategies. (4Q, 2017)
2.16	Demonstrate the use of new high-performance materials for hydrogen applications that are cost-competitive with aluminum alloys. (4Q, 2017)
2.17	Publication of updated international fuel quality standard to reflect fuel cell technology advancement. (3Q, 2018)
2.18	Implement validated mechanism-based models for hydrogen attack in materials (Q4, 2018)
2.19	Validate inherently safe design for hydrogen fueling infrastructure. (4Q, 2019)

Task 3: Test Measurement Protocols and Methods	
3.1	Develop, validate, and harmonize test measurement protocols. (4Q, 2014)
3.2	Publish hydrogen quality testing protocols. (4Q, 2015)
3.3	Reduce the time required to qualify materials, components, and systems by 50%, relative to 2011) with optimized test method development. (1Q, 2017)
3.4	Develop hydrogen material qualification guidelines including composite materials (Q4, 2017)

Task 4: Development and Harmonization of RCS	
4.1	Complete determination of safe refueling protocols for high pressure systems. (1Q, 2012)
4.2	Develop supporting research programs (round robins) to provide data and technologies. (2Q, 2012)
4.3	Identify and evaluate failure modes. (3Q, 2013)
4.4	Complete National Codes and Standards Chronological Development Plan. (4Q, 2014)
4.5	Complete fueling station codes and template. (4Q, 2014)
4.6	Completion of standards for critical infrastructure components and systems. (4Q, 2014)
4.7	Complete risk mitigation analysis for advanced transportation infrastructure systems. (1Q, 2015)
4.8	Revision of NFPA 2 to incorporate advanced fueling and storage systems and specific requirements for infrastructure elements such as garages and vehicle maintenance facilities. (3Q, 2016)
4.9	Completion of GTR Phase 2. (1Q, 2017)

Task 5: Dissemination of Data, Safety Knowledge, and Information	
5.1	Update safety bibliography and incidents databases. (4Q, 2011 – 2020)
5.2	Update materials compatibility technical reference. (4Q, 2011 – 2020)
5.3	Enhance hydrogen safety training props and deliver classroom curriculum for emergency response training. (4Q, 2012)
5.4	Develop and publish database for properties of structural materials in hydrogen gas. (2Q, 2013)
5.5	Implement standardized training mechanism and information for model codes. (4Q, 2015)

Outputs

C1 Output to Delivery, Technology Validation, and Program: NFPA2: Hydrogen code document. (2Q, 2012)

C2 Output to Production, Delivery, Storage, Fuel Cells, Technology Validation, Systems Integration, and Program: Hydrogen fuel quality standard (SAE J2719). (3Q, 2012)

C3 Output to Program: International hydrogen fuel specification standard. (3Q, 2012)

C4 Output to Education and Program: Updated best practices handbook on hydrogen safety. (4Q, 2012)

C5 Output to Program: GTR Phase 1. (1Q, 2013)

C6 Output to Production, Delivery, Storage, Technology Validation, Education, Systems Integration and Program: Updated materials compatibility technical reference manual. (4Q, 2013)

C7 Output to Production, Delivery, Storage, Technology Validation, Market Transformation, Manufacturing and Program: Materials reference guide and properties database. (4Q, 2014)

C8 Output to Delivery, Technology Validation, Market Transformation, and Program: National indoor fueling standard. (2Q, 2016)

C9 Output to Program: Revised NFPA 2. (1Q, 2017)

C10 Output to Program: GTR Phase 2. (4Q, 2017)

C11 Output to Program: Updated international fuel specification standard. (4Q, 2018)

Inputs

D6 Input from Delivery: Technology and material characteristics of advanced delivery systems. (2Q, 2018)

S3 Input from Storage: Material characteristics and performance data on advanced storage materials and systems. (1Q, 2015)

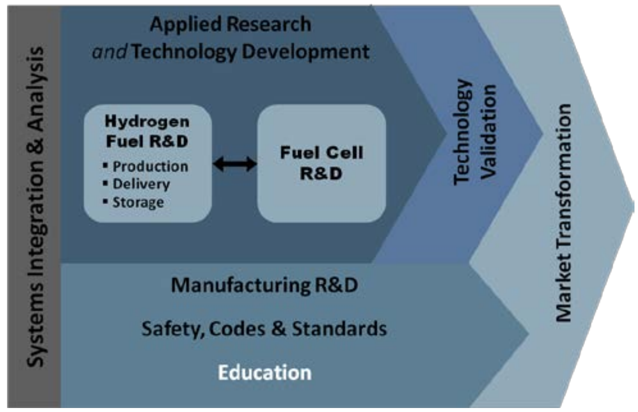
S4 Input from Storage: Update of fuel quality from promising storage materials. (Q3, 2015)

V2 Input from Technology Validation: 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 Input from Technology Validation: Publish/post composite data products for material handling and backup power, including safety event data. (3Q, 2012)

V6 Input from Technology Validation: Validate 700-bar fast fill fueling stations against DOE fueling targets. (3Q, 2016)

3.8 Education and Outreach



Expanding the role of hydrogen and fuel cell technologies as an integral part of the Nation's energy portfolio requires sustained education and outreach efforts. Increased efforts are required to facilitate near-term demonstration projects and early market fuel cell and hydrogen infrastructure installations, to increase public awareness and understanding, and to lower barriers to ease long-term market adoption. Fuel cell and hydrogen technologies are making an impact on the market *today* in stationary power, emergency backup power, material handling equipment, portable power, niche transportation, and telecommunications applications. Current knowledge and awareness levels of hydrogen and fuel cells are still low in the general public, and misunderstandings of hydrogen properties continue to impart negative opinions about the safe use of hydrogen as a fuel. A sustained education and outreach program is needed to continue to build upon the progress that has been made to date and to leverage the success stories of early adoption.

The Education and Outreach activities within DOE's Hydrogen and Fuel Cell Program (the Program) seek to facilitate hydrogen and fuel cell early deployments and support future broader commercialization by providing technically accurate and objective information to key target audiences that are both directly and indirectly involved in the use of hydrogen and fuel cells technologies today. These audiences, originally identified in the National Hydrogen Energy Roadmap[1], include state and local government representatives and stakeholders, potential end users, early adopters, safety and code officials, local communities, and the general public. University faculty, undergraduate and graduate students, and middle and high school teachers and students comprise another important audience, as they are our Nation's future researchers, scientists, engineers, technicians, teachers, and technology users.

3.8.1 Goal and Objectives

Goal

The goal of the Education and Outreach activities within the Fuel Cell Technologies Program (subsequently abbreviated as the Education sub-program) is to educate key audiences about hydrogen and fuel cell technologies to facilitate near-term deployment, early adoption, broad commercialization, and long-term market acceptance.

[1] U.S. Department of Energy. *National Hydrogen Energy Roadmap*. November 2002. p. 36. Available on the web at http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf

Objectives

The Education sub-program's objectives are closely coordinated with technology demonstration and validation, safety, codes and standards, and early market deployment and associated market transformation activities, as well as state and regional-based hydrogen and fuel cell outreach programs—as part of a comprehensive strategy to transform success in demonstrating and deploying technologies into success in the broader marketplace. Specific objectives include the following:

- Increase the acceptance of the use of hydrogen and fuel cell technologies as a part of *a clean energy portfolio of energy efficiency and renewable energy technologies* in federal, state, and local government investments, and private sector investments
- Decrease "soft costs" associated with the deployment and early adoption of hydrogen and fuel cell technologies in multiple applications (e.g., insurance, permitting, uniform codes and standards) through education, outreach, and training of "second generation" clean energy professionals
- Increase general knowledge and awareness of the benefits of the use of hydrogen and fuel cell technologies in multiple applications among the key target audiences
- Increase awareness of the potential full range of fuel cell and hydrogen applications (e.g., not just light-duty vehicles and buses)

3.8.2 Approach

By supporting the successes achieved by existing hydrogen and fuel cell demonstrations and deployments, the Education sub-program is able to capitalize on the interest generated by these activities to reach a broader and more engaged audience, as well as the most likely early adopters. In addition, by providing valuable third-party information and testimonials from "real-world" users, education and outreach activities and materials help spread the message to facilitate the implementation and establishment of these projects and contribute to their success. Integrating education and outreach efforts into active demonstration and deployment activities is critical and helps ensure that these investments lead to genuine transformation of the marketplace, ultimately leading to long-term market adoption and acceptance.

Strategy

Expanding use of hydrogen and fuel cells as part of a clean energy portfolio of energy efficiency and renewable energy technologies will require a combination of technological progress, increased market acceptance, and investments in infrastructure. The education and outreach efforts must assume a phased and focused approach that considers technology competitiveness in a given market application and the associated Program's overall market transformation strategy in that market.

The Education sub-program will "follow the technology" (and its accompanying applications) and concentrate on areas where hydrogen and fuel cells are publicly visible through demonstration projects and early market deployment and commercialization efforts. The efforts will evolve to ensure alignment with the Program's priorities in technology demonstration and validation; safety, codes and standards; and market transformation activities and investments.

The Education sub-program activities will support state and regional outreach efforts by providing consistent messages, readily available information resources, and other activities, as appropriate. Activities include the development and dissemination of information resources (e.g., fact sheets, business case studies, financial tools) and rely on partnerships to leverage limited resources and extend the reach of the Program's efforts. Examples include the following:

- **Webinars, Newsletters, and Online Media**
  Today's world is built on the Internet. From Smart Phones and tablets to video conferencing, the boundaries of today's workplace are fluid and multi-dimensional. By offering information that is portable and fully accessible, the Education sub-program ensures that it reaches a broader audience. Webinars provided in place of traditional in-person meetings can significantly increase audience participation. Newsletters and news alerts sent electronically not only decrease production costs, but increase market reach. The Education sub-program focuses on fully leveraging the online tools available to increase market expansion.
- **Educational Materials and Information Resources**
  Resources include traditional print materials, such as fact sheets, and information available on the Web, and via other forms of media including audio, CD, and video. Careful attention must be given to cost and to traditional forms of media/information delivery to which target audiences are accustomed. The primary distribution mechanism for education and outreach materials will be the Program Website, via Web pages, databases, electronic documents, and other interactive tools and resources.
- **Third-party Case Studies, Market Reports, and Project Tools**
  The Education sub-program coordinates with other sub-programs within the Fuel Cell Technologies Program (FCT Program) to capture performance data and "real-world" operating experience. Third-party commissioned studies provide additional tools to project developers and industry for formulating business cases to utilize hydrogen and fuel cells to increase energy efficiency, reduce environmental impact, and improve reliability and productivity. Products include industry market reports, compendia of state activities, specific deployment case studies, and financial tools to estimate economic impacts.
- **Partnerships and Collaboration**
  Coordination with other agencies and stakeholders helps to ensure effective use of taxpayer dollars by avoiding duplication and leveraging resources to achieve common goals. Partnerships with stakeholder organizations also provide a distribution channel for DOE-funded educational materials and information resources. Leveraging public-private partnerships such as U.S. DRIVE and the California Fuel Cell Partnership is critical. The Education sub-program will rely on strategic partnerships with hydrogen and fuel cell industry and clean energy trade associations such as the Fuel Cell and Hydrogen Energy Association, state energy programs, state and regional initiatives, and international partners (through the International Partnership for Hydrogen and Fuel Cells in the Economy and the International Energy Agency and its implementing agreements) to extend the reach of its efforts, as well as for informal feedback on ongoing efforts and future directions.

- **Training and Workforce Development Efforts**
As market demand for hydrogen and fuel cell technologies increases across sectors of our economy, there will be an increasing need for trained and experienced personnel and accompanying services such as qualified maintenance technicians, installers, manufacturing professionals, trainers, insurers, and educators, as examples. As market demand grows and resources allow, the Education sub-program will develop with stakeholders the "train the trainer" job certifications and curriculum required to support this growing workforce. In-person training via workshops or seminars can be an effective mode of targeted information delivery and training, as it essentially guarantees a captive audience with little distraction and allows for additional "unplanned" learning through interaction between and among the instructor and students. In-person training is expensive, however, and will be considered as budget allows and only for the areas with the greatest need (both geographic and topical, to align with the Program's market transformation plans). Online training through webcasts and webinars will be considered as an alternative to increase the number of training opportunities provided and extend the reach of DOE-funded efforts to a larger audience. Audiences for the training and outreach will include job seekers, energy service companies and utilities, venture capital firms, insurance and underwriter industries, state government workforce development agencies, government code officials, first responders, and local public and community outreach.

Messaging

The Education sub-program considers a balanced message to help target audiences become familiar with hydrogen and fuel cell technologies and how they fit in the clean energy portfolio, to develop an accurate understanding of hydrogen safety, to recognize opportunities, and to understand their part in facilitating the use of hydrogen and fuel cell technologies in multiple market applications across the economy. Maintaining the Program's reputation as a credible source of technically-accurate and objective information about hydrogen and fuel cell technologies is essential. All materials developed and funded by the Education sub-program will undergo critical review for accuracy of content, audience usability, and consistency with higher-level DOE programmatic material and messaging.

The Education sub-program will also utilize existing hydrogen and fuel cell deployments and early adoptions to showcase "real-world" success stories. By including these third party testimonials in outreach materials, the audience receives their information from their peers and colleagues, not just from the Federal Government. This approach provides the increased confidence with knowing that other customers are successfully using hydrogen and fuel cells.

The impact and effectiveness of messaging and education and outreach products can be assessed using survey tools. The FCT Program conducted a baseline survey in 2004 to evaluate basic understanding of hydrogen properties and align with simple messages relative to well-established energy security and environmental benefits of the use of hydrogen and fuel cell technologies. Data collected in the 2004 baseline survey indicated a direct correlation between knowledge of hydrogen and opinions about safety. As resources allow, the Education sub-program will conduct subsequent surveys in the mid to long-term to gauge progress of effective messaging and outreach efforts.

Target Audiences

Table 3.8.1 identifies the target audiences for hydrogen and fuel cell education and outreach and briefly describes their information needs. As illustrated in the table, target audiences for education have been prioritized according to their involvement or role in the use of hydrogen and fuel cell technologies in the near term. While activities to educate all key target audiences are important, the Education sub-program must focus its limited resources on those with the greatest near-term need.

Table 3.8.1 Key Target Audiences for the Education Sub-program

Target Audience	Rationale
Potential End Users	Potential early adopters in stationary power, portable power, material handling, niche transportation, and light-duty vehicle applications need information about near- and mid-term opportunities
State and Local Government Representatives	A broad understanding of hydrogen and fuel cells and potential deployment opportunities supports decision-making on current opportunities and lays the foundation for long-term change. Key goals are to ensure that hydrogen and fuel cells technologies are viewed as one tool in a portfolio of options to reach energy efficiency and GHG reduction goals and to improve reliability and productivity and to provide economic benefits.
Local Communities/ General Public	Will be more likely to welcome local demonstration projects when they are familiar with the benefits and limitations of hydrogen and fuel cells
Code Officials	Must be familiar with use of hydrogen to facilitate the permitting process and local project approval, as appropriate
First Responders	Must know how to handle potential incidents; their understanding can also facilitate local project approval
University Faculty and Students	Current interest is high; graduates needed for research and development in industry and academia
Middle School and High School Teachers and Students	Current interest is high; teachers looking for technically accurate information and usable classroom activities

3.8.3 Programmatic Status

New projects that were competitively awarded in FY2004 and FY2008 have been completed using FY2010 appropriations. Given budget constraints and the need for including hydrogen and fuel cells within the broader EERE portfolio, education and outreach activities will be coordinated with other DOE-wide efforts. Target audiences have been prioritized according to their near-term relevance and the effect on the use of hydrogen and fuel cell technologies today.

The Education sub-program first focused its efforts on cross-cutting information resources, including the program website, as well as technology introduction fact sheets and overview material appropriate to multiple target audiences with little background in hydrogen or fuel cells. Existing hard copy materials are available at the EERE Information Center, described previously.

Table 3.8.2 summarizes current activities focused on the key target audiences. Technical expertise and an understanding of the audience are crucial to usability of the final product, whether it is training, outreach, or an educational tool. As a guiding principle for all of its activities, the Education sub-program seeks to pair hydrogen and fuel cell technology experts with professionals representing (or those intimately familiar with) the target audience.

Table 3.8.2 Current Activities

Target Audience	Activity Description
Activities Led by the Safety, Codes and Standards Sub-program:	
First Responders	• "Introduction to Hydrogen Safety for First Responders" project; course modules include information about hydrogen properties, comparisons to other common fuels and technologies, and initial emergency response actions (Pacific Northwest National Laboratory and other partners).
Code Officials	• "Introduction to Hydrogen for Code Officials," an information package that builds on the first responders course with more information specific to codes and standards (National Renewable Energy Laboratory and other partners).
Activities Led by the Education & Outreach Sub-program (Coordinated with the Market Transformation Sub-program):	
Potential End Users	• Case studies of business models of the use of hydrogen and fuel cell technologies for applications such as back-up power and stationary power. • Economic tools such as employment and economic impact estimators at the state and regional level for early market fuel cell deployments. • Introductory information about hydrogen vehicles for fleets and other potential end users.
State and Local Government Representatives	• Database of state activities – demonstrations, policies, and initiatives (Fuel Cells 2000, Alternative Fuels Data Center). • Regular informational calls and public webinars with state and regional hydrogen and fuel cell initiatives
Local Communities/ General Public	• Materials are available for the general public through websites maintained by the Program and other hydrogen and fuel cell organizations. Local communities are served by the activities occurring with all of the other target audiences.

Table 3.8.2 Current Activities (continued)	
Target Audience	**Activity Description**
University Faculty and Students	• Undergraduate and graduate level curriculum developed through FY2008 university projects • Student "H2U" University Design Contest (Hydrogen Education Foundation) • Partnerships for student internships and post doctoral fellow opportunities
Other Teachers and Students	• Teacher and student curriculum developed through FY2004 Pre-college projects: • "H2 Educate!" for middle schools (National Energy Education Development Project and partners). • "Hydrogen Technology and Energy Curriculum (HyTEC)" for high schools (Lawrence Hall of Science at the University of California, Berkeley and partners).

3.8.4 Challenges

Considering our Nation's long relationship with the gasoline internal combustion engine and use of fossil fuels for stationary power, the move to hydrogen and fuel cell technologies for transportation, stationary power and portable power is a fundamental change in the way we use energy. Resistance or hesitance to change is the overarching challenge to education, and it is fed by several different factors.

The first factor is low awareness. Rumors, misinterpretation, and misunderstanding of historical events and the facts about hydrogen safety may prompt people to express a "not in my backyard" mentality. Technically accurate information from a trusted and objective source can raise awareness, correct misinformation or false perceptions, and help to build comfort levels with using new energy technologies.

The second factor is that examples of "real-world" market applications using hydrogen and fuel cell technologies are not as well publicized as they could be. Technology demonstrations, though increasingly visible in the public space, are not common throughout the country. The number of demonstrations is growing, but there are still limited "real-world" examples to which we can highlight when introducing the idea of using hydrogen and fuel cells as one option in a clean energy portfolio. Some people may embrace the opportunity to be among the first to experience cutting-edge technology, while others may not want to feel that they are "part of the experiment." Real-world examples and, better still, hands-on or first-hand experience, can greatly enhance understanding and comfort with using a new fuel and energy carrier and new power generation technologies.

The third factor that can feed resistance to change, and therefore influence the overall challenge to education, is the "what's in it for me" factor. Although hydrogen and fuel cell technologies are emerging in the commercial market in some specialized niche applications such as stationary and emergency back-up power and material handling equipment, they are considered primarily as technologies for the long term (e.g., fuel cell vehicles) – not readily available today and won't be for some time. When near-term and personal relevance or benefits are not obvious, engaging any of the key target audiences can be difficult.

3.8.5 Barriers

The following section outlines barriers to achieving the Education sub-program's goal and objectives.

A. Lack of Readily Available, Objective, and Technically Accurate Information

Although a significant body of technical information exists, there is little readily available information about hydrogen and fuel cells for individuals outside of the research and development community. Moreover, explaining hydrogen and fuel cells to a non-technical audience – clearly and succinctly, while still retaining technical accuracy – is challenging.

B. Mixed Messages

The growing public and mainstream media interest in energy has sparked increased outreach activity among many different organizations. The flurry of activity helps raise public awareness of energy issues, but it also creates potential for conflicting public messages, as well as confusion about how hydrogen and fuel cells fit in the portfolio of our Nation's energy choices.

C. Disconnect Between Hydrogen Information and Dissemination Networks

Educational materials and resources must reach their intended audiences to be effective, and institutional barriers can complicate or inhibit target audience access to information. Many target audiences have established training mechanisms and legacy networks through which they are accustomed to receiving information. Tapping into these traditional training and education mechanisms is often the most efficient way in which to ensure access to the target audience, but it is often difficult to do.

D. Lack of Educated Trainers and Training Opportunities

In-person training through webinars, workshops, or seminars is one of the most effective information delivery mechanisms – there is less distraction for students and an opportunity for interaction between and among all participants. Availability of suitable trainers is low, however, and can be resource-intensive at a level that is beyond the capability of most education programs to fund.

E. Regional Differences

Educational needs vary by audience, but they may also vary regionally. What works for a particular target audience group in one state, county, city, or district may not be the best approach for that same audience group in another area of the country (for example, education standards vary from state to state). Serving the education needs of a single target audience may therefore require multiple approaches tailored to serve the needs of various regions, which strains resources and can complicate activities developed at the national level.

F. Difficulty of Measuring Success

Quantifying the success of education activities is difficult. The number of fact sheets distributed or number of webinar attendees does not provide a meaningful measure of whether target audiences are actually gaining knowledge or understanding. External influences, such as mass media attention, can also affect public knowledge and opinion, making it difficult to determine whether or not measured changes in knowledge are actually the result of sub-program activities.

3.8.6 Task Descriptions

Task descriptions are presented in Table 3.8.3. All activities noted below will be developed and implemented according to the strategy described in the "Approach" section outlined above.

Table 3.8.3 Task Descriptions

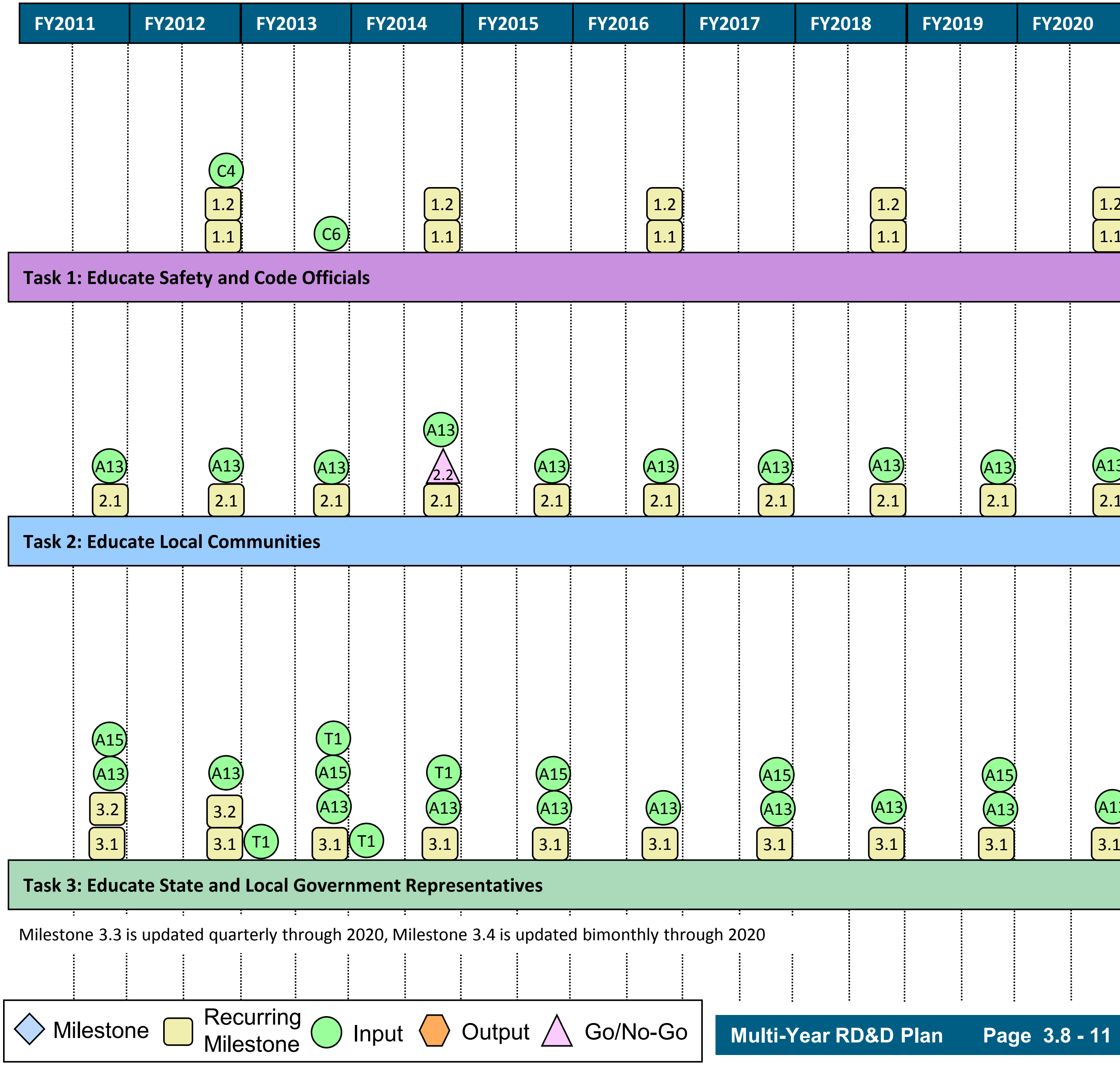
Task	Description	Barriers
1	**Educate Safety and Code Officials** • Disseminate and maintain introductory "awareness-level" course modules for first responders. • Disseminate the updated "prop-course" for first responders using hands-on training devices developed by the Safety sub-program. • Raise awareness of available information at audience-specific events. • Coordinate all activities under this task with Safety, Codes and Standards sub-program. • Increase awareness of "authority having jurisdiction" (AHJ). Reduce the permitting/construction cost and time for new hydrogen and fuel cell installations.	A, B, C, D
2	**Educate Local Communities** • Disseminate introductory information products that are designed for a non-technical audience. • Develop and conduct targeted public outreach through different forms of media. • Develop and conduct seminars to educate interested residents in communities.	A, B, C, D
3	**Educate State and Local Government Representatives** • Develop and make available introductory information appropriate for a non-technical audience and specific to state and local government needs. • Develop and conduct training workshops to increase understanding and share lessons learned. • Raise awareness of available information at audience-specific events.	A, B, C, D, E

Table 3.8.3 Task Descriptions (continued)		
Task	**Description**	**Barriers**
4	**Educate Potential End-Users** • Develop and make available introductory information focused specifically on the needs of different potential end-users. • Develop and conduct information seminars and training at audience specific events. • Work through traditional end-user information networks to develop and offer short courses specific to end-user needs.	A, B, C, D
5	**Facilitate Development and Expansion of College and University Hydrogen Technology Education Offerings** • Disseminate a database of college and university programs. • Disseminate a publicly available database of relevant textbooks and teaching resources for professors. • Support university hydrogen competitions that engage students from a variety of disciplines. • Work with university partners to develop and expand hydrogen technology course offerings and facilitate networking among schools with similar programs. • Develop and offer technician training at community colleges and facilitate networking among interested schools.	A, B
6	**Facilitate Development and Expansion of Hydrogen Technology Education in Middle Schools and High Schools** • Disseminate easily accessible, user-friendly classroom guides for teachers and students. • Raise awareness of available information and resources at audience-specific events.	A, B, C, D, E
7	**Assess Knowledge and Opinions of Hydrogen Technologies** • Recalibrate and conduct updated survey of target audiences' knowledge levels. • Repeat surveys in out years to evaluate changes in knowledge and opinions over time.	A, B, F

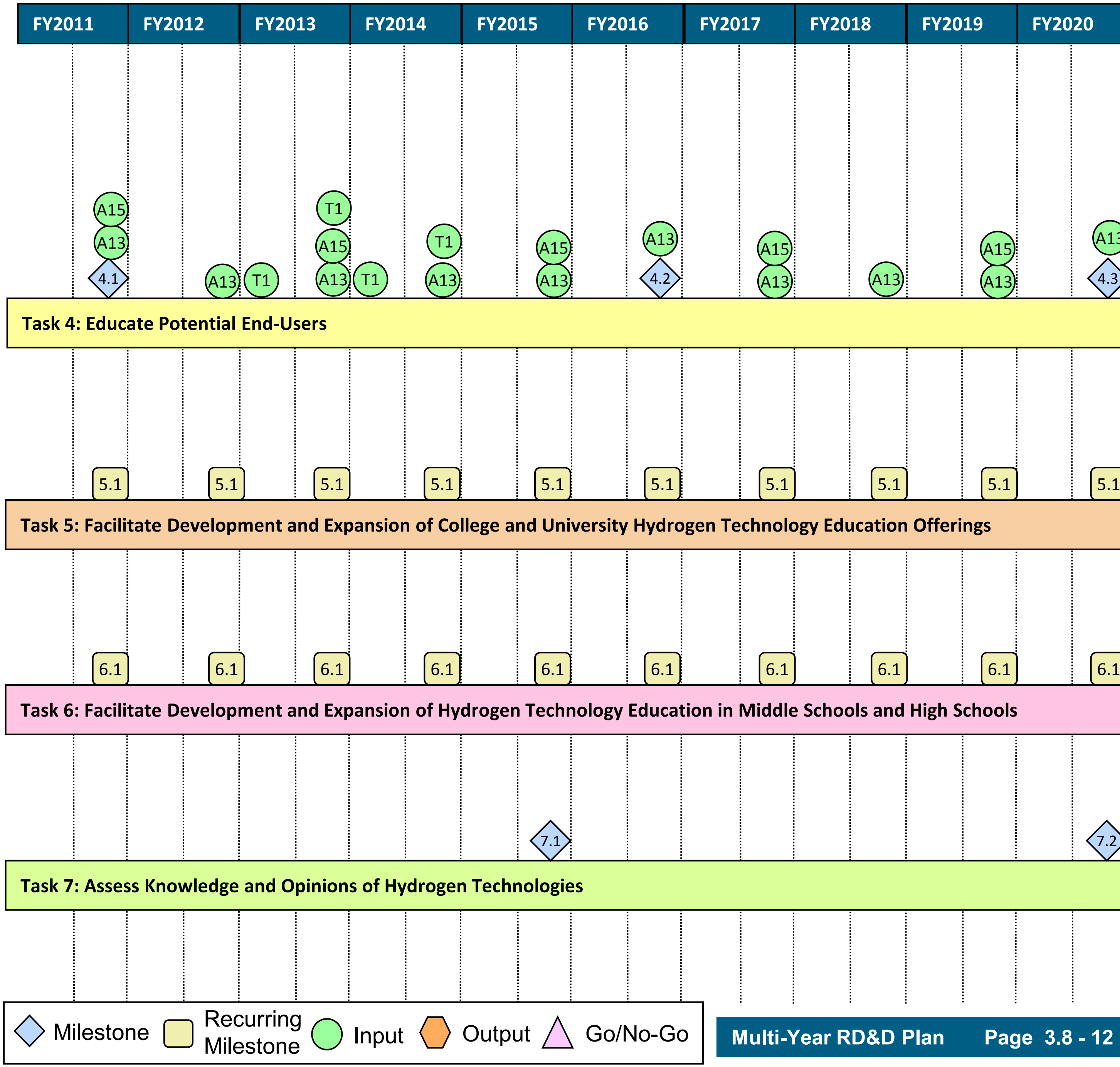
3.8.7 Milestones

The following chart shows the interrelationship of milestones, tasks, supporting inputs and outputs from other sub-programs from FY 2011 through FY 2020, subject to appropriations. This information is also summarized in Appendix B.

Education Milestone Chart



Education Milestone Chart



Task 1: Educate Safety and Code Officials	
1.1	Update “Introduction to Hydrogen Safety for First Responders” course for first responders. (Biannually)
1.2	Update “Introduction to Hydrogen Safety for Code Officials” course for code officials. (Biannually)

Task 2: Educate Local Communities	
2.1	Update website to reflect current information about hydrogen and fuel cells. (Annually)
2.2	Decision on national public education campaign. (4Q, 2014)

Task 3: Educate State and Local Government Representatives	
3.1	Update website with current state activities. (Annually)
3.2	Hold “Hydrogen 101” seminars. (through 4Q, 2012)
3.3	Update case studies, market reports, and projects tools on web site. (quarterly)
3.4	Hold frequent (bi-monthly) Hydrogen and Fuel Cell webinars. (through 4Q, 2020)

Task 4: Educate Potential End-Users	
4.1	Develop economic tools (e.g., employment and economic impact estimators). (4Q, 2011)
4.2	Update economic tools (e.g., employment and economic impact estimators). (4Q, 2016)
4.3	Update economic tools (e.g., employment and economic impact estimators). (4Q, 2020)

Task 5. Facilitate Development and Expansion of College and University Hydrogen Technology Education Offerings	
5.1	Update web site with current hydrogen and fuel cell university education coursework and programs. (Annually)

Task 6: Facilitate Development and Expansion of Hydrogen Technology Education in Middle Schools and High Schools	
6.1	Update website with current hydrogen and fuel cell middle school and high school programs. (Annually)

Task 7: Assess Knowledge and Opinions of Hydrogen Technologies	
7.1	Evaluate knowledge and opinions of hydrogen technology of key target audiences. (4Q, 2015)
7.2	Evaluate knowledge and opinions of hydrogen technology of key target audiences. (4Q, 2020)

Outputs

No Outputs for Education

Inputs

A13 Input from Systems Analysis: Annual market reports on status of fuel cell and hydrogen industry. (4Q, 2011 – 2020)

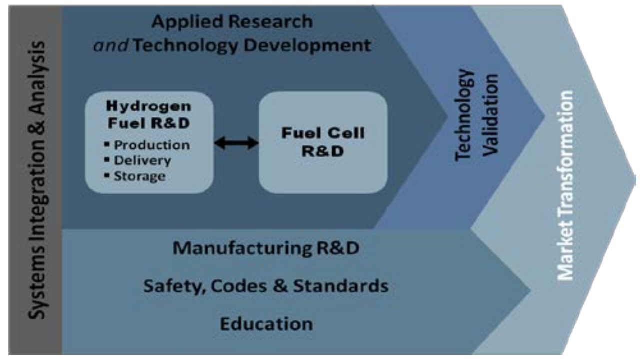
A15 Input from Systems Analysis: Report on the status of government policies on non-automotive fuel cell industry. (4Q, 2011; 4Q, 2013; 4Q, 2015; 4Q, 2017; 4Q, 2019)

C4 Input from Safety, Codes and Standards: Updated best practices handbook on hydrogen safety. (4Q, 2012)

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

T1 Input from Market Transformation: Report on the status of early market deployments and industry needs. (1Q & 4Q, 2013 – 2014)

3.9 Market Transformation



The Market Transformation sub-program is conducting activities to help implement and promote commercial and pre-commercial hydrogen and fuel cell systems in real world operating environments. These activities also provide feedback to research programs, U.S. industry manufacturers, and potential technology users. Currently, the capital and installation costs of early market fuel cells (i.e., stationary, backup power, and specialty vehicle power) are between two to three times higher than incumbent technologies. [1,2] One of the sub-program's goals is to achieve fuel cell volumes in emerging commercial applications that will enable cost reductions through economies of scale and other market acceptance factors, resulting in further expansion of market opportunities. Efforts are primarily focused on identifying opportunities for operating and testing fuel cells in emerging markets including specialty vehicles, backup/remote power (including products targeted at displacing diesel-fueled products), hydrogen storage with renewables, auxiliary power for transportation (e.g., truck auxiliary power units [APUs]), continuous recharging for batteries, distributed stationary power generation (e.g., combined heat and power [CHP] and combined heat, hydrogen and power [CHHP]), energy storage renewable grid power, and renewable hydrogen applications. In addition to the positive impact on the hydrogen and fuel cell market, these operational tests will provide valuable information and data on the status of integrated systems and non-hardware barriers and challenges.

3.9.1 Goal and Objectives

Goal

The sub-program's goal is to enable and accelerate expansion of hydrogen and fuel cell system use by lowering the life cycle costs of hydrogen and fuel cell power and by identifying and reducing the barriers impeding full technology commercialization.

Objectives

- Conduct market transformation deployment projects to enable life cycle cost and performance of fuel-cell powered lift trucks and emergency backup power systems to be on a par with conventional technologies by 2020.
- Establish baseline energy efficiency and reliability performance metrics for commercially available emergency backup, material handling, and light commercial/residential power systems and provide feedback to component suppliers regarding cost reduction opportunities by 2013.

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[1] U.S. Environmental Protection Agency, "Catalog of CHP Technologies" (December 2008) (http://www.epa.gov/chp/documents/catalog_chptech_full.pdf)

[2] Oak Ridge National Laboratory, "Status and Outlook for the U.S. Non-Automotive Fuel Cell Industry: Impacts of Government Policies and Assessment of Future Opportunities" (May 2011) (http://www-cta.ornl.gov/cta/Publications/Reports/ORNL_TM2011_101_FINAL.pdf)

- Develop and launch energy efficiency and reliability certification programs. This can be achieved, for example, by including fuel cell stationary power systems in the Environmental Protection Agency's (EPA) Energy Star rating program by 2015.
  - Develop and publish a best practices procurement guide for Federal agencies by 2012.
- Test emerging approaches to grid management using renewable hydrogen storage and fuel cell systems in coordination with the U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability by 2014.
- Advance the knowledge and expertise of waste-to-energy stationary fuel cells, shipboard auxiliary power unit applications, and aviation applications through targeted testing and evaluation efforts in coordination with the Technology Validation sub-program and in partnership with the U.S. Department of Defense (DOD), the U.S. Navy, the U.S. Army, and civilian agencies such as the U.S. Department of Agriculture (USDA) and the Federal Aviation Administration (FAA) by conducting design requirements planning for aircraft APUs by 2012, shipboard APUs by 2013, and waste-to-energy fuel cells by 2014.
- Identify lessons learned from promulgated policies and regulations and promote the development of the most effective and applicable incentives for hydrogen and fuel cell technologies by 2016.

3.9.2 Approach

DOE addresses hydrogen and fuel cell market transformation challenges through the enhancement of government and industry technology adoption activities. DOE provides information and tools to federal, state, and local governments and industry fuel cell users and assists them in the development of application programs. The Fuel Cell Technologies Program is also promoting hydrogen and fuel cell showcase activities by providing technical assistance on synergistic and novel energy efficient and renewable energy systems that include crosscutting technology applications.

The sub-program supports key implementation projects and partnerships (with state and local governments and other stakeholders) to develop and assess policies, practices, and business models that accelerate adoption of fuel cell technologies. Another critical activity is the deployment of emerging applications at the late-stage prototype and early commercial levels, which will assist industry with improving the affordability and reliability of hydrogen and fuel cell systems, expand user and servicing expertise, and better define the business case for multiple applications. A key approach to increasing domestic market penetration is to develop standard institutional and financial market practices such as power purchase agreements (PPAs)[3], other third party financing methods, and installation guides. A suite of user tools, methodologies, and predictive analysis models including financial analyses for multiple applications (e.g., net payback period estimates) is being developed to support more early application deployments.

[3] A power purchase agreement is an agreement between a private entity and a site owner. The private entity purchases, installs, owns, operates, and maintains the site equipment. The site owner purchases electricity from the private entity.

The sub-program is developing strategies to mitigate commercial risks and to develop new approaches that will ensure high capacity utilization and improved reliability under initial and mass market penetration scenarios. Also, the Market Transformation sub-program collaborates with the Safety, Codes and Standards sub-program to provide lessons learned and best practices. These efforts should facilitate the development of standard operating procedures to provide high-quality, economic and environmental performance data and to help secure private sector financing for high volume fuel cell system deployments.

3.9.3 Programmatic Status

Current Activities

Market Transformation activities encourage higher-volume purchases of hydrogen and fuel cell systems, which, in turn, reduce barriers and support domestic industry growth. Ongoing and planned activities focus on the following:

1. Using data collected by the Technical Validation sub-program to 1) validate the business case for various early market fuel cell systems and 2) assess the performance of these integrated systems in real world operating environments. Example business cases developed using these data are made publicly available so that additional stakeholders become aware of the benefits of integrated hydrogen and fuel cell systems.

2. Collaborating with other Federal agencies to 1) increase market-ready application use, 2) increase awareness of the benefits of these deployments, 3) provide "models" for adoption by other Federal agencies and industry, and 4) help to meet important inter-agency cooperative agreements such as the DOE-DOD Memorandum of Understanding.[4]

3. Testing fuel, (e.g., gas clean up and compression, and power generation concepts) to co-produce hydrogen and electricity, including CHHP (tri-generation) approaches using natural gas and waste biogas. Successful, high-visibility applications, such as tri-generation using wastewater treatment gas as a feedstock, tend to foster other waste-to-energy projects using renewable biogas to co-produce hydrogen for market ready fuel cell systems and electricity in distributed generation applications.

4. Communicating the benefits of using hydrogen and fuel cells for grid storage of variable renewable energy. The goal is to introduce innovative new approaches that demonstrate the potential of utility-scale hydrogen generation to provide energy storage benefits to the electricity grid and fuel cell applications such as emergency backup power and specialty vehicles.

5. Facilitating distributed fuel cell power generation in congested grid locations and other opportune markets. The sub-program will provide information to potential technology users in the private and public sectors about the costs and financial benefits of deploying fuel cells,

[4] Memorandum of Understanding Between U.S. Department of Energy and U.S. Department of Defense, July 2010 (http://www.energy.gov/news/documents/Enhance-Energy-Security-MOU.pdf)

including information about government incentives like tax credits and financing methods such as power purchase agreements. Power purchase agreements will reduce reliance on power generation from the grid that is heavily dependent on the combustion of fossil fuels.

6. Partnering with government and industry stakeholders to deploy pre-commercial applications by testing and evaluating new integrated fuel and power applications. Projects include innovative fuel cell applications such as fuel-cell-powered mobile lighting to displace diesel generator-based systems.

Current Market Transformation activities are summarized in Table 3.9.1.

Table 3.9.1 Current Activities for Market Transformation

Activity	Objective	Organizations
Interagency Coordination	Monthly coordination and collaboration meetings with federal agencies [5]	DOD, National Institute for Standards and Technology, Department of Commerce, U.S. Navy, U.S. Army, National Aeronautics and Space Administration (NASA), USDA, EPA, and FAA
Landfill and waste water biogas to power fuel cells	Cleanup and reforming of gas for fuel used in stationary and industrial truck fuel cells	Gas Technology Institute, South Carolina Research Authority
Shipboard APUs	DOE-DOD collaborative analysis and demonstration	U.S. Navy
Aircraft APUs and Airport Ground Support Vehicles	Conduct energy and cost evaluations for onboard APUs and Ground Support Equipment (GSEs)	U.S. Air Force, Pacific Northwest National Laboratory, Sandia National Laboratories (SNL)
Material Handling Deployments	Collect data and evaluate performance	DOD, Defense Logistics Agency, FedEx Freight, Sysco Houston, Nuvera Fuel Cells with deployment at H-E-B supermarket chain, GENCO with deployments at Coca Cola, Kimberly Clark, Sysco Philadelphia, Wegmans, and Whole Foods Market
Fuel Cell Federal Facilities Procurement Guidance	Develop methods and tools for stationary fuel cell deployment in federal buildings using third party financing	Oak Ridge National Laboratory (ORNL), SRA International, Inc.
Mobile Lighting	Conduct performance evaluations on mobile lighting using fuel cell power	SNL, Altergy Energy

[5] Energy Policy Act of 2005, Section 806

Table 3.9.1 Current Activities for Market Transformation (continued)		
Activity	**Objective**	**Organizations**
Fuel Cell power purchase agreements (PPAs)	Assist National Lab stationary power deployments through technical feasibility studies and third party financing support	Logan Energy
Hydrogen storage for grid management	Develop business cases using excess renewable energy from wind and geothermal power	Hawaii Natural Energy Institute, U.S. Navy
On Board Rechargers for Electric Vehicles	In collaborations with the EERE Vehicle Technologies Program and industry, evaluate the techno-economic and market feasibility of onboard fuel cell battery rechargers for medium class trucks and light duty vehicles	Argonne National Laboratory
Backup Power	To provide emergency power for critical loads such as telecommunications and to share lessons learned	Sprint, FAA, U.S. Army, NASA, National Park Service, Logan Energy, Idatech, ReliOn, Hydrogenics, Altergy

3.9.4 Challenges

While fuel cells are becoming competitive in a few markets, the range of these markets can be greatly expanded with improvements in durability and performance and reductions in manufacturing cost. Successful entry into emerging 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 high initial costs and lack of a supply base that many new technologies face in their critical early stages.

Early market sales stimulate further market activity by supporting the growth of a domestic industry, overcoming some of the logistical and other non-technical challenges associated with adoption of a new technology, and establishing key elements of the infrastructure that will be essential for later market growth. In addition, these deployments will 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 benchmark the benefits of the technologies.

Sub-program Targets

Market Transformation activities increase domestic hydrogen and fuel cell market penetration by removing non-technical market barriers and reducing non-hardware system costs which are still a significant cost barrier.[6] Non-technical challenges include the high costs of insurance, permitting, installation, and project management. The sub-program assists in the challenge of lowering the cost by identifying and reducing the market barriers to full technology commercialization. Efforts under

[6] University of California, Irvine, National Fuel Cell Research Center, "Fuel Cell Explained" http://www.nfcrc.uci.edu/2/FUEL_CELL_INFORMATION/FCexplained/challenges.aspx

this sub-program complement the RD&D work of other sub-programs, as well as Systems Analysis work, by focusing on these non-hardware system costs and barriers.

The sub-program focuses on achieving life cycle cost parity with incumbent technologies by deploying new high volume applications such as airport ground support vehicles and addressing non-hardware related costs such as delays in permitting, siting, and installation as well as performing key analyses of finance and technology options. For example, a fuel cell stack is manufactured using similar processes regardless of the equipment application. As a result, combining the market penetration of various fuel cells such as stationary power, specialty vehicles and other vehicle uses, and backup or auxiliary power results in a rapid reduction in capital costs. By 2016 – 2017, the markets are expected to reach a combined manufacturing volume of around 4 million kilowatts annually and trigger a rapid commercialization and the related reduction in fuel cell system costs. [7]

3.9.5 Barriers

The following section outlines barriers to achieving the Market Transformation sub-program's goal and objectives.

A. Inadequate standards and complex and expensive permitting procedures

- Hydrogen and fuel cell system's installation costs are too high[8]
- Hydrogen and fuel cell system's insurance costs are too high
- Hydrogen and fuel cell system's energy efficiency standards do not exist
- Permitting approval by local officials takes too long and is expensive
- Sufficient life cycle performance data to enable standards development is lacking

B. High hydrogen fuel infrastructure capital costs for Polymer Electrolyte Membrane (PEM) fuel cell applications

C. Inadequate private sector resources available for infrastructure development

D. Market uncertainty around the need for hydrogen infrastructure versus timeframe and volume of commercial fuel cell applications

E. A lack of flexible, simple, and proven financing mechanisms

- Inadequate private funds available for new projects
- Lack of sufficient financing instruments for large projects
- High cost of fuel cells using current low production volumes
- Shorter product warranty periods than for other commercial new or renewable energy technology products

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[7] U.S. Department of Energy Hydrogen and Fuel Cells Program Records, http://www.hydrogen.energy.gov/program_records.html, record currently in process as of April 2012

[8] ORNL/ TM-2011/ 101, table 5 (BUP PEM), page 67, May 2011 http://cta.ornl.gov/cta/Publications/Reports/ORNL_TM2011_101_FINAL.pdf

- Lack of government energy acquisition processes to facilitate large scale fuel cell deployments
- Lack of life cycle cost and performance data to demonstrate low investor risks
- Inadequate federal and state-level incentives relative to other clean or renewable energy technologies

F. Inadequate user experience for many hydrogen and fuel cell applications

G. Lack of knowledge regarding the use of hydrogen inhibits siting (e.g., indoor refueling)

H. Utility and other key industry stakeholders lack awareness of potential renewable hydrogen storage application

I. Lack of cross cutting information on how to use hydrogen and fuel cell systems in combination with energy efficiency and renewable energy technologies with existing projects

J. Insufficient numbers of trained and experienced servicing personnel

K. Inadequate installation expertise

L. Lack of qualified technicians for maintenance

M. Lack of certified service providing organizations for installation and maintenance

N. Policies and incentives (e.g., Investment Tax Credit) are not available to government or other non-profit entities - impeding early market adoption in the public sector

O. Lack of standard recycling/disposal processes

3.9.6 Task Descriptions

The technical task descriptions are presented in Table 3.9.2. The barriers associated with each task appear after the task title.

Table 3.9.2 Technical Task Descriptions

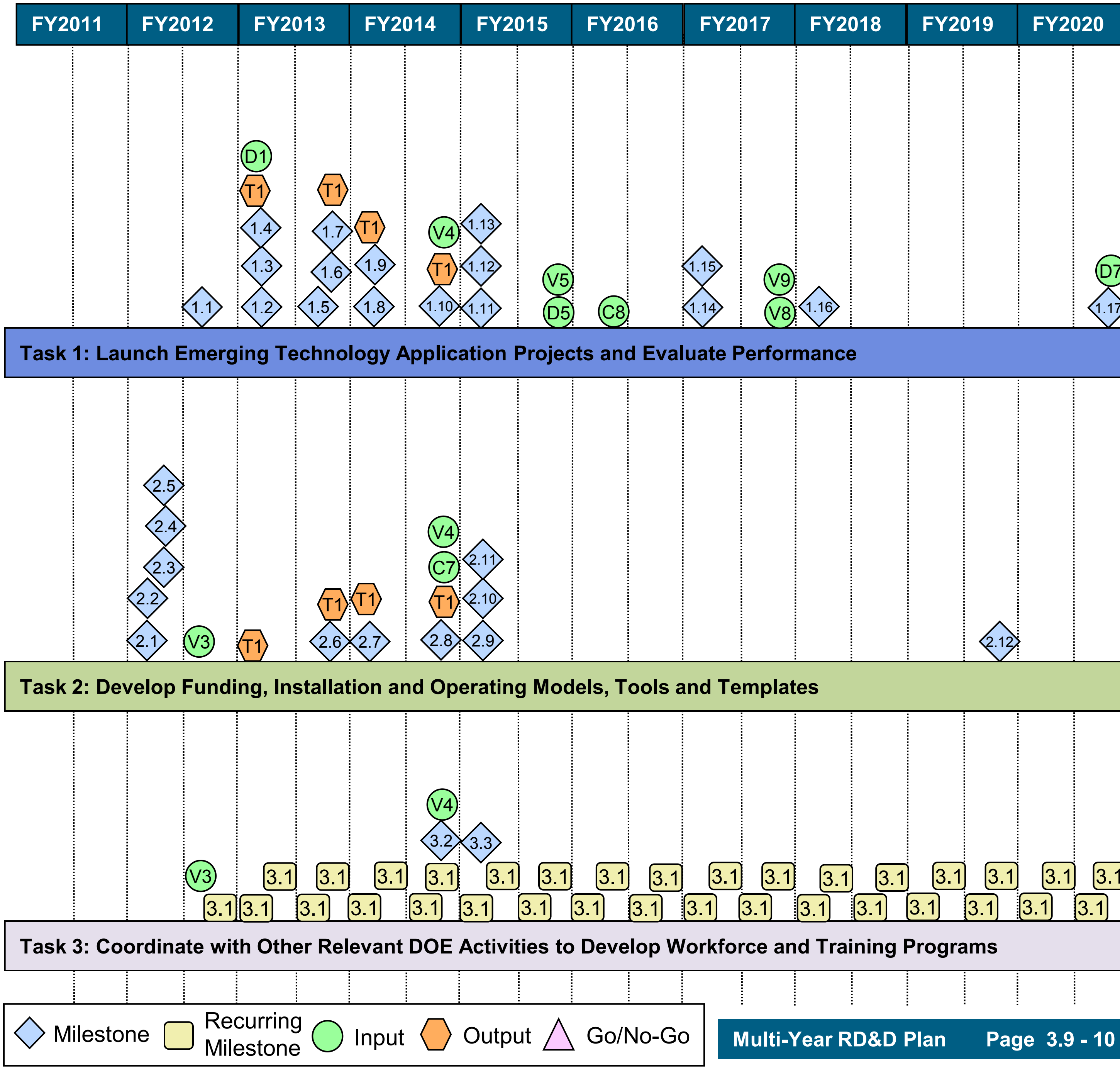
Task	Description	Barriers
1	**Launch emerging technology application projects and evaluate performance** • Demonstrate the value proposition and business case for freight support equipment and vehicles, emergency backup power systems, and small stationary power. • Test and evaluate port support equipment applications including motive (e.g., baggage tractors or drayage trucks) and non-motive (e.g., ground lighting and onboard APUs). • Test and evaluate onboard fuel cell rechargers and prime power for medium duty trucks and light duty battery electric vehicles. • Evaluate air emissions and energy effects of fuel cells in commercial passenger aircraft for APUs. • Conduct renewable hydrogen generation and energy storage performance and business case testing activities. Demonstrate at utility or near-utility scale. • Conduct user forums and adoption analysis for emerging commercial applications including power for lift trucks, airport ground support equipment, and small buildings. • Identify specific opportunities to increase deployments by aggregating demand for hydrogen and fuel cells to lower cost of both technologies. • Work with Recovery Act award winners to complete deployment of fuel cell-powered lift trucks and emergency backup installations. Support press events and media outreach. • Track energy benefits of completed installations in order to supply real-world results with potential end users and media. Develop case studies and outreach materials highlighting project results. • Evaluate business case studies for various low-cost hydrogen infrastructure pathways over near-, mid-, and long-term market time frames.	A through M
2	**Develop funding, installation and operating models, tools, and templates** • Develop installation and permitting procedure templates. • Develop best-practices for financing fuel cell projects. • Develop financial planning analysis tools and identify new, innovative finance methods (e.g., power purchase agreements for fuel cell micro-CHP residential power; project bundling). • Develop guidance detailing best practices for funding mechanisms such as power purchase agreements, third party financing, project bundling methods, and procurement guides. • Develop business cases. • Develop case studies of customer economic and environmental benefits of deploying fuel cells for emerging applications (e.g., stationary power for grocery stores). Disseminate these case studies widely across the public domain. • Develop near- and mid-term hydrogen infrastructure market case studies in collaboration with the Hydrogen Production, Delivery, and Technology Validation sub-programs.	A, E, I, N, O

Table 3.9.2 Technical Task Descriptions (continued)		
Task	**Description**	**Barriers**
3	**Coordinate with other relevant DOE activities to develop workforce and training programs** • Develop workforce training for fuel cell installation and maintenance with industry stakeholders. • Provide workforce development plan for fuel cell maintenance and installation. • Conduct outreach to energy service contractors, utilities, and venture capitalists. • In coordination with the Education sub-program conduct local public and community outreach events. • Conduct outreach actions for insurance and underwriter industries.	C, D, G, H, I , J, K, L, M

3.9.7 Milestones

The following chart shows the interrelationship of milestones, tasks, supporting inputs from sub-programs, and outputs for the Market Transformation sub-program. The input/output information is also summarized in Appendix B.

Market Transformation Milestone Chart



Task 1: Launch Emerging Technology Application Projects and Evaluate Performance	
1.1	Complete initial aircraft APU systems analysis. (3Q, 2012)
1.2	Implement cross-cutting interagency project for hydrogen infrastructure integrated with renewable energy generation. (1Q, 2013)
1.3	Complete data collection and assessment of deployed Direct Methanol Fuel Cell lift trucks. (1Q, 2013)
1.4	Deploy fuel cells and evaluate business cases for micro-CHP in light commercial applications. (1Q, 2013)
1.5	Deploy and test potential benefits of distributed generation fuel cells as a strategic tool to help mitigate grid congestion. Create users forums for backup fuel cells deployed with U.S. Army CERL and TARDEC. (3Q, 2013)
1.6	Deploy and test backup power at military installations in coordination with DOD and publish results and benefits analysis. (4Q, 2013)
1.7	As part of the Recovery Act, install approximately 1,000 backup and lift truck power fuel cell units at industry partners' sites. (4Q, 2013)
1.8	Complete deployment and evaluation of short haul/drayage trucks and range extenders. (1Q, 2014)
1.9	Deploy fuel cells and evaluate business cases for micro-CHP in residential applications. (1Q, 2014)
1.10	Enable >8 MW of fuel cell deployments in emerging markets. (4Q, 2014)
1.11	Complete design and test deployment of airport ground support vehicles using hydrogen from renewables. (1Q, 2015)
1.12	Complete test and business case analysis for onboard fuel cell rechargers for battery electric vehicles. (1Q, 2015)
1.13	Deploy, test, and develop business cases for renewable hydrogen energy systems for power, building, and transportation sectors. (1Q, 2015)
1.14	In collaboration with other Federal agencies and industry partners, begin deployment of fleets incorporating validated fuel cell vehicles (available on the GSA schedule) that have achieved 5,000-hour durability (service life of vehicle) and a driving range of 300 miles between fueling. (1Q, 2017)
1.15	In collaboration with DOD and industry partners, begin deployment of truck fleets incorporating validated APU fuel cell systems having 15,000-hour durability. (1Q, 2017)
1.16	In collaboration with State and Federal agencies, begin deployment of validated technology to produce hydrogen through distributed reforming of renewable liquid fuels at refueling stations for a cost of <$3.80/gge at the pump. (1Q, 2018)
1.17	Enable economies of scale to achieve cost-competitiveness. (4Q, 2020)

Task 2: Develop Funding, Installation and Operating Models, Tools, and Templates	
2.1	Develop and publish a fuel cell user's guide (e.g., third party financial planning guide) for use by energy managers or facility managers who are considering the deployment of stationary fuel cell systems. (1Q, 2012)
2.2	Develop installation and permitting templates for stationary and backup power. (1Q, 2012)
2.3	Develop case studies for deployed lift trucks and emergency backup power. (2Q, 2012)
2.4	Develop outreach materials for grocery retail and food distributors. (2Q, 2012)
2.5	Develop third party financing model for Federal users to aggregate and multiply power needs. (2Q, 2012)
2.6	As a result of Recovery Act deployments, publish fuel cell backup and lift truck power business cases. (4Q, 2013)
2.7	Begin to conduct information seminars to insurance underwriters and venture capitalists. (1Q, 2014)
2.8	Develop a case study for hydrogen infrastructure that services the MHE and other emerging fuel cell application markets. (4Q, 2014)
2.9	Complete peer-reviewed, on-line financial planning tool for emerging applications. (1Q, 2015)
2.10	Develop Best Practices Database as a web tool for permitting and installing fuel cell stationary power. (1Q, 2015)
2.11	Develop installation and permitting templates for airport ground support equipment. (1Q, 2015)
2.12	Develop a case study for hydrogen infrastructure that services mid-term (renewable) fuel applications markets. (4Q, 2019)

Task 3: Coordinate With Other Relevant DOE Activities to Develop Workforce and Training Programs	
3.1	Conduct seminars at customer end-users' forums to inform earlier adopters of economic and environmental benefits of fuel cells. (one per quarter - 1,000 attendees per year). (on-going starting in Q4, 2012)
3.2	In collaboration with other Federal and State agencies, develop training modules that can be used in implementing stationary fuel cell projects. (Q4, 2014)
3.3	Identify installation workforce needs for emerging applications. (1Q, 2015)

Outputs

T1 Output to Education: Report on the status of early market deployments and industry needs. (1Q & 4Q, 2013 – 2014)

Inputs

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)

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)

V3 Input from Technology Validation: Publish/post composite data products for material handling and backup power, including safety event data. (3Q, 2012)

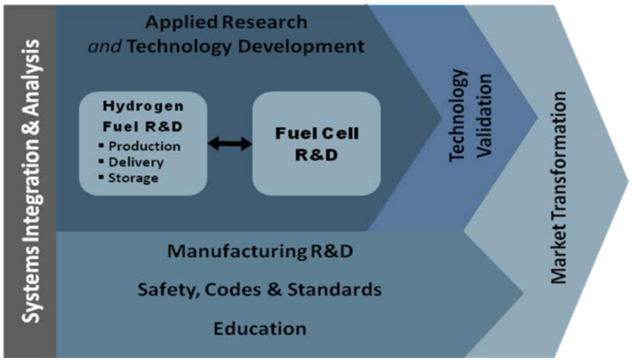
V4 Input from Technology Validation: Validate stationary fuel cell system that co-produces hydrogen and electricity and report on durability and efficiency. (4Q, 2014)

V5 Input from Technology Validation: Report on the validation of residential fuel cell micro combined heat and power systems’ efficiency and durability. (4Q, 2015)

V8 Input from Technology Validation: Complete validation of commercial fuel cell combined heat and power systems’ efficiency and durability. (4Q, 2017)

V9 Input from Technology Validation: Validate status of truck auxiliary power unit durability. (4Q, 2017)

4.0 Systems Analysis



The Fuel Cell Technologies Program (FCT Program) conducts a coordinated, comprehensive effort in modeling and analysis to clarify where hydrogen and fuel cells can be most effective from an economic, environmental, and energy security standpoint, as well as to guide RD&D priorities and set program goals. These activities support the FCT Program's decision-making process by evaluating technologies and pathways and determining technology gaps, risks, and benefits.

The Systems Analysis sub-program works at all levels of the program, including technology analysis for specific sub-programs, policy and infrastructure analysis, and high-level implementation and market analysis. Examples of activities include pathway analysis for hydrogen production, evaluating impacts of technology advancements on fuel cell cost, feasibility studies of combined heat, hydrogen and power production from stationary fuel cells, analyzing impacts of hydrogen quality on fuel cell performance and infrastructure, and complete "well-to-wheels" or life-cycle analysis of pathways to determine reductions in greenhouse gas emissions and petroleum use. Risk analysis is also performed to determine the effects of certain variables on the likelihood of meeting program targets and to help identify risk mitigation strategies. Policy analyses include investigating the effects of different policy options and scenarios, infrastructure and resource analysis, vehicle consumer choice analysis, and market penetration studies. Analysis of employment opportunities and needs, manufacturing capability and growth potential, and overall domestic competitiveness are also a critical part of the sub-program's activities.

To perform these analyses, the sub-program utilizes a diverse portfolio of models, including cost models such as Hydrogen Analysis (H2A), technology performance models such as Autonomie which is an improved version of the previous PSAT (Powertrain Systems Analysis Toolkit) vehicle simulation model, economic models such as NEMS (National Energy Modeling System), MARKAL (Market Allocation model), agent-based models, emissions models such as GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation), and integrated models, such as the Macro-System Model and Hydrogen Demand and Resource Analysis. The FCT Program is dually focused on using established models to address analysis gaps, and on enhancing existing models to broaden analysis capabilities.

4.1 Technical Goal and Objectives

Goal

Provide system-level analysis to support hydrogen and fuel cell technologies development and technology readiness by evaluating technologies and pathways including resource and infrastructure issues, guiding the selection of RD&D projects, and estimating the potential value of RD&D efforts.

Objectives

- By 2012, complete the evaluation of hydrogen for energy storage and as an energy carrier to supplement energy and electrical infrastructure.
- By 2012, complete the evaluation of fueling station costs for early vehicle penetration to determine the cost of fueling pathways for low and moderate fueling demand rates.
- By 2014, complete environmental studies that are necessary for technology readiness.
- By 2018, complete analysis of program performance, cost status, and potential for use of fuel cells for a portfolio of commercial applications.
- By 2019, complete analysis of the potential for hydrogen use in stationary fuel cells, fuel cell vehicles, and other fuel cell applications such as material handling equipment. The analysis will address necessary resources, hydrogen production, transportation infrastructure, performance of stationary fuel cells and vehicles, and the system effects resulting from the growth of fuel cell market shares in the various sectors of the economy.
- Provide milestone-based analysis (including risk analysis, independent reviews, financial evaluations and environmental analysis), to support the FCT Program's needs prior to technology readiness.
- Periodically update the life-cycle energy, petroleum use, greenhouse gas, and criteria emissions analysis for technologies and pathways for FCT Program to include technological advances or changes.

4.2 Technical Approach

The overall approach to implementing a robust Systems Analysis capability is based on the need to support FCT Program decision-making processes and milestones, to provide independent analysis when required to validate decisions and/or ensure objective inputs, and to respond to external review recommendations. Systems analysis generates outputs necessary to support programmatic needs, which include recommendations, reports, independent reviews, validation results, and supporting data. As depicted in Figure 4.2.1, the outputs are supported by fuel cell and hydrogen technologies transformation scenarios for environmental, economic, and other analyses. The analyses are dependent upon tools that the program is developing and/or modifying. Both the analyses and tools are dependent upon the framework that has been developed and are continuously updated. To ensure the analysis effort is focused, objective, and effective, internal and external peer reviews are conducted, annually and biennially (respectively).

The Systems Analysis sub-program continues to address relevant issues including infrastructure development, resource availability, life-cycle benefits, and domestic competitiveness. Examples of key focus areas include:

Model Development and Validation

- Validate analytical models with real-world data and refine models as required.

Technology Analysis and Quantification of Benefits

- Determine the potential for hydrogen as an energy storage medium or energy carrier to optimize the use of intermittent renewable resources such as wind and solar.
- Quantify the benefits of integrating hydrogen fuel production with stationary fuel cell power generation.
- Evaluate the potential for biogas, landfill gas, and stranded hydrogen streams as renewable fuel for stationary fuel cell power generation.
- Assess the Life Cycle Analysis (LCA) benefits of hydrogen and fuel cells for diverse applications and conduct a rigorous comparison to incumbent and emerging technologies such as gasoline engines and battery electric vehicles.

Infrastructure Analysis

- Work with industry and other stakeholders to assess and identify infrastructure scenarios and options for both long term transportation needs and early market opportunities for hydrogen and fuel cells.

Market and Policy Analysis

- Assess opportunities for diverse applications of fuel cells; including the potential for job growth, workforce development needs, manufacturing capacity, and the effects of a federal fuel cell acquisition program on fuel cell costs and market sustainability.

Studies and Analysis

Planned studies and analysis are separated into the following categories: understanding the initial phases of the fuel cell and hydrogen technologies early market penetrations; understanding the long-term potential and issues of fuel cell and hydrogen technologies; environmental analysis; and cross-cutting analytical studies that require quick response.

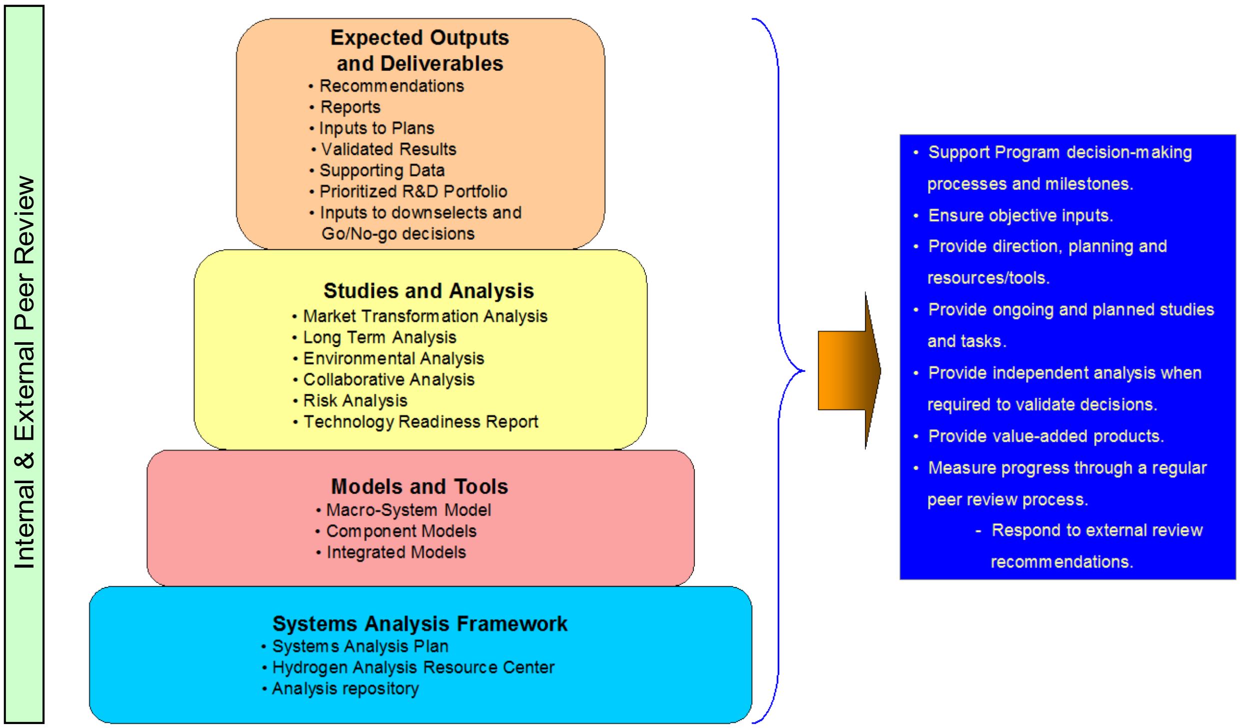


Figure 4.2.1 Systems analysis approach overview

Hydrogen Threshold Cost

In 2010, the Program developed a new hydrogen competitive threshold cost to replace the previous hydrogen cost goal. The hydrogen competitive threshold cost, which is independent of the production and delivery pathway, was adjusted from $2 – $3 per gallon of gasoline equivalent (gge) (untaxed) to <$4 per gge (untaxed). The new hydrogen threshold cost is based on the Energy Information Administration's 2009 forecast of gasoline cost in 2020 and the fuel economy and incremental vehicle cost of hydrogen fuel cell vehicles relative to hybrid electric vehicle technologies in 2020.

The methodology used ensures that consumers' operating cost (in $/mile) in a hydrogen fuel cell vehicle will be equal to or less than the competitive gasoline hybrid electric vehicle in 2020. The new hydrogen threshold cost is expressed as a range, which reflects the variability in future fuel efficiency improvement factors, competitive gasoline cost, and vehicle costs. The threshold cost guides the Department's execution of its hydrogen and fuel cell research and development responsibilities. The threshold cost includes the cost of delivery but excludes taxes, and it is expressed in 2007 dollars.

Market Transformation Analysis

Analysis is focused on assessing the early market introduction of fuel cells for backup, emergency, and remote power generation and specialty vehicles. Analysis also determines the potential for reducing fuel cell cost through economies of scale and the application of lessons learned. Potential technology pathways are modeled and analyzed to determine application requirements (targets), cost, risk, environmental consequence, and societal impact. From these analyses, key cost and technology barriers/gaps are identified, which further define and update the key RD&D needs and plans within each sub-program. In addition, future analyses will be undertaken to update energy, environmental impact, and financial impact/risk projections. This wide range of analyses is required to provide the necessary information about the fuel cell costs, infrastructure, resource requirements and availability, fuel quality, cost and profitability, and life-cycle emissions.

FCT Program-sponsored analyses include assessments of the impacts of government purchases and incentives on fuel cell cost reduction, as well as progress in capitalizing on the economies of scale for manufacturing and potential market penetration. These analyses yield reports and critical information, similar to the Oak Ridge National Laboratory 2011 report *Status and Outlook for the U.S. Non-Automotive Fuel Cell Industry: Impacts of Government Policies and Assessment of Future Opportunities*[1], critical to guiding sub-program target development.

Long-term Analysis

Long-term analysis involves the same focus areas that are addressed by market transformation and social-economic analyses. These analyses, however, entail the investigation of stationary fuel cells for combined heat and power and impact a larger economic sector than the early adopter applications. Long-term analysis requires an understanding of both the availability and the constraints of the hydrogen feedstocks required to fuel stationary and transportation fuel cell applications. Likewise, the importance of centrally produced hydrogen and the potential integration of hydrogen delivery with the natural gas infrastructure merit ongoing analysis.

Future market penetration will continue to have a positive social-economic impact on the creation of domestic jobs. FCT Program's job modeling tool enables examinations of the analysis of the national job growth and regional impacts of specific fuel cell manufacturing installations. This analytical tool assesses job growth and provides job estimates by application sector, such as material handling and distributed power.

Environmental Analysis

This work focuses on completing all environmental analyses necessary before technology readiness. Initial studies involve understanding the potential effects of hydrogen and its infrastructure on the environment. The studied effects include both primary (releases of hydrogen to the atmosphere, construction of pipelines and their associated ecological impacts, materials used for fuel cells, hydrogen storage and other components of the hydrogen systems), as well as secondary effects (i.e., changes in urban criteria pollutants and greenhouse gas (GHG) emissions). Environmental data

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[1] Greene D., Oak Ridge National Laboratory, K. Duleep, ICF International, G. Upreti, University of Tennessee, (2011). *Status and Outlook for the U.S. Non-Automotive Fuel Cell Industry: Impacts of Government Policies and Assessment of Future Opportunities* ORNL/TM-2011/101, Oak Ridge National Laboratory, Oak Ridge, TN, May.

produced from sub-program projects are compiled and analyzed to support Go/No-Go decisions and independent reviews.

Analyses assess greenhouse gas emissions and criteria emissions on a life cycle basis for multiple fuel cell applications and fuel pathways on an ongoing basis. The results are intended to identify benefits for fuel cell applications.

Models and Tools

Systems analysis models include component models (simulate individual portions of hydrogen and fuel cell scenarios), integrated models (economic and environmental factors), and the macro-system model (MSM) that links other models and facilitates consistency and communication between them. Modeling tools provide the basis for analyzing alternatives in terms of their cost, performance, benefit, and risk impacts on the macro system. Analysis is done across key activity boundaries such as using stationary fuel cells to supply heat and power for buildings and to generate hydrogen for specialty and light duty vehicle fuel supply.

To ensure model integrity and analysis consistency, the models are updated and validated with data and information from sub-program projects, independent reviews, and technology validation.

Macro-System Model

The macro-system model (MSM) is a structure that links other existing and emerging models to perform cross-cutting analysis of engineering issues. A number of models exist to analyze components and subsystems of the long-term applications of hydrogen; however, the MSM integrates many of them via a common architecture and calculates overall results (i.e., treating the overarching hydrogen fuel infrastructure as a system). The primary objective of the MSM is to support programmatic decisions regarding investment levels and to focus funding. The MSM also facilitates consistency between models due to its use of common terms and techniques to facilitate information transfer.

Component Models

These models are engineering models used individually to generate technology-specific information and perform techno-economic analyses. Examples of these models are the Fuel Cell Power (FC Power), H2A Production and the Hydrogen Delivery Scenario Analysis (HDSAM v2.2) models. The FC Power and H2A Production models are standardized tools for economic calculations of various stationary fuel cell configurations and hydrogen production technologies. These models are publicly available and enable analysis for a number of different production technologies and pathways. The publicly available HDSAM model has been developed for both delivery component cost and specific delivery scenario cost estimation.

Vehicle costs and performance required for FCT Program analysis are estimated with the Argonne National Laboratory (ANL) Model Autonomie.

Integrated Models

Multiple integrated models are engineering models that have been modified to answer overarching fuel cell and hydrogen related questions, including impacts of various policy actions on hydrogen and fuel cell technologies. The models include the following: HyTrans (for transition to fuel cells studies); an Agent-Based Modeling System; Market Allocation (MARKAL) with fuel cell and hydrogen representation; and the Production Infrastructures Options model. Additionally, the GREET model (used for life-cycle energy and emissions analysis) and SERA (Scenario Evaluation and Regionalization Analysis), which is an infrastructure assessment model, are used for programmatic analysis.

Systems Analysis Framework

The systems analysis framework is designed to support all modeling and analysis efforts. It involves establishing a source of consistent data for analytical efforts, determining and prioritizing the analysis tasks, organizing them so that they use consistent techniques and data, and formatting the results so that they can be easily found and used for decision making.

Systems Analysis Plan

A Systems Analysis Plan (SAP) details the overall approach, tasks and processes for the systems analysis efforts of the sub-program. It defines how specific analysis activities relate to the objectives of the overall FCT Program. The SAP contains a catalog of resources, the systems analysis processes, and the analysis results of past studies.

Hydrogen Analysis Resource Center (HyARC)

A technical data management system has been developed to provide a consistent database, a list of assumptions, information standards and tools for analytical activities supporting the sub-program. This analysis resource center provides data for standardized input to analysis activities and helps ensure consistency in the analyses conducted by the sub-program. The database is updated annually and made available to the community of analysts (DOE, national laboratories, universities, private companies, etc.) at http://hydrogen.pnl.gov/cocoon/morf/hydrogen.

Analysis Repository

A repository of technical analysis and evaluation activities has been established. The repository is a web-based database that contains information on analysis and modeling projects and results. It is available at http://www.hydrogen.energy.gov/analysis_repository/ and is updated periodically to ensure that the analytical activities provide direction, focus, and support to the FCT Program's research and development activities.

4.3 Systems Analysis Collaboration

This plan only describes the specific activities performed and funded by the Systems Analysis sub-program of the FCT Program. However, the analytical activities needed to support the entire DOE Hydrogen and Fuel Cells Program are more extensive, and to a large degree, coordinated by and performed in collaboration with the efforts described in this section. These include the following:

- **Analysis activities sponsored by FCT sub-programs:** Sub-programs fund analysis projects which address specific issues relevant to the sub-program and target results to help determine future RD&D focus. The Technology Validation and Production and Delivery sub-programs conduct scenario analysis to improve understanding of the impact of infrastructure development on early market penetration of fuel cells.
- **Hydrogen analysis efforts sponsored by other DOE Offices:** The Office of Fossil Energy and the Office of Nuclear Energy, Science and Technology each perform analysis to support their respective RD&D efforts in the production of hydrogen. These activities are coordinated with Systems Analysis and are reflected in the overall Analysis Portfolio maintained by the Systems Analysis organization for the entire DOE Program.
- **Corporate analyses:** Within EERE, the corporate analysis team performs policy and benefits analysis across the EERE portfolio, but also specifically in support of individual programs – such as the Fuel Cell Technologies Program. The Technology Analyst and Systems Integrator coordinate analyses and studies with this team to ensure the synergy and timeliness of the policy and benefits analysis to support program needs.
- **Coordinated analyses:** Analyses include vehicle life cycle cost, energy use, greenhouse gas emission analysis with Vehicle Technologies and Biomass Programs. An example of this analysis is shown in Figure 4.3.1. Other coordinated analyses include the levelized cost of electricity from a portfolio of technologies including stationary fuel cells with the Office of Electricity, and the Wind and Solar Programs.

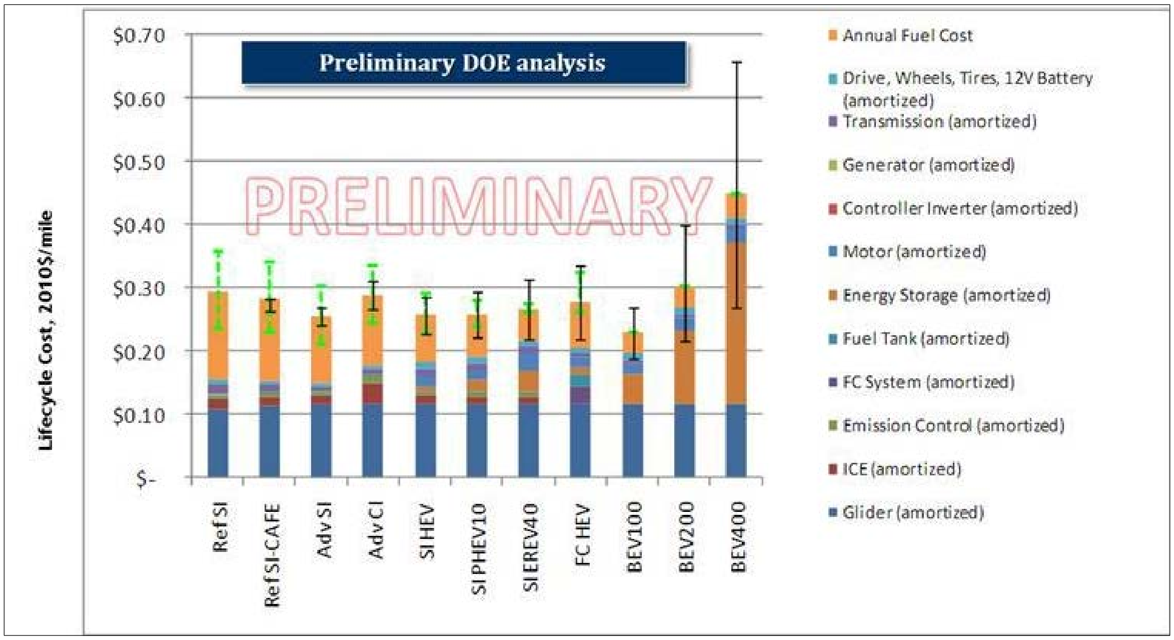


Figure 4.3.1 Lifecycle Costs of Advanced Vehicles

- **External reviews and analyses:** These include such external activities as reviews by the National Academy of Sciences, efforts under the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC), and future international work which might be undertaken by the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). Although by their nature these are independent of the FCT Program, the Technology Analyst is typically involved in briefing these organizations on program status and needs, participating in working groups which frame the analytical elements, and interpreting the results for use by the program.

4.4 Programmatic Status

Current Activities

Major Systems Analysis activities are listed in Table 4.4.1.

Table 4.4.1 Current Systems Analysis Activities			
Task	**Subtask**	**Approach**	**Organization**
Perform Studies and Analysis	Early market analysis	Conduct analysis of infrastructure requirements and cost for the early market emergence of fuel cells for stationary and backup power, material handling equipment, and light duty transportation	Multiple DOE national laboratories, academia, industry and stakeholders
	Production and delivery infrastructure analysis	Analysis of the ability of the fossil, nuclear, and renewable energy infrastructures, as well as the electrical grid, to support hydrogen production facilities	National Renewable Energy Laboratory (NREL): Infrastructure Development Analysis
	Resource analysis	Quantify location, amount, and cost of resources used to produce hydrogen and develop Geographical Information System (GIS) resource maps for use in infrastructure development studies	NREL: GIS studies of renewable resources for hydrogen
	Life-cycle energy and emissions analysis	Conduct life-cycle energy and emissions analysis to compare existing and developing transportation and stationary technologies in terms of emissions and total energy requirements	ANL and NREL: Analysis of life-cycle energy and emissions associated with stationary fuel cells and fuel cell vehicles using the GREET model, with Macro-System Model interface

Table 4.4.1 Current Systems Analysis Activities (continued)			
Task	**Subtask**	**Approach**	**Organization**
Provide Support Functions and Conduct Reviews	Develop Macro-System Model computational infrastructure	Develop a modeling system to link component and integrated hydrogen models	Sandia National Laboratories (SNL): Developing the enterprise modeling system, including a user interface to allow users from across the country to access the MSM
	Maintain and upgrade H2A production and delivery, and FCPower Models	Maintain and upgrade cash flow tool to determine potential economic viability of hydrogen and fuel cell technologies	NREL: Standards and tools for consistent analysis of hydrogen technologies.
	Maintain and upgrade SERA Model	Maintain and upgrade the model that supports analysis of generalized regional energy issues related to hydrogen	NREL: Geographic-specific hydrogen infrastructure model to study hydrogen production and its interface to the electric grid
	Maintain and upgrade HyTrans	Maintain and upgrade the model that analyzes vehicle selections by consumers and those effects on energy cost	Oak Ridge National Laboratory (ORNL): HyTrans hydrogen infrastructure model to study fuel cell vehicle market penetration
	Maintain and update hydrogen capabilities in the MARKAL	Maintain and update hydrogen analysis capabilities of the MARKAL Model to support the impact analysis of hydrogen production on U.S. energy markets	Brookhaven National Laboratory (BNL)
	Maintain and update Production Infrastructure Options Model	Develop model for use in hydrogen production infrastructure options analysis	Directed Technologies, Inc.
	Maintain and Update the HyARC	Keep the modeling information in the web-based HyARC up-to-date and add new data as required by analysts and modelers	Pacific Northwest National Laboratory (PNNL)

4.5 Technical Challenges

The following discussion details the various technical and programmatic barriers that must be overcome to attain the Systems Analysis goal and objectives.

Barriers

A. Future Market Behavior

Understanding the behavior and drivers of the fuel cell, fuel, and vehicle markets are necessary to determine the long-term applications. Other major issues include the hydrogen supply infrastructure, vehicle supply interaction with fuels supply, and the requirements to meet demand. To analyze various hydrogen fuel and vehicle scenarios, models need to be developed to understand these issues and their interactions.

B. Stove-piped/Siloed Analytical Capability

Analytical capabilities and resources have been largely segmented functionally by sub-program (production, storage, fuel cells, etc.) and organizationally by DOE office (EERE, Fossil Energy, Nuclear Energy, and Science) as well as by performers/analysts (laboratories, specialized teams, industry/academia, etc.). Successful systems analysis requires the coordination and integration of analysis resources across all facets of the analytical domain.

C. Inconsistent Data, Assumptions and Guidelines

Analysis results are strongly influenced by the data sets employed, as well as the assumptions and guidelines established to frame the analytical tasks. These elements have been largely uncontrolled in the past, with individual analysts and organizations making their own value decisions. Although this approach does not necessarily make the results wrong, it does make it more difficult to put the results and ensuing recommendations in context with other analyses and the overall objectives of the FCT Program. Establishing a Program-endorsed consistent set of data, assumptions, and guidelines is challenging because of the large number of stakeholders involved and the breadth of technologies and system requirements.

D. Insufficient Suite of Models and Tools

The program currently has a group of models to use for analysis; however, the models are not sufficient to answer all analytical needs. A macro-system model is necessary to address the overarching hydrogen infrastructure as a system. Improvement of component models is necessary to make them more useable and consistent. Model validation is required to ensure credible analytical results are produced from the suite of modeling tools

E. Unplanned Studies and Analysis

Every year, many analysis questions are raised that require analysis external to, and, in some cases, instead of the plans made for that year. Many analysis questions need responses in brief periods of time, particularly when they are driven by priority requests or needs (DOE senior management, Congress, OMB [Office of Management and Budget], HTAC, etc.). An approach for accommodating both unforeseen, real time assessment requirements as well as planned FCT Program analysis is necessary.

4.6 Technical Task Descriptions

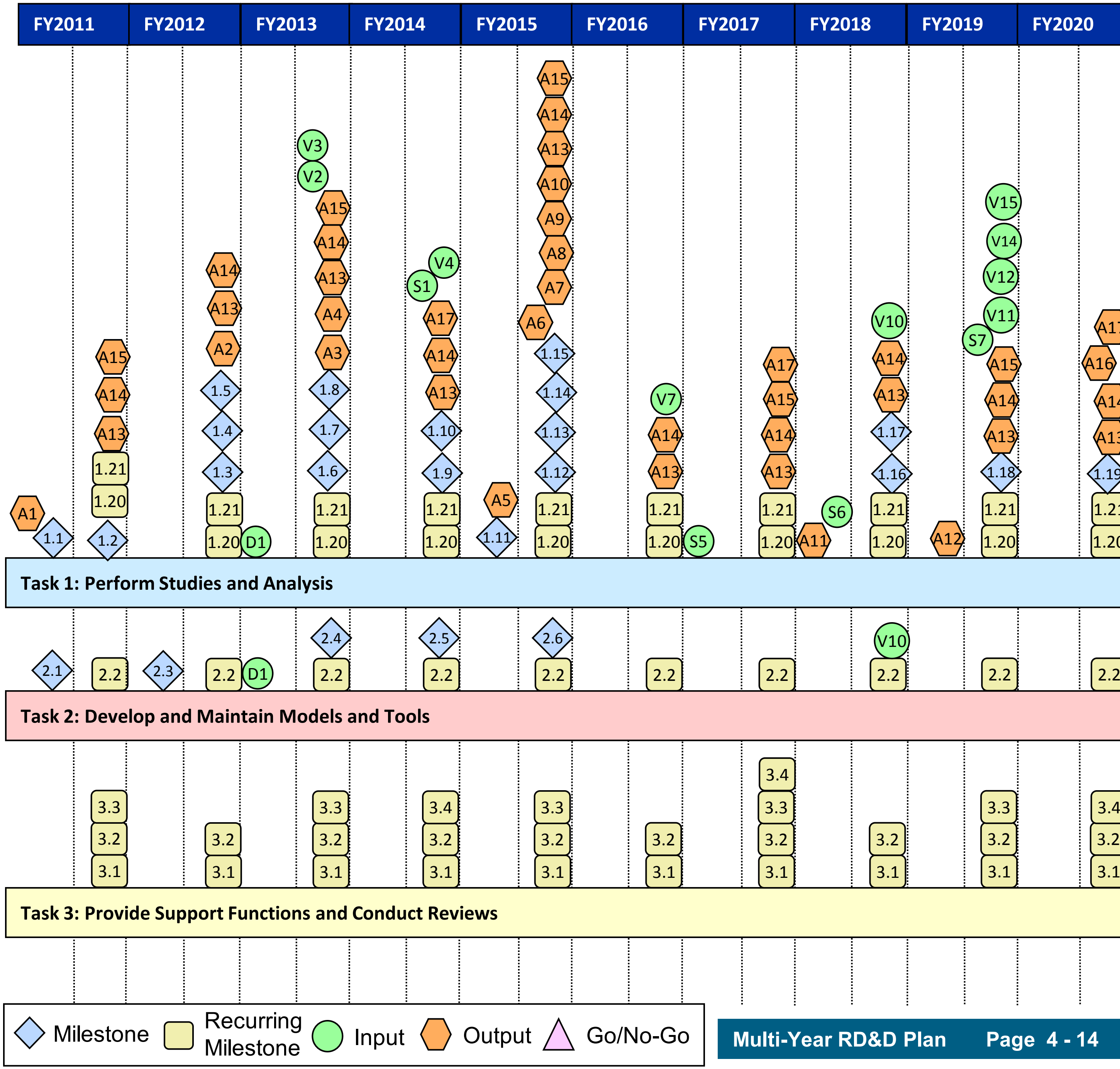
The technical task descriptions are presented in Table 4.6.1.

Table 4.6.1 Current Systems Analysis Activities		
Task	**Description**	**Barriers**
1	**Perform Studies and Analysis** • Analyze issues related to infrastructure for fuel and resource supply, including the effects on vehicle options customers have and how they make those decisions, non-vehicular hydrogen use, feedstock quality issues for fuel cells, cost/profitability analysis, and life-cycle energy and emissions analysis • Analyze early market opportunities for fuel cell applications including auxiliary power units (APUs), specialty vehicles, and stationary and backup power generation • Analyze the long-term impact of hydrogen fuel and vehicles, including the necessary infrastructure development, vehicle options, resource analysis, fuel quality analysis, cost/profitability analysis, and life-cycle energy and emissions analysis • Analyze environmental impact assessments • Perform risk analysis across FCT sub-programs • Conduct collaborative analyses with other DOE offices, and other government organizations, and international organizations	A, B, D, E
2	**Develop and Maintain Models and Tools** • Maintain and update H2A, HDSAM, FCPower model, and the Macro-System Model • Provide the following component models: geographic models; H2A production models; HDSAM; and FCPower model • Maintain the following integrated models: infrastructure models; hydrogen capabilities in MARKAL; the Hydrogen Infrastructure Options model; GREET; and SERA	A, B, C, D
3	**Provide Support Functions and Conduct Reviews** • Maintain and update the Hydrogen Analysis Resource Center through a configuration-managed change process • Maintain and update the Analysis Repository • Provide other support to the program and other organizations • Conduct workshops and conferences to focus and highlight program and hydrogen-related analysis activities • Utilize reviews and a working group to continuously improve Systems Analysis	B, C

4.7 Milestones

The following chart shows the interrelationship of milestones, tasks, supporting inputs from other FCT sub-programs, and technology/analytical outputs from the Systems Analysis function from FY 2011 through FY 2020. The inputs/outputs are also summarized in Appendix B.

Systems Analysis Milestone Chart



Task 1: Perform Studies and Analysis	
1.1	Complete an analysis of the hydrogen infrastructure and technical target progress for hydrogen fuel and vehicles. (2Q, 2011)
1.2	Update well-to-wheels analysis and quantify reductions in petroleum use, greenhouse-gas emissions, and criteria pollutant emissions. (Q4, 2011)
1.3	Complete analysis of the impact of biogas quality on stationary fuel cell cost and performance. (4Q, 2012)
1.4	Complete evaluation of fueling station costs for early vehicle penetration to determine the cost of fueling pathways for low and moderate fueling demand rates. (4Q, 2012)
1.5	Complete evaluation of hydrogen for energy storage and as an energy carrier to supplement energy and electrical infrastructure. (4Q, 2012)
1.6	Complete analysis of biogas availability for stationary power generation and hydrogen production. (4Q, 2013)
1.7	Complete analysis of job impact for fuel cell growth in material handling equipment sector through 2020. (4Q, 2013)
1.8	Determine economies of scale required for government ramp down of funding for RD&D. (4Q, 2013)
1.9	Complete analysis and studies of resource/feedstock, production/delivery, and existing infrastructure for technology readiness. (4Q, 2014)
1.10	Complete analysis of job impact for fuel cell growth in distributed power generation sector through 2020. (4Q, 2014)
1.11	Complete analysis of the impact of hydrogen quality on the hydrogen production cost and the fuel cell performance for the long range technologies and technology readiness. (2Q, 2015)
1.12	Complete an analysis of the hydrogen infrastructure and technical target progress for technology readiness. (4Q, 2015)
1.13	Complete environmental analysis of the technology environmental impacts for hydrogen and fuel cell scenarios and technology readiness. (4Q, 2015)
1.14	Complete analysis of the job impact from fuel cell growth in stationary power generation sector through 2020. (4Q, 2015)
1.15	Complete analysis of program milestones and technology readiness goals - including risk analysis, independent reviews, financial evaluations, and environmental analysis - to identify technology and risk mitigation strategies. (4Q, 2015)
1.16	Complete analysis of program performance, cost status, and potential use of fuel cells for a portfolio of commercial applications. (4Q, 2018)

1.17	Complete analysis of program technology performance and cost status, and potential to enable use of fuel cells for a portfolio of commercial applications. (4Q, 2018)
1.18	Complete life cycle analysis of vehicle costs for fuel cell electric vehicles compared to other vehicle platforms. (4Q, 2019)
1.19	Complete analysis of the potential for hydrogen, stationary fuel cells, fuel cell vehicles, and other fuel cell applications such as material handling equipment including resources, infrastructure and system effects resulting from the growth in hydrogen market shares in various economic sectors. (4Q, 2020)
1.20	Complete review of fuel cell and hydrogen markets. (4Q, 2011 through 4Q, 2020)
1.21	Complete review of commercial products and patents resulting from government funding for fuel cell and hydrogen technology R&D. (4Q, 2011 through 4Q, 2020)

Task 2: Develop and Maintain Models and Tools	
2.1	Complete the 2nd version of the Macro-System Model to include the analytical capabilities to evaluate the electrical infrastructure. (2Q, 2011)
2.2	Annual model update and validation. (4Q, 2011 through 4Q, 2020)
2.3	Complete development of job estimation model. (2Q, 2012)
2.4	Complete validation of job estimation model for material handling equipment sector. (4Q, 2013)
2.5	Complete validation of job estimation model for distributed fuel cell power generation. (4Q, 2014)
2.6	Complete validation of job estimation model for stationary fuel cell power generation. (4Q, 2015)

Task 3: Provide Support Functions and Conduct Reviews	
3.1	Annual update of Analysis Portfolio. (4Q, 2011 through 4Q, 2020)
3.2	Annual update of Hydrogen Analysis Resource Center. (4Q, 2011 through 4Q, 2020)
3.3	Complete review of status and outlook of non-automotive fuel cell industry. (biennially from 4Q, 2011 through 4Q, 2019)
3.4	Review Hydrogen Threshold Cost status. (4Q, 2014; 4Q, 2017; 4Q, 2020)

Outputs

A1 Output to Systems Integration: Report on the status of the technologies and infrastructure to meet the demands for the hydrogen fuel and vehicles. (1Q, 2011)

A2 Output to Fuel Cells: Cost of competing vehicle powertrain. (4Q, 2012)

A3 Output to Delivery and Storage: Preliminary well-to-wheel power plant efficiency analysis for advanced material systems. (4Q, 2013)

A4 Output to Delivery: Analysis for costs for optimal hydrogen pressure contributions at each point in the system from production to dispensing at point of use. (4Q, 2013)

A5 Output to Program: Update on hydrogen delivery and refueling data for well to power plant efficiency analysis for advanced material systems. (2Q, 2015)

A6 Output to Storage: Report on the status of composite tank costs. (3Q, 2015)

A7 Output to Program: Update on onboard automotive fuel cell system power, input pressure, and vehicle refill time. (4Q, 2015)

A8 Output to Systems Integration: Report on the results of the infrastructure analysis for the long term technologies and requirements for technology readiness. (4Q, 2015)

A9 Output to Storage: Update on onboard automotive fuel cell system power, input pressure, degree of hybridization and vehicle refill time. (4Q, 2015)

A10 Output to Systems Integration: Report on the environmental analysis of the Hydrogen and Fuel Cells Program. (4Q, 2015)

A11 Output to Storage: Report on the projected performance of materials-based systems for onboard hydrogen storage. (1Q, 2018)

A12 Output to Storage: Report on the status of advanced materials system costs. (2Q, 2019)

A13 Output to Education and Program: Annual market reports on status of fuel cell and hydrogen industry. (4Q, 2011 – 2020)

A14 Output to Program: Annual report on the status of commercial products and patents resulting from government funded R&D. (4Q, 2011 – 2020)

A15 Output to Education and Program: Report on the status of government policies on non-automotive fuel cell industry. (4Q, 2011; 4Q, 2013; 4Q, 2015; 4Q, 2017; 4Q, 2019)

A16 Output to Storage: Report on the projected performance of hydrogen storage systems for non-automotive applications. (3Q, 2020)

A17 Output to Program: Revised hydrogen threshold cost based on fuel and automotive technology advances, if required. (4Q 2014; 4Q, 2017; 4Q, 2020)

Inputs

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)

S1 Input from Storage: Update status of composite tank costs. (3Q, 2014)

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

S6 Input from Storage: Update status of advanced materials system costs. (2Q, 2018)

S7 Input from Storage: Projected performance of hydrogen storage systems for non-automotive applications. (3Q, 2019)

V2 Input from Technology Validation: 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 Input from Technology Validation: Publish/post composite data products for material handling and backup power, including safety event data. (3Q, 2012)

V4 Input from Technology Validation: Validate stationary fuel cell system that co-produces hydrogen and electricity and report on durability and efficiency. (4Q, 2014)

V7 Input from Technology Validation: Validate novel hydrogen compression technology durability and efficiency. (4Q, 2016)

V10 Input from Technology Validation: 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)

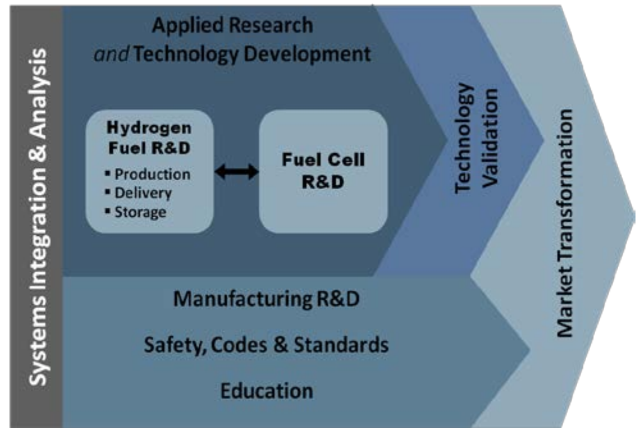
V11 Input from Technology Validation: Validate station compression technology provided by the delivery team. (4Q, 2019)

V12 Input from Technology Validation: Validate light duty fuel cell vehicle durability. (4Q, 2019)

V14 Input from Technology Validation: Validate liquefaction technology provided by the delivery team. (4Q, 2019)

V15 Input from Technology Validation: Validate pipeline technology provided by the delivery team. (4Q, 2019)

5.0 Systems Integration



The Systems Integration function of the DOE Hydrogen and Fuel Cells Program (the Program) provides independent, strategic, systems-level expertise and processes to enable system-level planning, data-driven decision-making, effective portfolio management, and program integration. System Integration ensures that system-level targets are developed, verified, and met and that the sub-programs are well-coordinated. Systems Integration provides tailored technical and programmatic support to ensure a disciplined approach to the research, design, development, and validation of complex systems. Systems Integration provides such support by employing systems engineering-based processes and practices to calibrate internal management processes for enhanced internal efficiency and overall performance. Tailored to the particular requirements of a robust, comprehensive research, development, and demonstration (RD&D) program, these tools and processes take advantage of experience and lessons learned from industry, academia, international sources, and other federal agencies [particularly the Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA)]. The systems differ from DOD and NASA in that DOD and NASA's systems are for their operations (e.g., fighter jets, spacecraft), whereas the systems supported by this effort are national-scale, industry and consumer applications under investigation by the program. The systems applications include hydrogen / fuel cell energy systems for on-road light duty vehicles; material and freight handling systems; combined heat and power systems (with and without hydrogen production); backup power systems; auxiliary power units; and portable power.

5.1 Goal and Objectives

Goal

To provide an independent, strategic, systems-level framework to ensure that system-level targets are developed, verified, and met and that the various Fuel Cell Technologies Program (FCT Program) sub-programs are well-coordinated.

Objectives

- Provide periodic independent verification of progress toward key technical targets, review of project performance, and ensure that the overall course of RD&D satisfies the FCT Program needs.
- Update the FCT Program work breakdown structure (WBS) and resource loaded plan (RLP) in 2012 and in following years.
- By 2012, develop a portfolio management tool that allows the FCT Program to estimate effects of changing funding level or distribution on the expected time and effort to achieve program goals.
- By 2015, complete an analysis of hydrogen infrastructure and technical target progress for technology readiness, in cooperation with the Systems Analysis sub-program.

- Coordinate the Annual Merit Review and Peer Evaluation (AMR) meeting and report, the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC), and the Program's **web site (**www.hydrogen.energy.gov**).**

5.2 Approach

Systems Integration provides technical and programmatic support to the Program by performing the following five activities: (1) systems level planning and integration (multiyear targets, work breakdown structure, and change control); (2) developing and providing tools and information necessary for portfolio analysis including risk identification and quantification; (3) systems analysis and modeling including the macro-system model (MSM); (4) verification of technical performance; and (5) coordinating the AMR, HTAC, and Program's website. See Figure 5.2.1 for a graphic description of how the planning, portfolio analysis, systems analysis, and verification functions inter-relate. Descriptions of the five tasks' activities follow in this section.

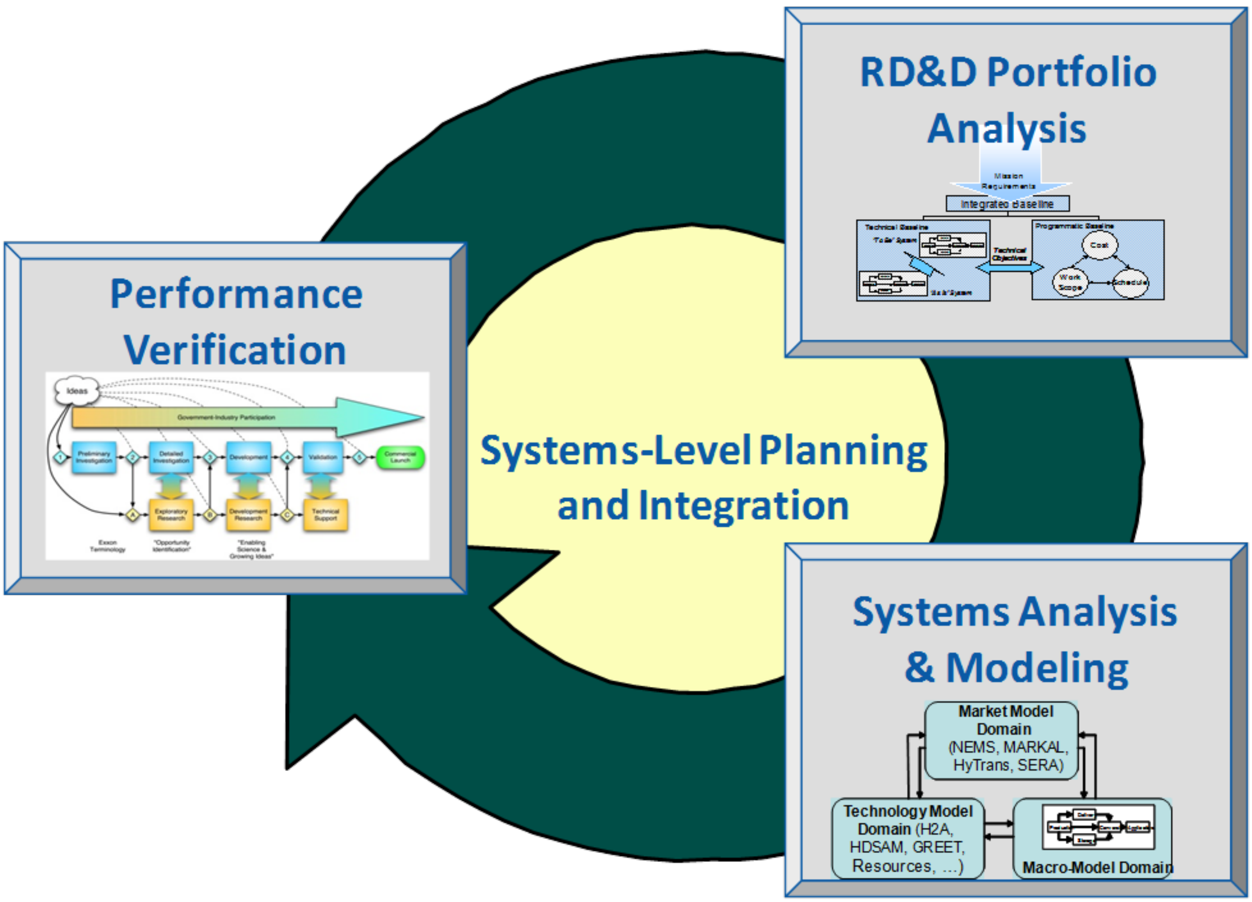


Figure 5.2.1 Systems Integration Approach Overview

System Level Planning and Integration

The FCT Program requires coordinated planning including Multi-Year Research, Development, and Demonstration (MYRD&D) plans, WBSs, and program-level RLPs. The Systems Integration function supports the FCT Program in developing, updating (including change control), and publishing those plans. Coordinated development of the plans are challenging due to the dynamic environment both technically, due to unpredictability in evolution of the technology and competing technologies, and organizationally, due to changing priorities. Another challenge is integrating the plans across multiple technology platforms.

The MYRD&D plan documents the FCT Program's objectives, approach, targets, barriers, milestones, and sub-program inputs/outputs. The Systems Integration function coordinates development and updating of the plan so that it defines the tasks necessary to meet the FCT Program's objectives; it is internally consistent; and it incorporates technology advances, program learning, and changes in direction and priority. All changes to the MYRD&D plan undergo a formal change control process that has been established to ensure that their potential impacts are evaluated, coordinated, controlled, reviewed, approved, and documented in a manner that best serves the FCT Program and its projects.

The decision-making body for approving proposed changes to the MYRD&D plan is the Change Control Board (CCB), headed by the FCT Program's Chief Engineer. All proposed changes are submitted and individually reviewed by all CCB members. Input from each member is collected and incorporated, and a meeting is held to discuss and finalize the input. Following CCB approval, the change is implemented and final approval from the FCT Program's Chief Engineer is sought. Once it is received, Systems Integration publishes the updated MYRD&D plan.

The Systems Integration function supports the development of an integrated WBS and RLP. Both are key elements necessary to manage and control a program. The WBS is a definition of the necessary work to perform the activities and achieve the targets defined in the MYRD&D plan. The WBS is built as a hierarchy that divides the effort into well-defined activities and identifies dependencies among activities. The RLP reports an estimate of the budget and schedule necessary to perform the activities defined in the WBS but does not define specific personnel, tools, facilities, or other resources.

Portfolio Analysis

Portfolio analysis is performed to assist the FCT Program in identifying the optimal portfolio of technologies and projects to achieve its performance and market targets. Factors considered include the level of benefits expected, scope, cost, schedule, and risk to realizing the program benefits. It is an iterative process that weighs benefits against costs and risks while taking into account the latest external information regarding market, technical status, and barriers. The process also incorporates the updated status of portfolio efforts based on verified, externally reviewed progress.

Systems Integration utilizes portfolio analysis tools and processes that help manage the FCT Program by ensuring that (1) RD&D and analysis projects are properly addressing all of the FCT Program requirements and (2) that the cost, schedule, and performance of the FCT Program and its projects are understood and controlled. In other words, the first ensures that the FCT Program is "doing the right things" and the second that it is "doing things right." These two components are represented by the Technical Baseline (TB) and Programmatic Baseline (PB), respectively, which are then linked by the technical objectives of the FCT Program to provide the "integrated" aspects of the overall baseline. As shown in Figure 5.2.2, an Integrated Baseline (IB) for the FCT Program was originally derived from the overarching policy, strategy, and planning documents associated with the FCT Program including the Energy Policy Act of 2005 (EPACT), the U.S. DRIVE Partnership Plan and its preceding agreements, the National Hydrogen Vision and Roadmap, the DOE Strategic Plan, individual DOE Office strategic plans, the Hydrogen and Fuel Cells Program Plan, and individual DOE Office MYRD&D Plans. It will be updated regularly to represent the FCT Program's status and targets.

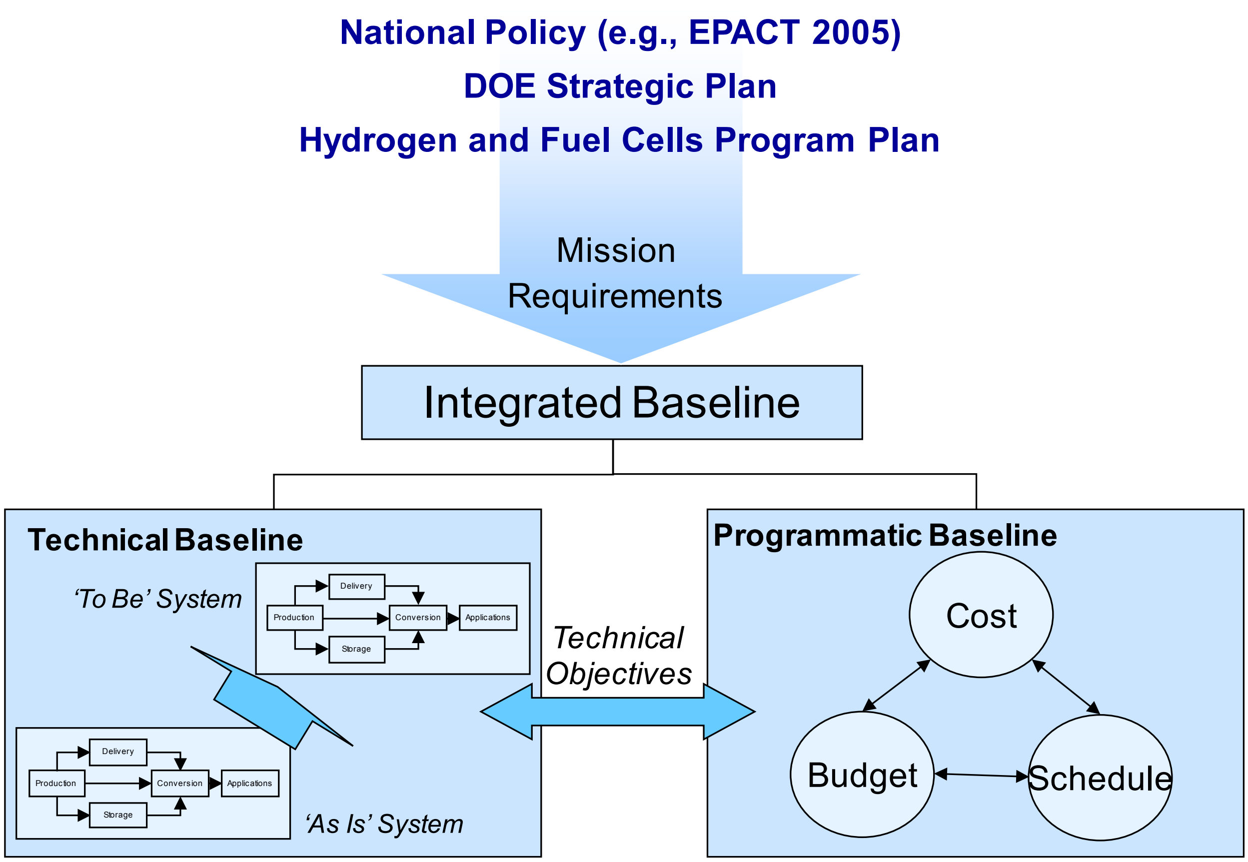


Figure 5.2.2 The Integrated Baseline

Tracking Status against Targets - Technical Baseline. To ensure that the FCT Program is "doing the right things," the TB provides a detailed map starting from the overall requirements, down through the objectives and barriers of the individual FCT Program sub-programs, and finally to the task and individual project level. The TB includes the prioritization of activities, as well as information on the risk level of individual activities.

Questions that can be addressed and answered using the TB include:

Does the RD&D portfolio properly address all the FCT Program requirements?

Are there gaps or weaknesses in coverage of technical areas?

Are the high priority items receiving the proper level of programmatic attention?

Are there sufficient approaches and projects in the higher risk areas to mitigate those risks?

When funding or focus changes, in what areas should the FCT Program redistribute, add, or decrease resources?

Are technical targets supporting system level configurations synchronized and monitored for consistency in an on-going manner?

Tracking Status against the Plan - Programmatic Baseline. To ensure that the FCT Program is "doing things right," the PB provides a tool and process to track the cost, schedule, and budget performance of the FCT Program.

Questions that can be addressed and answered using the PB include:

Are budgets and schedules on track – for the FCT Program, an FCT sub-program, or a task?

If there is a delay in a particular activity's schedule, what is the cost and schedule impact on dependent or related activities?

When funding or focus changes, in what areas should the FCT Program redistribute, add, or decrease resources?

How does the FCT Program scope change given different funding-level scenarios?

Figure 5.2.3 illustrates the interactions between the WBS, schedule, and budget in the programmatic baseline.

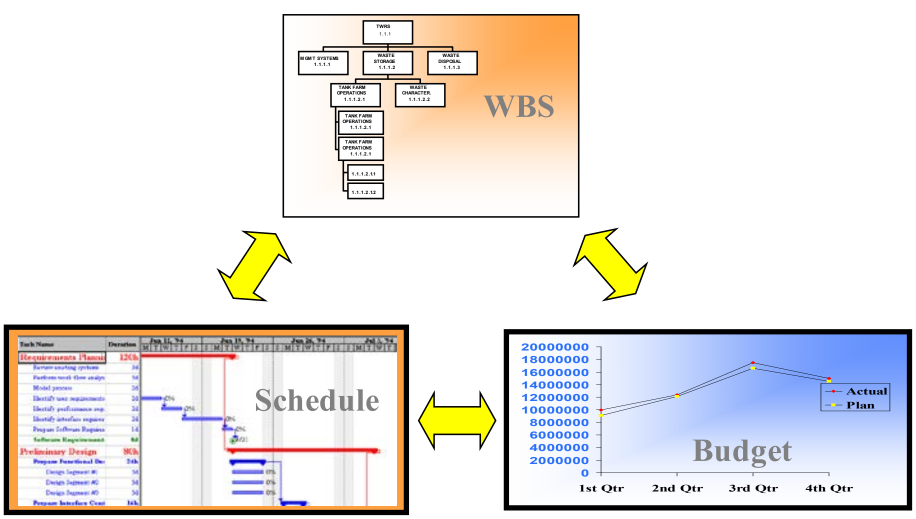


Figure 5.2.3 Programmatic Baseline Interaction

Integrated Baseline (IB). The IB tracks work against the baselines developed in the System Level Planning and Integration task described above with the intent of defining scope, schedule, and costs.

- *Scope Baseline*. Program management, with the aid of Systems Integration, establishes the boundaries of the system to be developed and operated. Within the boundaries are the overall Program mission, description of the Program and its sub-programs, and interfaces to related systems and organizations.
- *Schedule Baseline*. Systems Integration aids the FCT Program in establishing multi-year and annual milestones. The major milestones include those needed to establish the foundation of the program, and to enable key decisions to be made against documented criteria.
- *Cost Baseline*. The FCT Program establishes cost baselines, using estimates of the cost to achieve scope objectives within the defined schedule, but tempered by expectations of actual funding available through annual appropriations. The Cost Baseline is periodically updated to reflect program plan changes.

The overall approach that Systems Integration takes to bring together the TB and the PB into an IB for the Program is to first establish individual IBs for each sub-program and build these into a baseline for the overall program. Various direction and guidance documents, along with policy and direction from DOE management, guide the FCT Program staff in defining the mission requirements for the FCT Program; these mission requirements provide overarching guidance and a common framework for development of IBs for the sub-programs. As depicted in Figure 5.2.4, the TB is developed first; the PB is then derived from the TB and from other program management requirements.

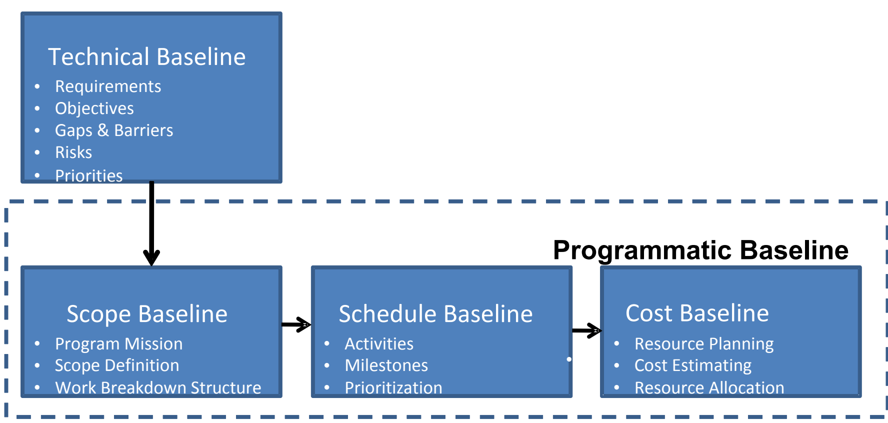


Figure 5.2.4 Establishing the Integrated Baseline

Risk Management. Systems Integration supports implementation of a risk management process to identify potential risks and determine actions that will mitigate the impact of those risks. The Risk Management Plan (RMP) describes methods for identifying, assessing, prioritizing, and analyzing risk drivers; developing risk-handling plans; and planning for adequate resources to handle risk. The RMP assigns specific responsibilities for the management of risk and prescribes the documenting, monitoring, and reporting processes to be followed. A six-step risk process—risk awareness, identification, quantification, handling, impact determination, and reporting, and tracking—will be used. Throughout the life of the FCT Program, Systems Integration helps identify "potential" risks, focusing on the critical areas that could affect program outcome such as:

- System Requirements
- Environment, Safety, and Health
- Modeling and Simulation Accuracy
- Technology Capability
- Budget and Funding Management
- Schedule
- Stakeholder, Legal, and Regulatory Issues.

Systems Analysis and Modeling

Systems Integration assists the Systems Analysis sub-program in improving the understanding of individual components' contributions, interactions, and synergies in achieving the FCT Program's objectives. One focus area is the review and assessment of alternatives necessary to meet the needs of a future hydrogen system as well as the FCT Program's progress toward that goal. Systems Integration also provides independent analysis and analytical reviews. In addition, the Systems Integration function is responsible for development of a MSM and analyses using it.

Systems Integration provides the analysis necessary to determine the requirements of future hydrogen and fuel cell systems. The results of those analyses are used to set specific program targets. For example, Systems Integration performed the analyses necessary to set the hydrogen threshold cost and its apportionment. Systems Integration also performs parametric studies to understand tradeoffs between capital and operating costs and between production and utilization. Those analyses are important because the resulting information is necessary to define specific technology targets and understand tradeoffs between them – information necessary to help ensure objective and substantiated portfolio management decisions. Systems Integration also performs analyses of pathway cost, energy use, and emissions to assure that FCT Program targets support national goals to reduce petroleum use and greenhouse gas emissions.

Systems Integration performs independent analyses to verify and provide a definitive set of parameters for FCT Program use. These analyses include reports on the cost, energy use, and emissions of hydrogen production, delivery, and dispensing pathways. The methodology and parameters in those analyses are reviewed by FCT Program staff and external partners to guarantee their veracity. Systems Integration participates in the FCT Program's partnerships to pull in external experts to verify analytical conclusions.

Systems Integration leads the development of the MSM. The MSM was developed to act as an overarching system that provides a cross-cutting simulation capability necessary to perform analyses of production, delivery, and dispensing options while consistently propagating assumptions throughout the analysis. It was developed to meet the following specific objectives:

- To perform rapid, cross-cutting analysis in a single location by linking existing applicable models;
- To improve consistency of technology representation (i.e., consistency between models);
- To allow for consistent use of hydrogen models without requiring all users to be experts in all models;

- To support decisions regarding programmatic investments, focus of funding, and research milestones through analyses and sensitivity runs.

The MSM has a structure that links other existing and emerging models. A number of models exist to analyze components and subsystems of a hydrogen infrastructure; however, the MSM integrates some of those component and subsystem models using a common architecture to compute overall results (i.e., it is a tool that addresses the overarching hydrogen fuel infrastructure as a system). The MSM structure was inspired by the example of the federated object model (FOM), as exemplified in the DOD High Level Architecture (HLA). The FOM approach requires the explicit definition of the messages (objects and interactions) through which the models interact with their environment, providing a common communication format and structure for the models. Scalability is achieved because there is only one such interface module per model, rather than one for each pair of models.

Additionally, Systems Integration supports the Systems Analysis sub-program in a variety of efforts. These efforts include:

- Updates to the annual Analysis Portfolio – this Appendix to the Systems Analysis Plan provides information on all the analysis and modeling projects funded in the current fiscal year.
- Organization of Systems Analysis Workshops and Systems Analysis Working Groups – these are important activities in terms of dissemination of Systems Analysis products, as well as analysis community input to, and review of, the Systems Analysis sub-program.
- Population of the Analysis Repository – this online database captures products and outputs of all the analysis and modeling projects funded by Systems Analysis, as well as other sub-programs and offices contributing to hydrogen and fuel cells.

Technical Performance Verification

As the FCT Program develops new technologies and produces research results, Systems Integration is responsible for reporting and review processes necessary to verify that selected/key technologies and system designs are on track to meet the FCT Program's cost and performance targets. To do so, Systems Integration facilitates technical reviews to evaluate the strategic fit with FCT Program objectives, technical potential, economic/market potential, and environmental, health, and safety considerations along with the plan and potential for further development. Verification is accomplished through peer reviews, analysis, testing, and/or demonstration. Criteria and approaches will vary depending on the maturity of the technology and project funding status. For example, at early stages of development, information available to evaluate concepts is likely to be more general and have higher uncertainty than that available at later stages. Thus, information stemming from a review will be used to re-evaluate the baseline. At later stages of development, more information is available and programmatic targets may need to be adjusted based on results from reviews.

In some cases, Systems Integration convenes technical review panels of peer experts to provide an independent assessment of technology status and potential to DOE for consideration during decision processes. Independent assessments are particularly useful for major go/no-go decisions and are helpful when an assessment of progress toward one of the key technical targets of the FCT Program is warranted. Independent reviews of the following have been completed:

- Hydrogen Production Cost Estimate Using Biomass Gasification
- 1–10 kW Stationary Combined Heat and Power Systems Status and Technical Potential
- Current (2009) State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis
- Fuel Cell System Cost for Transportation—2008 Cost Estimate
- Go/No-Go Recommendation for Sodium Borohydride for On-Board Vehicular Hydrogen Storage
- Measurement of Hydrogen Production Rate Based on Dew Point Temperatures
- Cryo-compressed Hydrogen Storage for Vehicular Applications
- Distributed Hydrogen Production from Natural Gas
- Fuel Cell System for Transportation—2005 Cost Estimate
- On-Board Fuel Processing Go/No-Go Decision

Reports from those reviews are available at http://www.hydrogen.energy.gov/peer_reviews.html.

In addition, Systems Integration works closely with the DOE Technology Development Managers to facilitate reviews based on system-level requirements and review criteria. In particular, the Systems Integration function develops a report compiling all reviewer comments and scores during the AMR. The Systems Integration sub-program is also responsible for the annual progress report that summarizes the objectives, approach, technical accomplishments, and future plans for each of the Program's projects in professional journal format. Systems Integration also conducts stage gate reviews at key progress points for significant projects.

Program Support

Systems Integration provides analyses and recommends DOE-sponsored activities to make sure that RD&D results are shared throughout the technical community, thus ensuring the further development of the requisite technologies. Specific support is provided to the overall Program in the following areas:

- AMR – Systems Integration coordinates the annual review of the Program, during which primary investigators from typically 300 funded projects present their results in oral or poster formats. In addition, a team of ~200 peer reviewers evaluate approximately two-thirds of the presented projects for feedback to the Program. More information about the AMR is available at http://www.annualmeritreview.energy.gov/

- HTAC – Systems Integration provides coordination and technical support to this Federal Advisory Committee Act (FACA)-level committee which reviews DOE efforts in hydrogen and fuel cell RD&D and provides information and recommendations to the Secretary of Energy. More information about the HTAC is available at http://www.hydrogen.energy.gov/advisory_htac.html

- DOE Hydrogen and Fuel Cells Program Website – This website provides a one-stop-shop for all of the hydrogen and fuel cell activities of DOE, across the offices of Energy Efficiency and Renewable Energy (EERE), Fossil Energy (FE), Nuclear Energy (NE), and Science (SC). The site is available at http://www.hydrogen.energy.gov/.

5.3 Programmatic Status

Table 5.3.1 provides the current set of Systems Integration activities.

Table 5.3.1 Current FY12 Systems Integration Activities

Activities	Description
Systems Level Planning and Integration	• Coordination of an update to the Multi-Year RD&D Plan including update coordination, facilitating change control processes and boards, and publication. • Initiation of an update to the FCT Program's WBS and RLP.
Portfolio Analysis	• Initiation of an update to the integrated baseline. • Completion of technical uncertainty assessments of fuel cells for vehicles.
Systems Analysis and Modeling	• Development of pathway parameter tables and results for combined heat, power, and hydrogen systems. • Analysis of 'tipping' points in hydrogen transition scenarios. • Addition of combined heat, power, and hydrogen systems to the HyPro model. • Updates to the MSM as linked models are updated. • Addition of MSM capabilities (e.g., compressed hydrogen gas and cryo-compressed trucks) and user features (e.g., outputs in the graphical user interface).
Verification of Technical Performance	• Publication of the AMR report. • Coordination of an independent review of cost of hydrogen produced from biomass using gasification.
Program Support	• Coordination of the AMR meeting. • Publication of the Annual Progress Report. • Coordination of the Hydrogen and Fuel Cells Technical Advisory Committee. • Providing timely and value-added updates to the DOE Hydrogen and Fuel Cells Program website.

5.4 Challenges

The following discussion details the various technical and programmatic barriers that must be overcome to attain the DOE Hydrogen and Fuel Cells Program Systems Integration goal and objectives.

A. Program Complexity.

The Program has targets spanning multiple sectors and is comprised of nearly 300 projects spread across different organizations. Those projects address a variety of technological disciplines, many of which are on the leading edge of technology. Further complicating the ability to properly integrate the Program is the geographical dispersal of these organizations, its relatively long-term duration, and the multitude of external stakeholders. Both vertical and horizontal integration is necessary to integrate the Program under a unified system and to ensure integrated management and optimization of work flow across organizational boundaries. The four DOE offices (EERE, FE, NE, and SC) and other programs and agencies (e.g., Department of Transportation) that are involved in hydrogen and fuel cell work have their own baselining and scheduling requirements, which must be consistent and interrelated.

B. Adapting System Integration Functions to an RD&D Program.

Systems integration has most often been applied to the design, development, production, and maintenance of large, complex acquisition or construction projects. Implementing systems integration within an ongoing RD&D program without delaying or disrupting current efforts represents a significant challenge, especially when the process has not been institutionalized within the organization.

C. Inherent Unpredictability of RD&D.

Most systems integration and engineering efforts have been applied to large hardware and software acquisition projects, not RD&D programs. Given the inherent unpredictability of achieving desired outcomes from the R&D of new technologies, tailoring the systems integration procedures and tools to the RD&D paradigm is a challenge. Obtaining Program and stakeholder acceptance of these processes as value-added and important to both sub-program and overall Program success is also a challenge.

D. Unpredictability of competing technologies' future performance.

The potential improvements to the incumbent technologies and emerging competing technologies are unpredictable. In addition, resource supplies are uncertain and the world-wide markets are unpredictable so the future costs of competing technologies are unknown. The overall unpredictability makes target setting and tracking challenging.

E. Accessibility/Availability of Technical Information.

The cost-effective availability and accessibility of the most up-to-date technical results are necessary to support programmatic decision making. Within the Program, technical information relevant to a particular issue must be collected from a wide array of sources—from people in different organizations, who developed it originally without necessarily considering its role in management decision-making. To ensure that results from many sources are technically and practically realistic, these diverse technical results require a vetting process.

5.5 Task Descriptions

The task descriptions are presented in Table 5.5.1.

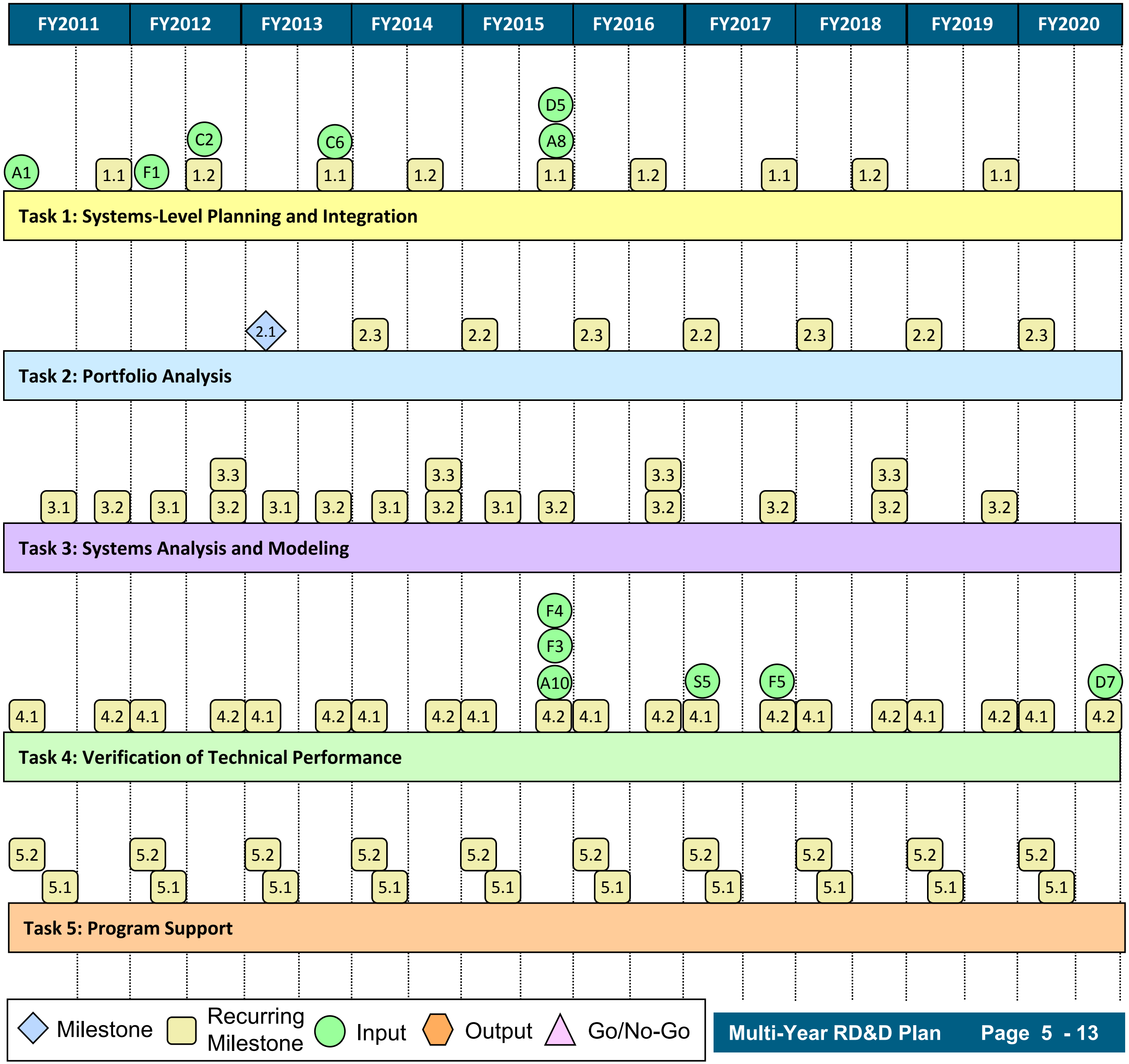
Table 5.5.1 Task Descriptions

Task	Description	Challenges
1	Systems Level Planning and Integration • Update the FCT Program's Multi-Year Plan. • Update the FCT Program's WBS and RLP. • Continue Change Management/Change Control processes.	A, B
2	Portfolio Analysis • Support updates to the FCT Program master budget and schedule. • Analyze the effect of variances in performance and funding on the schedule. • Continue uncertainty assessments.	A, B, C
3	Systems Analysis and Modeling • Develop and maintain the MSM infrastructure. • Support of the analysis community in use of the MSM. • Analyze pathways to identify gaps and other performance issues. • Provide other system modeling support	C, D, E
4	Verification of Technical Performance • Perform Stage Gate Reviews. • Conduct independent technical target assessments. • Publish AMR report.	A, B, C
5	Program Support • Conduct the Annual Merit Review and Peer Evaluation Meeting. • Publish the Annual Progress Report. • Support HTAC technical needs and reporting. • Update DOE Program websites.	A, B

5.6 Milestones

The following chart shows the interrelationship of milestones, tasks, and supporting inputs from other sub-programs for the Systems Integration function through FY2020. The inputs/outputs are also summarized in Appendix B.

Systems Integration Milestone Chart



Task 1: Systems-Level Planning and Integration	
1.1	Updates to the MYRD&D Plan (4Q, 2011; 4Q, 2013; 4Q, 2015; 4Q, 2017; 4Q, 2019)
1.2	Updates to WBS and RLP (3Q, 2012; 3Q, 2014; 3Q, 2016; 3Q, 2018)

Task 2: Portfolio Analysis	
2.1	Improved system for tracking programmatic baseline (1Q, 2013)
2.2	Updates to programmatic baseline (1Q, 2015; 1Q, 2017; 1Q, 2019)
2.3	Updates to programmatic targets (1Q, 2014; 1Q, 2016; 1Q, 2018; 1Q, 2020)

Task 3: Systems Analysis and Modeling	
3.1	Analysis Portfolio and Analysis Repository annual updates. (2Q, 2011; 2Q, 2012; 2Q, 2013; 2Q, 2014; 2Q, 2015)
3.2	MSM updates. (4Q, 2011; 4Q, 2012; 4Q, 2013; 4Q, 2014; 4Q, 2015; 4Q, 2016; 4Q, 2017; 4Q, 2018; 4Q, 2019)
3.3	Updates to pathways cost, energy use, and emissions report (4Q, 2012; 4Q, 2014; 4Q, 2016; 4Q, 2018)

Task 4: Verification of Technical Performance	
4.1	Annual Merit Review Peer Review Report published. (1Q, 2011; 1Q, 2012; 1Q, 2013; 1Q, 2014; 1Q, 2015; 1Q, 2016; 1Q, 2017; 1Q, 2018; 1Q, 2019; 1Q, 2020)
4.2	Independent Reviews of progress on Technical Targets. (4Q, 2011; 4Q, 2012; 4Q, 2013; 4Q, 2014; 4Q, 2015; 4Q, 2016; 4Q, 2017; 4Q, 2018; 4Q, 2019; 4Q, 2020)

Task 5: Program Support	
5.1	Produce Annual Progress Report. (2Q, 2011; 2Q, 2012; 2Q, 2013; 2Q, 2014; 2Q, 2015; 2Q, 2016; 2Q, 2017; 2Q, 2018; 2Q, 2019; 2Q, 2020)
5.2	Facilitate HTAC meetings and provide technical support (1Q, 2011; 1Q, 2012; 1Q, 2013; 1Q, 2014; 1Q, 2015; 1Q, 2016; 1Q, 2017; 1Q, 2018; 1Q, 2019; 1Q, 2020)

Outputs

No outputs from Systems Integration

Inputs

A1 Input from Systems Analysis: Report on the status of the technologies and infrastructure to meet the demands for the hydrogen fuel and vehicles. (1Q, 2011)

A8 Input from Systems Analysis: Report on the results of the infrastructure analysis for the long term technologies and requirements for technology readiness. (4Q, 2015)

A10 Input from Systems Analysis: Report on the environmental analysis of the Hydrogen and Fuel Cells Program. (4Q, 2015)

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)

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)

F1 Input from Fuel Cells: Cost of the baseline automotive fuel cell system. (1Q, 2012)

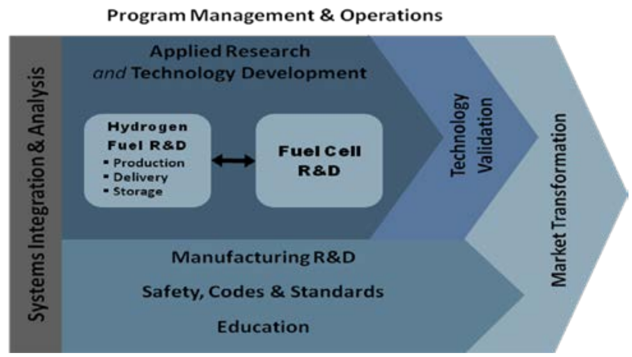
F3 Input from Fuel Cells: Provide micro-combined heat and power system test data from documented sources indicating performance status. (4Q, 2015)

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)

S5 Input from Storage: Projected performance of materials-based systems for onboard hydrogen storage. (1Q, 2017)V18 Input from Technology Validation: 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)

6.0 Program Management and Operations



The U.S. Department of Energy's (DOE's) Hydrogen and Fuel Cells Program (the Program) is composed of activities within the Offices of Energy Efficiency and Renewable Energy (EERE); Fossil Energy (FE); Nuclear Energy (NE); and Science (SC). EERE's Fuel Cell Technologies Program (FCT Program) represents the major component of this effort. The FCT Program Manager manages the Program to maintain a cohesive overall program and to be consistent with the National Academies recommendations. This structure allows for clear lines of communication and integrates the many participating offices, agencies, laboratories, and contractors.

The Program includes research, development, and demonstration (RD&D), systems analysis, systems integration, safety, codes and standards, and education activities, requiring the integrated efforts of federal offices, field offices, national laboratories, academic institutions, and numerous contractors spread across the country. Many individuals and organizations participate through partnerships with automotive and power equipment manufacturers, energy and chemical companies, electric and natural gas utilities, building designers, diverse component suppliers, other federal agencies, state government agencies, universities, national laboratories, and other stakeholder organizations. The diversity and size of the Program require a Program Management and Operations approach based on a uniform set of requirements, assumptions, expectations, and procedures.

6.1 Program Organization

The Program's organizational structure is shown in Figure 6.1.1. Program management takes place at DOE Headquarters in Washington, D.C. Project management is conducted in the field office locations in Golden, CO; Morgantown, WV (National Energy Technology Laboratory); Idaho Falls, ID; and Chicago, IL. Project implementation is carried out at the national laboratories, industry and universities, and through coalitions with state and local government agencies.

The management approach is grounded in the following results-oriented management principles:

- A vertical organization with clear lines of responsibility and authority
- Top-down (to project) program planning from conception to technology validation, and time-phased technical, cost and schedule baselines
- Centralization of key functions to ensure effective integration of the Program's projects
- Independent Program control systems ensuring maximum visibility/transparency.

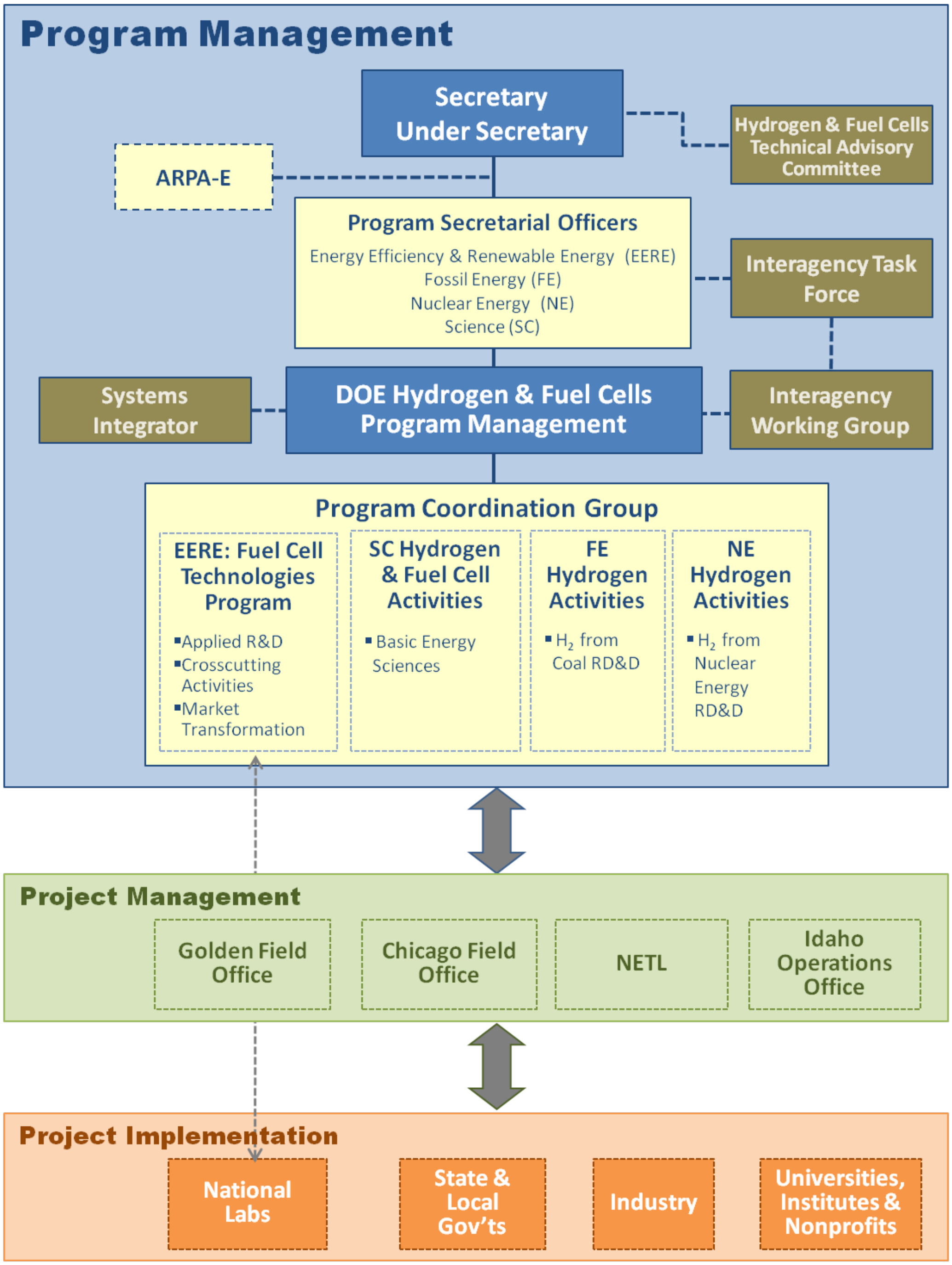


Figure 6.1.1 DOE Hydrogen and Fuel Cells Program Organization Chart.

Advisory Groups

The Program seeks the best available information from experts in a variety of fields, such as chemistry, chemical engineering, materials science, environmental sciences, biology, physics, mechanical engineering, and systems engineering. Since the creation of the Program, a variety of groups have been identified or created to oversee, review, or advise Program activities. Two examples of advisory groups include the following:

National Academies

At DOE's request, the executive arm of the National Academy of Engineering appointed a committee in September 2002 to conduct a study of Alternatives and Strategies for Future Hydrogen Production and Use. The study evaluated the status and cost of technologies for production, delivery, storage, and end-use of hydrogen, as well as reviewed DOE's hydrogen research, development, and demonstration strategy. The final report is available at http://books.nap.edu/books/0309091632/html/index.html. The initial evaluation was followed up with a second analysis in 2004 to evaluate technology costs and barriers and research and development (R&D) needs in the Program. The final report for this evaluation is available at http://books.nap.edu/catalog/10922.html. The Energy Policy Act of 2005 (EPACT) requests that the National Academy of Sciences (NAS) conduct a review of the Program every fourth year from the date of enactment. The NAS also conducts biennial reviews of DOE's RD&D progress under the U.S. DRIVE partnership (U.S. DRIVE). U.S. DRIVE includes the DOE; the United States Council for Automotive Research LLC (USCAR – the collaborative research company representing Chrysler Group LLC, Ford Motor Company, and General Motors); Tesla Motors; five energy companies – BP America, Chevron Corporation, ExxonMobil Corporation, Phillips 66 Company, and Shell Oil Products U.S.; two utilities – Southern California Edison and Michigan-based DTE Energy; and the Electric Power Research Institute (EPRI). The most recent reviews were published in August 2005, available at http://www.nap.edu/openbook.php?isbn=0309097304, March 2008, available at http://www.nap.edu/catalog.php?record_id=12113, and November 2010, available at http://www.nap.edu/catalog.php?record_id=12939.

Hydrogen and Fuel Cell Technical Advisory Committee (HTAC)

HTAC was established under Section 807 of EPACT to provide technical and programmatic advice to the Energy Secretary on hydrogen research, development, and demonstration efforts. Announced in June 2006, HTAC is composed of up to 25 members representing domestic industry, academia, professional societies, government agencies, financial organizations, and environmental groups, as well as experts in the area of hydrogen safety. HTAC is tasked with reviewing and making recommendations to the Secretary in an annual report on:

- The implementation of programs and activities under Title VIII of EPACT;
- The safety, economic, environmental, and other consequences of technologies for the production, distribution, delivery, storage, and use of hydrogen energy and fuel cells;
- The plan under section 804 of EPACT (i.e., Hydrogen and Fuel Cells Program Plan http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/program_plan2011.pdf.

The Secretary will consider, but is not required to adopt, HTAC recommendations and will either describe the implementation of each recommendation or provide an explanation to Congress for the reasons that a recommendation will not be implemented. The Secretary also provides the resources necessary for HTAC to carry out its responsibilities.

Partnerships

Through cooperative partnerships, the Program leverages the capabilities and experience of stakeholders in industry, state and local governments, and international organizations. The roles of these groups vary, as does the nature of their collaboration with DOE. In broad terms, the roles that these stakeholder groups play are as follows:

- **Industry**. Partnerships in developing, validating, and demonstrating advanced fuel cell and hydrogen energy technologies.
- **State and Local Governments**. Partnerships in codes and standards, field validation, and education.
- **International**. Partnerships in R&D, validation, codes and standards, and safety.

Industry

U.S. DRIVE facilitates frequent and detailed precompetitive technical information exchange on a broad portfolio of technologies, including hydrogen and fuel cells. By providing a framework for discussing R&D needs, developing technology roadmaps, and evaluating R&D progress, U.S. DRIVE helps to accelerate R&D progress, to avoid duplication of efforts, and to ensure that industry commercialization needs inform DOE R&D targets. The Partnership's Executive Steering Group (ESG) oversees U.S. DRIVE, with responsibility for high level technical and management priorities (see Figure 6.1.2). The ESG includes the DOE Assistant Secretary for Energy Efficiency and Renewable Energy and Vice President-level executives from each of the U.S. DRIVE member companies.

U.S. DRIVE's operations groups support the ESG, manage U.S. DRIVE activities, and enable regular and strong coordination across U.S. DRIVE. Operations group members include the DOE Program Managers for the FCT Program and the Vehicle Technologies Program, as well as DOE's U.S. DRIVE Director. The Vehicles Operations Group includes the senior technical managers from the automotive companies, the Fuel Operations Group includes senior level technical directors from energy companies, and the Electric Utility Operations Group includes senior level technical managers from the utilities and EPRI.

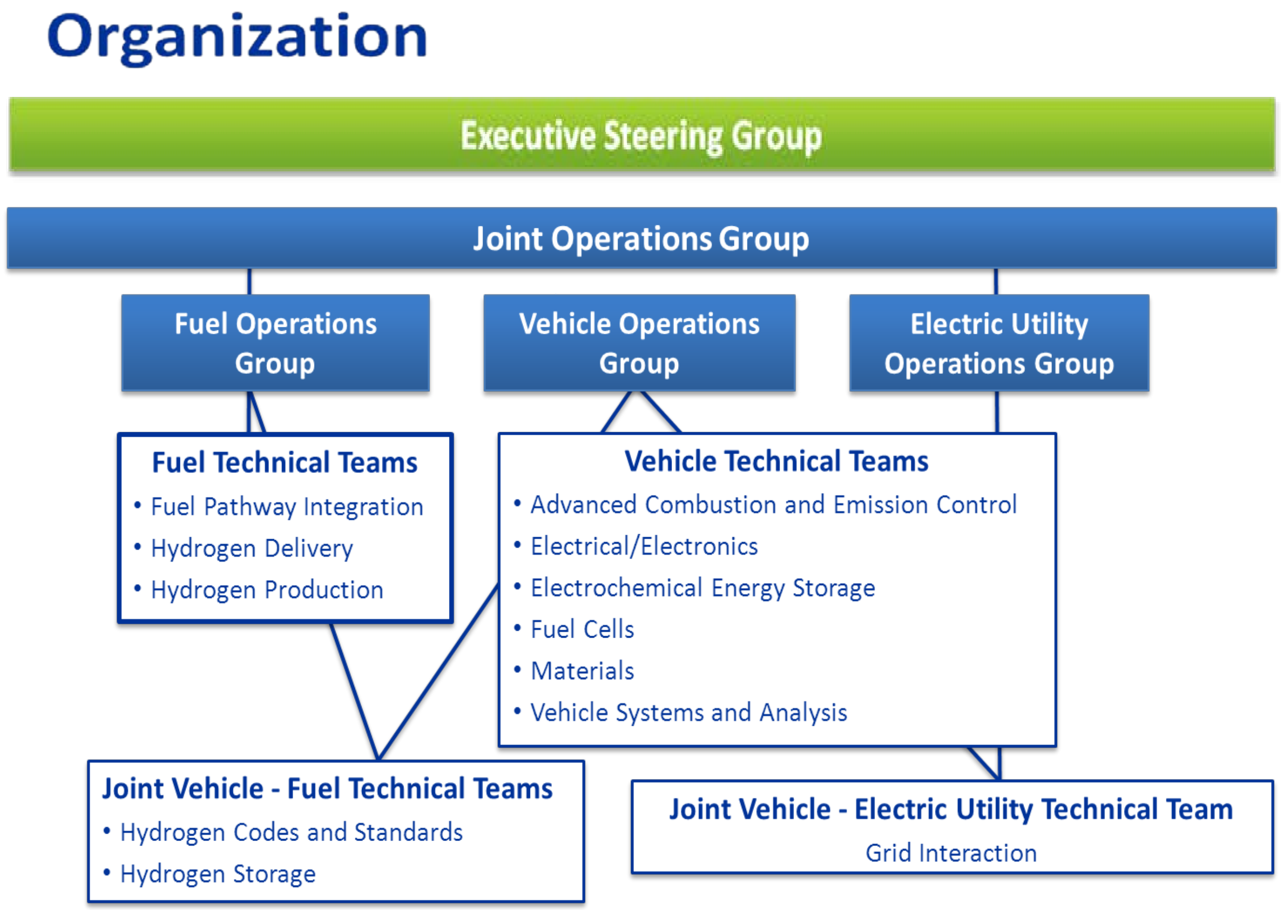


Figure 6.1.2 U.S. DRIVE Organization Chart

The Partnership's technical teams consist of scientists and engineers with technology-specific expertise from DOE, national laboratories, and the automotive, energy, and electric utility partner companies. Teams meet monthly to discuss R&D challenges, develop/update technology roadmaps, and evaluate R&D progress toward goals and technical targets.

State, Local, and Regional Entities

The FCT Program collaborates with state and local government organizations and various regional entities to promote development and demonstration of hydrogen technologies. For example, the California Fuel Cell Partnership is a unique collaboration of auto manufacturers, energy companies, fuel cell technology companies and government agencies that is placing fuel cell vehicles on the roads in California. This partnership is showcasing new vehicle technology that could move the world toward more practical and affordable environmental solutions. In addition to DOE, the other government partners include the California Air Resources Board, the California Energy Commission, the South Coast Air Quality Management District, the Upper Midwest Hydrogen Initiative, the U.S. Department of Transportation (DOT), and the U.S. Environmental Protection Agency (EPA).

A comprehensive database has been developed that catalogues initiatives, policies and partnerships involving stationary fuel cell installations, hydrogen fueling stations and vehicle demonstrations in the United State. Details may be found at www.fuelcells.org/info/charts/h2fuelingstations-US.pdf and www.fuelcells.org/info/statedatabase.html.

State and local partnerships are the primary vehicle through which DOE meets the needs of individual citizens, cities, counties and states across the nation. The FCT Program does the following:

- Works with states and communities to promote the Program
- Identifies and engages community and state partners
- Coordinates with public and private sector activities.

International

On April 23, 2003, DOE called for an international partnership to accelerate progress in hydrogen and fuel cell technologies. As a result of the Secretary's vision, efforts were initiated with 16 countries and the European Commission in the areas of codes and standards, fuel cells, hydrogen production, hydrogen storage, economic modeling, and education. These efforts led to formation of the International Partnership for Hydrogen and Fuel Cells in the Economy (www.iphe.net).

The Department's call for the international partnership built on the efforts of the previous several years, during which DOE coordinated international activities to advance hydrogen and fuel cell technologies. DOE continues to take a leadership role in the International Energy Agency Hydrogen Implementing Agreement (www.iea.org) and Advanced Fuel Cell Implementing Agreement (see Table 6.1).

In addition, the FCT Program is working with international groups, such as the International Organization of Standards, to develop a comprehensive set of codes and standards, which will facilitate the global demonstration and commercialization of hydrogen and fuel cell technologies.

Table 6.1 International Energy Agency Hydrogen and Advanced Fuel Cells Implementing Agreements Tasks

Hydrogen	Fuel Cells
Hydrogen From Renewables:	Polymer Electrolyte Fuel Cells
Biohydrogen	Molten Carbonate Fuel Cells
Advanced Materials for Waterphotolysis	Solid Oxide Fuel Cells
Near-term Market Routes to Hydrogen by Co-utilization of biomass as a renewable energy source with fossil fuels	Fuel Cells for Stationary Applications
High Temperature Production of Hydrogen	Fuel Cell Systems for Transportation
Fundamental and Applied Hydrogen Storage Materials Development	Fuel Cells for Portable Applications
Hydrogen Systems	
Small-scale Hydrogen Reformers for On-site Hydrogen Supply	
Wind Energy and Hydrogen Integration	
Distributed and Community Hydrogen Systems	
Hydrogen Safety	
Analysis	
Global Hydrogen Systems Analysis	
Large Scale Hydrogen Delivery Infrastructure	

Coordination

Interagency Task Force and Interagency Working Group

The Hydrogen and Fuel Cell Interagency Working Group, which has been meeting regularly since early 2003, provides a key mechanism for collaboration among federal agencies involved in hydrogen and fuel cell RD&D. Co-Chaired by DOE and the White House Office of Science and Technology Policy (OSTP), the working group has now focused its activities more specifically on fulfilling the responsibilities assigned to it in EPACT (Section 806). Principal activities involve education and information-sharing across federal agencies to promote the development of safe, economical, and environmentally friendly hydrogen energy systems. The working group is also responsible for assisting DOE with decisions related to federal agency procurements of fuel cells and hydrogen energy systems and with support for the development of hydrogen and fuel cell safety codes and standards. The working group web site, www.hydrogen.gov, provides additional information and a portal to details about federal activities to advance the development of hydrogen and fuel cell technologies.

In August 2007, a high level Interagency Task Force was established to assist DOE with decisions related to improving efficiency in the federal government by promoting federal agency deployment of fuel cells and hydrogen energy systems.

6.2 Program Management Approach

The overall management of the Program consists of a performance-based planning, budgeting, analysis, and evaluation system:

Program Planning

The Energy Policy Act provides the foundation for the Program. The Program integrates the hydrogen planning in EERE, SC, FE, and NE, which is reflected in the Program Plan. Each office has its own research plan, which supports the Program Plan and provides more technical detail. These plans are coordinated to ensure consistency throughout DOE and to avoid duplicative research efforts.

Program Budgeting

The budget for the Program falls under the jurisdiction the Energy and Water subcommittees. The key activities by DOE office are shown in Table 6.2.

Table 6.2 DOE Hydrogen and Fuel Cells Program Key Activities	

EERE
• Hydrogen Fuel R&D
  ○ Hydrogen Storage
  ○ Hydrogen Production and Delivery
• Fuel Cell Systems R&D
• Technology Validation
• Safety, Codes and Standards
• Systems Analysis
• Education
• Manufacturing R&D
• Market Transformation
	Office of Fossil Energy
	• Fuels, Hydrogen from Coal
	• Carbon Sequestration [a]
	• Pipeline Infrastructure [a]
	Office of Nuclear Energy
	• Generation IV Nuclear Systems Initiative [a]
	Office of Science
	• Chemical Science, Geoscience, and Energy Science
	• Materials Science and Engineering

[a] These appropriations support the DOE Hydrogen and Fuel Cells Program, but are not directly a part of it, and would be funded even without it.	

Analysis and Evaluation

Program budget performance is regularly evaluated by the Office of Management and Budget (OMB), in consultation with the OSTP. Each year, each Office reports its current status against pre-established Program goals. In addition, projects are evaluated through both the Program's Annual Merit Review and Peer Evaluation and also U.S. DRIVE technical team review.

6.3 FCT Sub-Programs

Using hydrogen as an energy carrier will require successfully addressing RD&D challenges including lowering the cost of hydrogen production, delivery, storage, and fuel cells; establishing effective codes and standards to address safety issues; and education to raise awareness, accelerate technology transfer, and increase public understanding of hydrogen energy systems. To ensure the success of the hydrogen infrastructure, the Program established sub-programs that are shown in Figure 6.3.1.

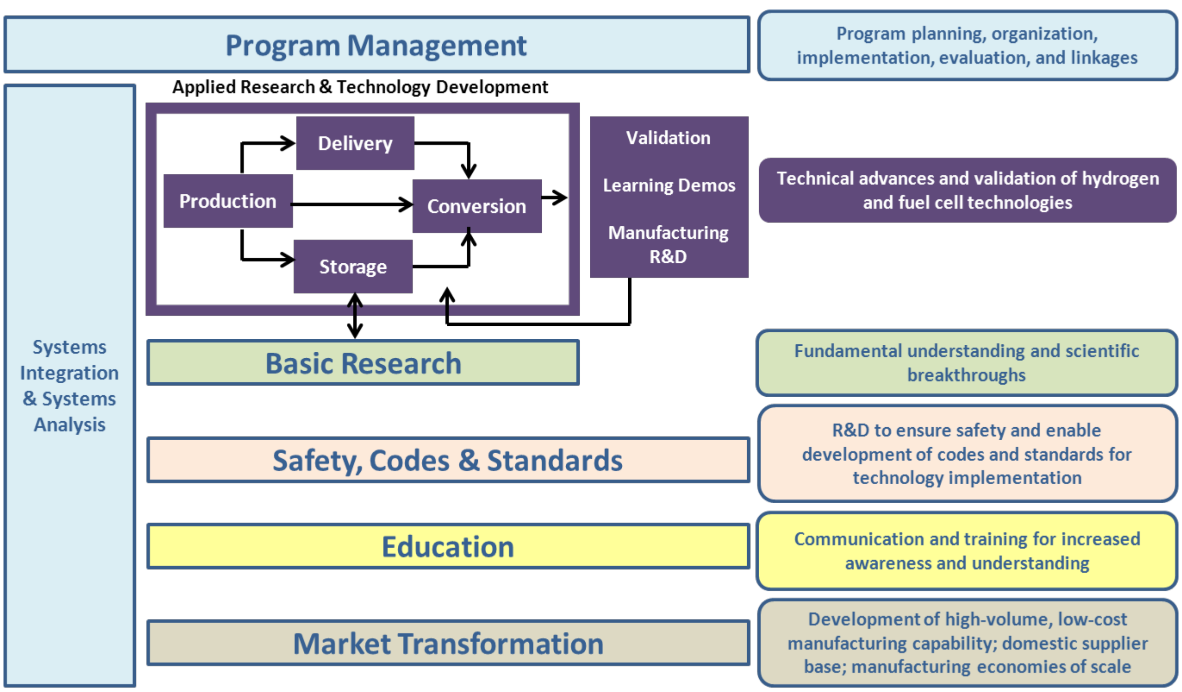


Figure 6.3.1 Sub-programs of DOE's Fuel Cell Technologies Program

6.4 Program Implementation

The implementation strategy is based on three guiding principles:

Linking the RD&D and Education Efforts to Policies, Requirements, and the Process for Selecting Options

The Program's mission is to research, develop, and validate technologies for producing, storing, delivering and using hydrogen in an efficient, clean, safe, reliable, and affordable manner. [1] An implementation strategy has been developed to ensure that all Program activities and procedures are consistent with the overall mission and the requirements contained in the Hydrogen Program Plan.

Organizing the Work

To ensure an appropriate master schedule and defensible budget request for the FCT Program through 2020, a detailed Work Breakdown Structure (WBS) was developed. The WBS serves two main purposes: (1) to ensure that the right work is being done and (2) to ensure that the right work is done correctly. Program goals were imposed "top-down," consistent with the policies and requirements contained in the Program's Plan, whereas detailed tasks, schedules, and budgets were established "bottoms-up." The WBS divides the Program into manageable segments of work to facilitate program management, cost estimating and budgeting, schedule management, cost and schedule control, and reporting of cost and schedule performance. It ensures all required work is incorporated in the Program and that no unnecessary work is included.

Managing and Monitoring the Program

The Program is managed in accordance with its approved integrated baseline: the technical baseline (i.e., a compilation of the Program's technical requirements) and the programmatic baseline (i.e., the work scope, schedule, and cost deemed necessary to satisfy the technical requirements). The programmatic portion of the integrated baseline ensures that the amount of work to be accomplished, the time allotted to accomplish the Program activities, and the resources required to complete the work scope are evenly balanced.

Program Control

To ensure that the Program remains on schedule and within cost, a Program control system has been instituted with the following objectives:

- Provide assurance that all work has been planned and considered in developing the cost and schedule baselines
- Identify the necessary procedures and organizational measures required for effective and timely management of the effort

[1] The Department of Energy Hydrogen Program Plan: An Integrated Strategic Plan for the Research, Development, and Demonstration of Hydrogen and Fuel Cell Technologies, September 2011, available at http://www.hydrogen.energy.gov/pdfs/program_plan2011.pdf

- Ensure that these measures are implemented and that the resulting information accurately reflects the status of the Program
- Establish a review and decision-making process that addresses Program dynamics.

Under the Program control system, integrated cost, schedule, and technology baselines are developed. The performance of the Program offices and supporting organizations in completing tasks is measured against these baselines and reported back to their organizations, to track program performance and take corrective actions, if necessary. The Program uses a change control process, a procedure by which changes to an accepted work product are carefully proposed, assessed, conditionally accepted, and applied. The change control process provides a measure of stability to the Program and ensures consistency across sub-programs.

Responsibilities for Program Control

The Chief Engineer is responsible for the Program's integrated baseline oversight. The Systems Integrator – in support of the Chief Engineer – gathers, integrates, and analyzes information on the scope, schedule, and budget of the sub-programs. The sub-program plans and schedules are integrated into a Program plan, work breakdown structure, and master schedule. Together these plans comprise the programmatic baseline that is associated with a specific version of the technical baseline. The Systems Integrator analyzes this information to ensure that all technical requirements are addressed and are consistent, and to identify critical paths, milestones, and decision points. The Systems Integrator provides tools and information to support DOE in monitoring performance against schedule and budget and in identifying risk.

Implementation of Program Control

Figure 6.4.1 provides an overview of the Program's control process. The primary inputs to Program control include the integrated baseline (refer to the Systems Integration section of the Multi-Year Research, Development and Demonstration Plan), budget guidance, and results of prior Program reviews.

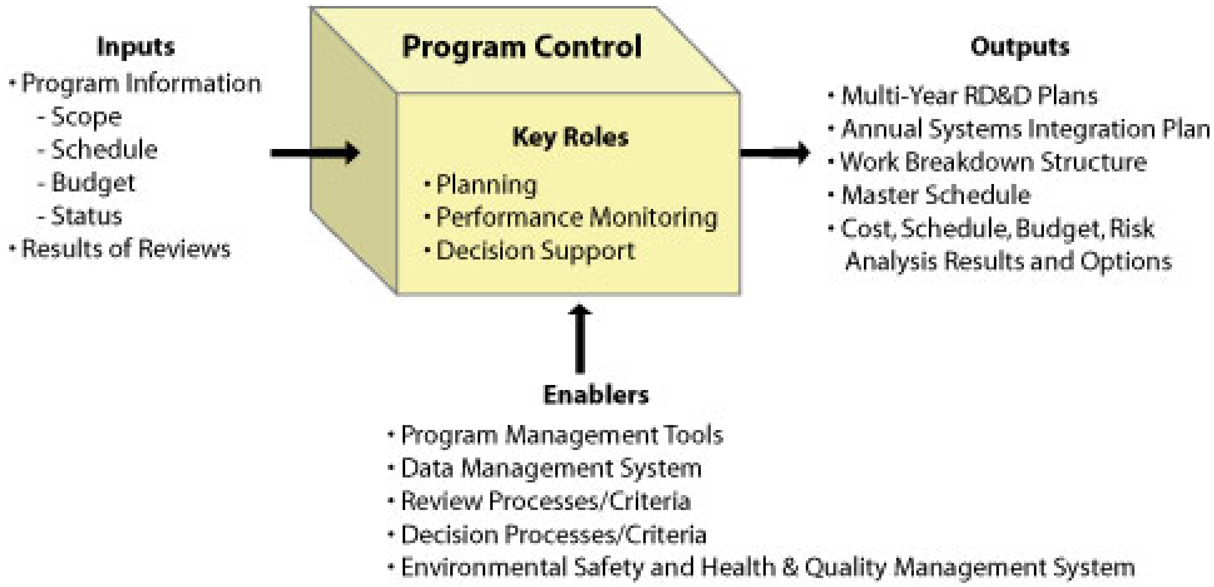


Figure 6.4.1 Program-Control Process

Decision-Making Process

A stage-gate type process is being used to manage R&D investments. The stage-gate process is a disciplined approach for evaluating projects at key points. The stage-gate process being used includes go/no-go decisions and down-select points that must be passed before work on the next stage can begin. Reviews held at these key stages ensure that a project has met its milestones and satisfies the criteria for proceeding to the next stage of the program. Reviewers may include individuals from government agencies, national laboratories, and the private sector.

Technical criteria are used at each stage and decisions are made to either:

- Advance the project to the next stage
- Continue the current effort because not all goals have been met
- Place the project on hold because the need appears to have gone away, but could re-emerge
- Conclude the project because it is unlikely to meet its goals or there is no longer a need for the effort.

Each of the gate reviews considers the impact on the direction of the overall Program of both new knowledge and insights that have been gained during the progression of the Program.

Appendix A –Budgetary Information

The schedule for completing the milestones and achieving the targets and RD&D priorities outlined in this plan is based on expected funding levels, the current stage of development of different technologies, and the perceived difficulty in attaining the targets. Deviation from the expected funding levels may alter the schedule for completion of the tasks and milestones. For example, if funding falls short of expected levels, the target dates for completion of certain milestone may be extended to later dates. If additional funding is made available over the expected amount, the rate of technology development could be accelerated in key research areas.

Funding Profile:

The following table shows the funding profile (in millions) for the Fuel Cell Technologies Program (the EERE part of the DOE Hydrogen and Fuel Cells Program) from FY 2007 through FY 2011, with a breakdown by key activity. To reach its targets, the Fuel Cell Technologies Program expects funding to be provided at the level projected within internal DOE planning documents. If funding deviates from these projections, priorities have been established to reallocate funds.

Major Activity	FY 2007 Funding	FY 2008 Funding	FY 2009 Funding	FY 2010 Funding	FY 2011 Funding
Hydrogen Production & Delivery	33.7	38.6	10.0	14.6	17.5
Hydrogen Storage	33.7	42.4	57.8	31.1	14.6
Safety, Codes & Standards	13.5	15.4	12.2	8.7	6.9
Education	2.0	3.9	4.2	2.0	0.0
Systems Analysis	9.6	11.1	7.5	5.4	3.0
Market Transformation	0.0	0.0	4.8	15.0	0.0
Manufacturing	1.9	4.8	4.5	4.9	2.9
Fuel Cells	55.7	60.4	80.1	75.6	41.9
Technology Validation	39.4	29.6	14.8	13.0	9.0
TOTAL Hydrogen and Fuel Cells	**189.5**	**206.2**	**195.9**	**170.3**	**95.8**

Source: Congressional Budgets, Energy and Water Development Appropriations

APPENDIX B: Input/Output Matrix

revised June 2013

Appendix B shows the linkages of all the inputs and outputs from various technical sections of the MYPP to one another. These inputs and outputs are also reported in the R&D Milestone Charts at the end of each technical section. The task numbers reported in Appendix B are those from the associated R&D Milestone Chart

Outputs						Inputs											
Output From	Output #	Title	Quarter	FY	Task	Product-ion Task	Delivery Task	Storage Task	Fuel Cells Task	Safety, Codes, & Stds. Task	Tech Valid'n Task	Edu. Task	Market Trans. Task	Systems Analysis Task	Systems Integ'tion Task	Manu-facturing Task	Program
Systems Analysis	A1	Report on the status of the technologies and infrastructure to meet the demands for the hydrogen fuel and vehicles.	1	2011	1										1		
Systems Analysis	A2	Cost of competing vehicle powertrain.	4	2012	1				10								
Systems Analysis	A3	Preliminary well-to-wheel power plant efficiency analysis for advanced material systems.	4	2013	1		4	3									
Systems Analysis	A4	Analysis for costs for optimal hydrogen pressure contributions at each point in the system from production to dispensing at point of use.	4	2013	1		1										
Systems Analysis	A5	Update on hydrogen delivery and refueling data for well to power plant efficiency analysis for advanced material systems.	2	2015	1												
Systems Analysis	A6	Report on the status of composite tank costs.	3	2015	1			3									
Systems Analysis	A7	Update on onboard automotive fuel cell system power, input pressure, and vehicle refill time.	4	2015	1												
Systems Analysis	A8	Report on the results of the infrastructure analysis for the long term technologies and requirements for technology readiness.	4	2015	1										1		
Systems Analysis	A9	Update on onboard automotive fuel cell system power, input pressure, degree of hybridization and vehicle refill time.	4	2015	1			3									
Systems Analysis	A10	Report on the environmental analysis of the Hydrogen and Fuel Cells Program.	4	2015	1										4		
Systems Analysis	A11	Report on the projected performance of materials-based systems for onboard hydrogen storage.	1	2018	1			3									

Outputs						Inputs											
Output From	Output #	Title	Quarter	FY	Task	Product-ion Task	Delivery Task	Storage Task	Fuel Cells Task	Safety, Codes, & Stds. Task	Tech Valid'n Task	Edu. Task	Market Trans. Task	Systems Analysis Task	Systems Integ'tion Task	Manu-facturing Task	Program
Systems Analysis	A12	Report on the status of advanced materials system costs.	2	2019	1			3									
Systems Analysis	A13	Annual market reports on status of fuel cell and hydrogen industry.	4	2011 - 2020	1							2, 3, 4					
Systems Analysis	A14	Annual report on the status of commercial products and patents resulting from government funded R&D.	4	2011 - 2020	1												
Systems Analysis	A15	Report on the status of government policies on non-automotive fuel cell industry.	4	2011, 2013, 2015, 2017, 2019	1							3, 4					
Systems Analysis	A16	Report on the projected performance of hydrogen storage systems for non-automotive applications.	3	2020	1			3									
Systems Analysis	A17	Revised hydrogen threshold cost based on fuel and automotive technology advances, if required.	4	2014, 2017, 2020	1												
Safety, Codes & Standards	C1	NFPA2: Hydrogen code document.	2	2012	4		6				1 - 3						
Safety, Codes & Standards	C2	Hydrogen fuel quality standard (SAE J2719).	3	2012	4	1-6	1	1, 2	5		1 - 3				1		
Safety, Codes & Standards	C3	International hydrogen fuel specification standard.	3	2012	4												
Safety, Codes & Standards	C4	Updated best practices handbook on hydrogen safety.	4	2012	5							1					
Safety, Codes & Standards	C5	GTR Phase 1.	1	2013	4												
Safety, Codes & Standards	C6	Updated materials compatibility technical reference manual.	4	2013	2, 5	1-6	6	1, 2			1 - 3	1			1		
Safety, Codes & Standards	C7	Materials reference guide and properties database.	4	2014	2, 5	1-6	6	1			1-3		2			1-8	

Outputs						Inputs											
Output From	Output #	Title	Quarter	FY	Task	Product-ion Task	Delivery Task	Storage Task	Fuel Cells Task	Safety, Codes, & Stds. Task	Tech Valid'n Task	Edu. Task	Market Trans. Task	Systems Analysis Task	Systems Integ'tion Task	Manu-facturing Task	Program
Safety, Codes & Standards	C8	National indoor fueling standard.	2	2016	2, 4		1, 6				1-3		1				
Safety, Codes & Standards	C9	Revised NFPA 2.	1	2017	4												
Safety, Codes & Standards	C10	GTR Phase 2.	4	2017	4												
Safety, Codes & Standards	C11	Updated international fuel specification standard.	4	2018	4												
Delivery	D1	Delivery pathways that can meet an as-dispensed hydrogen cost of <\$4/gge (\$1/100ft^{3}) for emerging fuel cell powered early markets.	1	2013	1						3		1	1, 2			
Delivery	D2	Provide candidate station compression technologies for potential technology validation.	1	2014	2						3						
Delivery	D3	Provide candidate liquefaction technologies for potential validation.	4	2014	5						3						
Delivery	D4	Recommended pipeline technology for validation.	4	2014	3						3						
Delivery	D5	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.	4	2015	1						3		1		1		
Delivery	D6	Technology and material characteristics of advanced delivery systems.	2	2018	6					2, 3							
Delivery	D7	Provide options that meet <\$2/gge for hydrogen delivery from the point of production to the point of use in consumer vehicles.	4	2020	1						3		1		4		
Fuel Cells	F1	Cost of the baseline automotive fuel cell system.	1	2012	10										1		
Fuel Cells	F2	Report on the effect of impurities from storage materials on fuel cells.	3	2014	5			1, 2									

Outputs						Inputs											
Output From	Output #	Title	Quarter	FY	Task	Product-ion Task	Delivery Task	Storage Task	Fuel Cells Task	Safety, Codes, & Stds. Task	Tech Valid'n Task	Edu. Task	Market Trans. Task	Systems Analysis Task	Systems Integ'tion Task	Manu-facturing Task	Program
Fuel Cells	F3	Provide micro-combined heat and power system test data from documented sources indicating performance status.	4	2015	9						1				4		
Fuel Cells	F4	Provide auxiliary power unit system test data from documented sources indicating performance status.	4	2015	9						2				4		
Fuel Cells	F5	Provide automotive stack test data from documented sources indicating performance status.	4	2017	5						2				4		
Manufacturing	M1	Report on high-speed, low-cost fabrication of gas diffusion electrodes for membrane electrode assemblies.	4	2013	3				5								
Manufacturing	M2	Report on fabrication and assembly processes for high pressure hydrogen storage tanks that cost 10% less than the baseline cost of $18/kWh for Type IV, 700 bar tanks.	4	2015	7			2									
Manufacturing	M3	Report on fabrication and assembly processes for polymer electrolyte membrane fuel cells that meet the transportation fuel cell system cost target of $30/kW.	4	2017	4				3								
Vehicle Technologies Program	O1	U.S. DRIVE baseline vehicle system architecture (e.g., hybridization) and fuel economy.	1	2012					10								
Production	P1	Hydrogen production system based on centralized biomass gasification technology producing hydrogen at a projected cost of $2.10/kg at the plant gate.	4	2015	3						3					8	
Production	P2	System based on distributed production of hydrogen from electrolysis at a projected cost of $3.90/kg without compression, storage and dispensing.	4	2015	2						3					8	

Outputs						Inputs											
Output From	**Output #**	**Title**	**Quarter**	**FY**	**Task**	**Product-ion Task**	**Delivery Task**	**Storage Task**	**Fuel Cells Task**	**Safety, Codes, & Stds. Task**	**Tech Valid'n Task**	**Edu. Task**	**Market Trans. Task**	**Systems Analysis Task**	**Systems Integ'tion Task**	**Manu-facturing Task**	**Program**
Production	P3	Hydrogen production system based on centralized electrolysis technology producing hydrogen at a projected cost of $3.00/kg at the plant gate.	1	2016	2						3					8	
Production	P4	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.	4	2020	4						3						
Production	P5	Solar hydrogen production system based on photolytic biological hydrogen production from water at a solar to hydrogen conversion efficiency of 5%.	4	2020	6						3						
Production	P6	Solar hydrogen production system based on photoelectrochemical hydrogen production from water at a solar to hydrogen conversion meeting 2020 targets.	4	2020	5						3						
Storage	S1	Update status of composite tank costs.	3	2014	3									1		7	
Storage	S2	Technical and economic update from storage on promising storage material system.	1	2015	2, 3		4										
Storage	S3	Material characteristics and performance data on advanced storage materials and systems.	1	2015	1, 2					2,4							
Storage	S4	Update of fuel quality from promising storage materials.	3	2015	1				5	2,4							
Storage	S5	Projected performance of materials-based systems for onboard hydrogen storage.	1	2017	2, 3		4				2			1	4		
Storage	S6	Update status of advanced materials system costs.	2	2018	2, 3									1			

Outputs						Inputs											
Output From	Output #	Title	Quarter	FY	Task	Product-ion Task	Delivery Task	Storage Task	Fuel Cells Task	Safety, Codes, & Stds. Task	Tech Valid'n Task	Edu. Task	Market Trans. Task	Systems Analysis Task	Systems Integ'tion Task	Manu-facturing Task	Program
Storage	S7	Projected performance of hydrogen storage systems for non-automotive applications.	3	2019	2, 3									1			
Market Transformation	T1	Report on the status of early market deployments and industry needs.	1, 4	2013, 2014	1, 2							3, 4					
Technology Validation	V1	Final learning demonstration summary report published.	3	2012	4												
Technology Validation	V2	Validate achievement of a refueling time of 3 minutes or less for 5 kg of hydrogen at 5,000 psi using advanced communication technology.	3	2012	2		6	3		2				1			
Technology Validation	V3	Publish/post composite data products for material handling and backup power, including safety event data.	3	2012	4					1			2, 3	1			
Technology Validation	V4	Validate stationary fuel cell system that co-produces hydrogen and electricity and report on durability and efficiency.	4	2014	3								1, 2, 3	1			
Technology Validation	V5	Report on the validation of residential fuel cell micro combined heat and power systems' efficiency and durability.	4	2015	1				9				1				
Technology Validation	V6	Validate 700-bar fast fill fueling stations against DOE fueling targets.	3	2016	4		6			2							
Technology Validation	V7	Validate novel hydrogen compression technology durability and efficiency.	4	2016	3		2							1			
Technology Validation	V8	Complete validation of commercial fuel cell combined heat and power systems' efficiency and durability.	4	2017	1				9				1				

Outputs						Inputs											
Output From	Output #	Title	Quarter	FY	Task	Product-ion Task	Delivery Task	Storage Task	Fuel Cells Task	Safety, Codes, & Stds. Task	Tech Valid'n Task	Edu. Task	Market Trans. Task	Systems Analysis Task	Systems Integ'tion Task	Manu-facturing Task	Program
Technology Validation	V9	Validate status of truck auxiliary power unit durability.	4	2017	2				9				1				
Technology Validation	V10	Validate distributed production of hydrogen from electrolysis at a projected cost of $3.90/kg with an added delivery cost of <$4/gge.	4	2018	3	1								1, 2			
Technology Validation	V11	Validate station compression technology provided by the delivery team.	4	2019	3		1							1			
Technology Validation	V12	Validate light duty fuel cell vehicle durability.	4	2019	2				6					1			
Technology Validation	V13	Validate onboard storage system weight capacity and energy density.	4	2019	2			2									
Technology Validation	V14	Validate liquefaction technology provided by the delivery team.	4	2019	3		5							1			
Technology Validation	V15	Validate pipeline technology provided by the delivery team.	4	2019	3		3							1			

Appendix C – Hydrogen Quality

The hydrogen fuel quality specification in Table C.1 below is based on the SAE International Surface Vehicle Standard *SAE-2719 - Hydrogen Fuel Quality Guideline for Fuel Cell Vehicles,* June 2011. This specification has been harmonized to the extent possible with the draft international standard, ISO/*DIS 14687-2, Hydrogen Fuel – Product Specification – Part 2: Proton exchange membrane (PEM) fuel cell applications for road vehicles*, recently approved by the International Organization for Standardization (ISO).

The primary purpose of this specification is to ensure that the effects of possible fuel contaminants on fuel cell performance and durability in early commercial vehicles are acceptable. Modeling and analysis have shown that the impact on the cost of producing hydrogen fuel that complies with the specification is not significant. However, the costs of analyzing and verifying compliance with the specification are still under study. ASTM International has developed and is validating standardized methods to sample and analyze the presence of contaminants at the levels prescribed in the specification.

Additional fuel quality RD&D, fuel cell testing, operational data from fuel cell vehicles, improvements in the impurity tolerance of fuel cells, and advanced material storage options that are likely to introduce or impose different impurities may lead to revisions of these limits. Fuel Cell and Hydrogen Program RD&D planning will address hydrogen quality issues as they relate to cost and performance goals for each technology area— production, delivery, storage, fuel cells, and safety, codes and standards. Those issues and RD&D activities specific to each of these areas will be included in those sections of the RD&D Plan.

Table C.1: Hydrogen Fuel Quality Specification				
Constituent	Chemical Formula	Limits [e]	Laboratory Test Methods to Consider and Under Development [f]	Minimum Analytical Detection Limit
Hydrogen fuel index	H_2	>99.97%		
Total allowable non-hydrogen, non-helium, non-particulate constituent		100 µmol/mol		
Acceptable limit of each individual constituent				
Water[a]	H_20	5 µmol/mol	ASTM D7653-10, ASTM D7649-10	0.12 µmol/mol
Total hydrocarbons[b] (C_1 basis)		2 µmol/mol	ASTM D7675-11	0.1 µmol/mol
Oxygen	O_2	5 µmol/mol	ASTM D7649-10	1 µmol/mol
Helium	He	300 µmol/mol	ASTM D1945-03	100 µmol/mol
Nitrogen, Argon	N_2, Ar	100 µmol/mol	ASTM D7649-10	5 µmol/mol
Carbon dioxide	CO_2	2 µmol/mol	ASTM D7649-10, ASTM D7653-10	0.1 µmol/mol
Carbon monoxide	CO	0.2 µmol/mol	ASTM D7653-10	0.01 µmol/mol
Total sulfur[c]		0.004 µmol/mol	ASTM D7652-11	0.00002 µmol/mol
Formaldehyde	HCHO	0.01 µmol/mol	ASTM D7653-10	0.01 µmol/mol
Formic acid	HCOOH	0.2 µmol/mol	ASTM D7550-09 , ASTM D7653-10	0.02 µmol/mol
Ammonia	NH_3	0.1 µmol/mol	ASTM D7653-10	0.02 µmol/mol
Total halogenates[d]		0.05 µmol/mol	ASTM WK23815, WK34574	0.01 µmol/mol
Particulate Concentration		1 mg/kg	ASTM D7650-10, ASTM D7651-10	0.005 mg/kg

[a] Due to water threshold level, the following constituents should not be found, however they should be tested for if there is a question on water content:
Sodium (Na+) @ <0.05 µmole/mole H_2 or <0.05 µg/liter
Potassium (K+) @ <0.05 µmole/mole H_2 or <0.08 µg/liter
or Potassium hydroxide (KOH) @ <0.05 µmole/mole H_2 or <0.12 µg/liter

[b] Includes, for example, ethylene, propylene, acetylene, benzene, phenol (paraffins, olefins, aromatic compounds, alcohols, aldehydes). THC may exceed 2 micromoles per mole due only to the presence of methane, in which case the summation of methane, nitrogen and argon is not to exceed 100 ppm.

[c] Includes, for example, hydrogen sulfide (H_2S), carbonyl sulfide (COS), carbon disulfide (CS_2) and mercaptans.
[d] Includes, for example, hydrogen bromide (HBr), hydrogen chloride (HCl), chlorine (Cl_2) and organic halides (R-X).
[e] Limits are upper limits except for the hydrogen which is a lower limit. All limits are subject to revision after additional testing under operational conditions and improved standardized analytical procedures.
[f] Gaseous sampling uses procedures in ASTM D7606-11

DOE Hydrogen Program
2011 Annual Merit Review
Project Evaluation Form

Project Number: ______________ **Reviewer:** ______________

Title of Project: ______________________________

Presenter Name: ______________________________

Provide **specific, concise** comments to support your evaluation.

1. **Relevance**
To overall DOE objectives – the degree to which the project supports the Hydrogen and Fuel Cells Program and the goals and objectives in the Multi-Year RD&D Plan. (Weight = 20%)

	score	comments
4 - Outstanding. Project is critical to the Hydrogen and Fuel Cells Program and fully supports DOE RD&D objectives. **3 - Good.** Most project aspects align with the Hydrogen and Fuel Cells Program and DOE RD&D objectives. **2 - Fair.** Project partially supports the Hydrogen and Fuel Cells Program and DOE RD&D objectives. **1 - Poor.** Project provides little support to the Hydrogen and Fuel Cells Program and DOE RD&D objectives.		

2. **Approach**
To performing the work – the degree to which barriers are addressed, the project is well designed, feasible, and integrated with other efforts. (Weight = 20%)

	score	comments
4 - Outstanding. Sharply focused on critical barriers; difficult to improve approach significantly. **3 - Good.** Generally effective but could be improved; contributes to overcoming some barriers. **2 - Fair.** Has significant weaknesses; may have some impact on overcoming barriers. **1 - Poor.** Not responsive to project objectives; unlikely to contribute to overcoming the barriers.		

3. **Accomplishments and progress**
Toward overall project and DOE goals – the degree to which progress has been made and measured against performance indicators, and the degree to which the project has demonstrated progress toward DOE goals. (Weight = 40%)

	score	comments
4 - Outstanding. Excellent progress toward objectives; suggests that barrier(s) will be overcome. **3 - Good.** Significant progress toward objectives and overcoming one or more barriers. **2 - Fair.** Modest progress in overcoming barriers; rate of progress has been slow . **1 - Poor.** Little or no demonstrated progress towards objectives or any barriers.		

4. Collaboration and coordination with other institutions
The degree to which the project interacts with other entities and projects. (Weight = 10%)

	score	comments
4 - Outstanding. Close, appropriate collaboration with other institutions; partners are full participants and well coordinated. **3 - Good.** Some collaboration exists; partners are fairly well coordinated. **2 - Fair.** A little collaboration exists; coordination between partners could be significantly improved. **1 - Poor.** Most work is done at the sponsoring organization with little outside collaboration; little or no apparent coordination with partners.		

5. Proposed future work
The degree to which the project has effectively planned its future in a logical manner by incorporating appropriate decision points, considering barriers to its goals and, when sensible, mitigating risk by providing alternate pathways. (Weight = 10%)

	score	comments
4 - Outstanding. Plans clearly build on past progress and are sharply focused on barriers. **3 - Good.** Plans build on past progress and generally address overcoming barriers. **2 - Fair.** Plans may lead to improvements, but need better focus on overcoming barriers. **1 - Poor.** Plans have little relevance toward eliminating barriers or advancing the Program		

Project strengths:

Project weaknesses

Recommendations for additions/deletions to project scope

Project Number: ____________ **Reviewer:** ____________

Appendix E — Acronyms

AEI	Advanced Energy Initiative
AEO	Annual Energy Outlook
AFC	Alkaline Fuel Cell
AHJ	Authorities Having Jurisdiction
AMFC	Alkaline Membrane Fuel Cells
AMR	Annual Merit Review
ANL	(DOE) Argonne National Laboratory
APU	Auxiliary Power Unit
ARRA	American Recovery and Reinvestment Act of 2009
ASES	American Solar Energy Society
ASME	American Society of Mechanical Engineers
AST	Accelerated Stress Test
ASTM	American Society for Testing and Materials
ATP	Adenosine-5'-Triphosphate
Bchl	Bacteriochlorophyll
BES	(DOE Office of) Basic Energy Sciences
BEV	Battery Electric Vehicle
BNL	(DOE) Brookhaven National Laboratory
BOP	Balance of Plant
BPVC	Boiler and Pressure Vessel Code
C/N	Ratio of Carbon to Nitrogen
CaFCP	California Fuel Cell Partnership
CARB	California Air Resource Board
CCB	Change Control Board
CcH2	Cryo-Compressed Hydrogen
CCM	Catalyst Coated Membrane
CDO	Code Development Organization
CDP	Composite Data Products
CEC	California Energy Commission
CERL	(U.S. Army's) Construction Engineering Research Laboratory
CFD	Computational Fluid Dynamics
CH2P	Combined Hydrogen and Power
CHG	Compressed Hydrogen Gas
CHHP	Combined Heat, Hydrogen and Power
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CoE	Center of Excellence
COP	Coefficient of Performance
CRADA	Cooperative Research and Development Agreement
CSA	Canadian Standards Association
CSD	Compression, Storage, and Dispensing
CSTT	Codes and Standards Technical Team

Appendix E — Acronyms

DDP	Detailed Data Products
DFMA	Design for Manufacture and Assembly
DG	Distributed Generation
DLA	Defense Logistics Agency
DMFC	Direct Methanol Fuel Cell
DNGR	Distributed Natural Gas Reforming
DOC	U.S. Department of Commerce
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EERE	(DOE) Office of Energy Efficiency and Renewable Energy
EIA	U.S. Energy Information Administration
EISA	Energy Independence and Security Act of 2007
EPA	U.S. Environmental Protection Agency
EPAct	Energy Policy Act of 2005
EPRI	Electric Power Research Institute
ER	Emergency Response
ESG	Executive Steering Group
EWD	Energy and Water Development
FAA	(DOT) Federal Aviation Administration
FACA	Federal Advisory Committee Act
FCB	Fuel Cell Bus
FCEV	Fuel Cell Electric Vehicle
FCHEA	U.S. Fuel Cells and Hydrogen Energy Association
FCH JU	Fuel Cell and Hydrogen Joint Undertaking
FCT	(DOE) Fuel Cell Technologies (Office)
FCV	Fuel Cell Vehicles
FE	(DOE) Office of Fossil Energy
FOM	Federated Object Model
FPITT	Fuel Pathway Integration Technical Team
FRB	Fiber-Reinforced Polymer
FTE	Full-Time Equivalent
GDE	Gas Diffusion Electrode
GDL	Gas Diffusion Layer
GGE	Gallon of Gasoline Equivalent
GHG	Greenhouse Gases
GIS	Geographical Information System
GPRA	Government Performance and Results Act
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (Model)
GSE	Ground Support Equipment
GTI	Gas Technology Institute
GTR	Global Technical Regulations
H2A	Hydrogen Analysis Tool (computer model)
HAMMER	Hazardous Materials Management and Emergency Response
HCSTT	Hydrogen Codes and Standards Technical Team

HDPE	High-Density Polyethylene
HDSAM	Hydrogen Delivery Scenario Analysis Model
H-E-B	Here Everything's Better (supermarkets)
HEV	Hybrid Electric Vehicle
HFCEV	Hydrogen Fuel Cell Electric Vehicle
HFCIT	(DOE) Hydrogen, Fuel Cells and Infrastructure Technologies (Program)
HFCV	Hydrogen and Fuel Cell Vehicle
HFI	Hydrogen Fuel Initiative
HHV	Higher Heating Value
HIPOC	Hydrogen Industry Panel on Codes
HLA	High Level Architecture
HNEI	Hawaii Natural Energy Institute
HSDC	Hydrogen Secure Data Center
HSECoE	Hydrogen Storage Engineering Center of Excellence
HSP	Hydrogen Safety Panel
HTAC	The Hydrogen and Fuel Cell Technical Advisory Committee
HyARC	Hydrogen Analysis Resource Center
HyPRO	Hydrogen Production Simulation Tool
HyTEC	Hydrogen Technology and Energy Curriculum
HyTrans	Hydrogen Transition Model
IB	Integrated Baseline
ICAO	International Civil Aviation Organization
ICC	International Code Council
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IPEC	Incident Photon-to-Electron Conversion
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IRES	Integrated Renewable Energy Station
ISO	International Organization for Standardization
ITER	International Thermonuclear Experimental Reactor
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Energy
LH2	Liquid Hydrogen
LHC	Light Harvesting Complex
LHV	Lower Heating Value
LLNL	(DOE) Lawrence Livermore National Laboratory
LPG	Liquefied Petroleum Gas (also called Liquid Propane Gas)
M&O	Management and Operations
MACRS	Modified Accelerated Cost-Recovery System
MARKAL	Market Allocation Model
MCFC	Molten Carbonate Fuel Cell
MEA	Membrane Electrode Assembly
MEC	Microbial Electrolysis Cell

MHE	Material Handling Equipment
MiniCAM	Mini-Climate Assessment Model
MMBtu	Million (Thousand Thousand) Btu
MOF	Metal Organic Framework
MPL	Micro-Porous Layer
MSM	Macro-System Model
MTBF	Mean Time Between Failures
MYPP	Multi-Year Program Plan
MYRD&D	Multi-Year Research, Development, and Demonstration (Plan)
NA	Not Available
NAE	National Academy of Engineering
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NDE	Nondestructive Evaluation
NE	(DOE) Office of Nuclear Energy
NEMS	National Energy Modeling System
NETL	(DOE) National Energy Technology Laboratory
NFCBP	National Fuel Cell Bus Program
NFPA	National Fire Protection Association
NHA	National Hydrogen Association
NHTSA	National Highway Transportation Safety Administration
NIST	National Institute for Standards and Technology
NO_X	Nitrogen Oxide
NPS	U.S. National Park Service
NRC	National Research Council
NREL	(DOE) National Renewable Energy Laboratory
O&M	Operations and Maintenance
OBD	On-Board Diagnostics
OEM	Original Equipment Manufacturers
OMB	(White House) Office of Management and Budget
ORNL	(DOE) Oak Ridge National Laboratory
OSTP	(White House) Office of Science and Technology Policy
OTR	Over the Road
PAN	Polyacrylonitrile
P/R	Photosynthesis/Respiration Capacity Ratio
PAE	Planning, Analysis and Evaluation
PAFC	Phosphoric Acid Fuel Cell
PAR	Photosynthetically Active Radiation
PART	(OMB) Program Assessment Rating Tool
PB	Programmatic Baseline
PBA	(EERE Office of) Planning, Budget and Analysis
PBI-type	Polybenzimidazole-type (Fuel Cell)
PDA	Personal Digital Assistant
PEC	Photoelectrochemical
PEM	Polymer Electrolyte Membrane

PEMFC	Polymer Electrolyte Membrane Fuel Cell
PHEV	Plug-In Hybrid Electric Vehicle
PM	Particulate Matter
PM	Program Manager
PMC	Project Management Center
PMOP	Program Management and Operations Plan
PNNL	(DOE) Pacific Northwest National Laboratory
PNS	Purple Non-Sulfur (Bacteria)
POF	Polymeric Organic Framework
PPA	Power Purchase Agreement
PROX	Preferential Oxidation
PSA	Pressure Swing Adsorption
PSAT	Powertrain Systems Analysis Toolkit
PTC	Production Tax Credit
R&D	Research and Development
RCS	Regulations, Codes and Standards
RCSWG	Regulations, Codes and Standards Working Group
RD&D	Research, Development and Demonstration
RDD&D	Research, Development, Demonstration and Deployment
RFP	Request for Proposal
RH	Relative Humidity
RLP	Resource Loaded Plan
RMP	Risk Management Plan
SAE	Society of Automotive Engineers
SAIC	Science Applications International Corporation
SAP	Systems Analysis Plan
SBIR	Small Business Innovation Research (Program)
SC	(DOE) Office of Science
SCRA	South Carolina Research Authority
SCS	Safety, Codes and Standards
SDO	Standards Development Organizations
SECA	Solid State Energy Conversion Alliance
SERA	Scenario Evaluation and Regionalization Analysis
SIP	Systems Integration Plan
SMR	Steam Methane Reforming
SNL	(DOE) Sandia National Laboratories
SOFC	Solid Oxide Fuel Cell
SOW	Statement of Work
SRA	SRA International, Inc.
SRNL	(DOE) Savannah River National Laboratory
STCH	Solar Thermochemical Hydrogen (Production)
STH	Solar to Hydrogen
TAG	U.S. Technical Advisory Groups
TARDEC	(U.S. Army's) Tank Automotive, Research, Development, and Engineering Center
TB	Technical Baseline

TBD	To Be Determined
TDM	Technology Development Manager
TEA	Techo-Economic Analysis
TIR	Technical Information Report
TRL	Technology Readiness Level
U.S. DRIVE	Driving Research and Innovation for Vehicle efficiency and Energy sustainability (Partnership)
UL	Underwriters Laboratories
UN	United Nations
UNECE	United Nations Economic Commission for Europe
USCAR	U.S. Council for Automotive Research
USDA	U.S. Department of Agriculture
VSATT	Vehicle Systems Analysis Technical Team
VT	(EERE) Vehicle Technologies (Office)
VTP	Vehicle Technologies Program
WBS	Work Breakdown Structure
ZBus	Zero-Emission Bus
ZIF	Zeolitic Imidazolate Framework