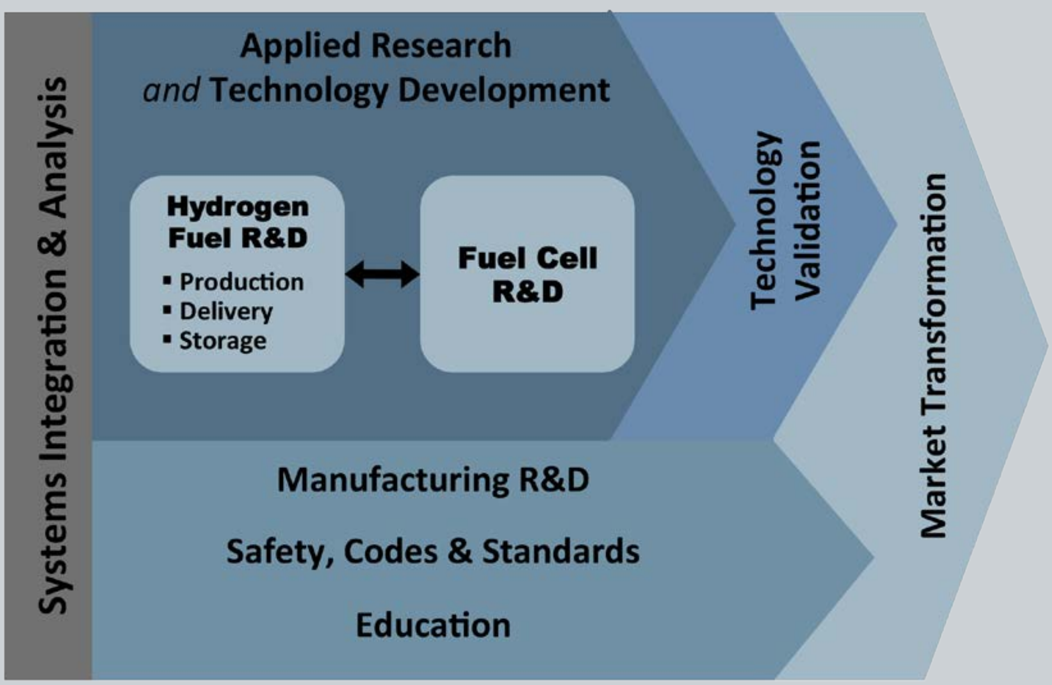
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Fuel Cell Technologies Office

Multi-Year Research, Development, and Demonstration Plan

Planned program activities for 2011-2020



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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

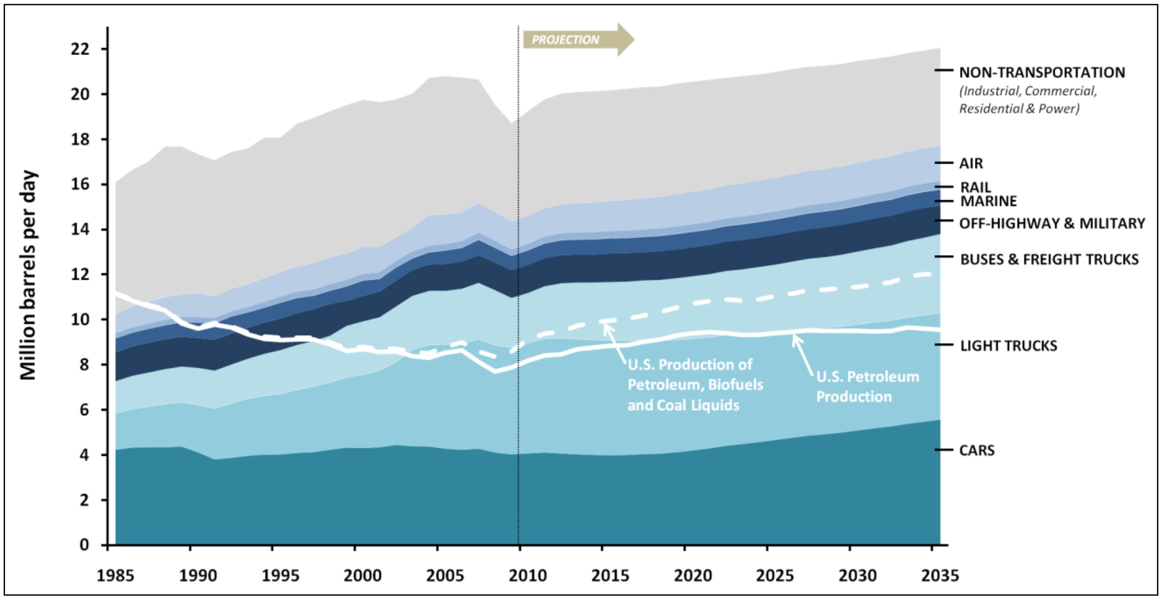

Figure 1.1. America's Widening "Oil Gap." *America's reliance on imported oil is the key challenge to our energy security. While oil is used in all sectors and for a wide variety of uses, the large majority is used for transportation—and a majority of that is used in light-duty passenger vehicles (cars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

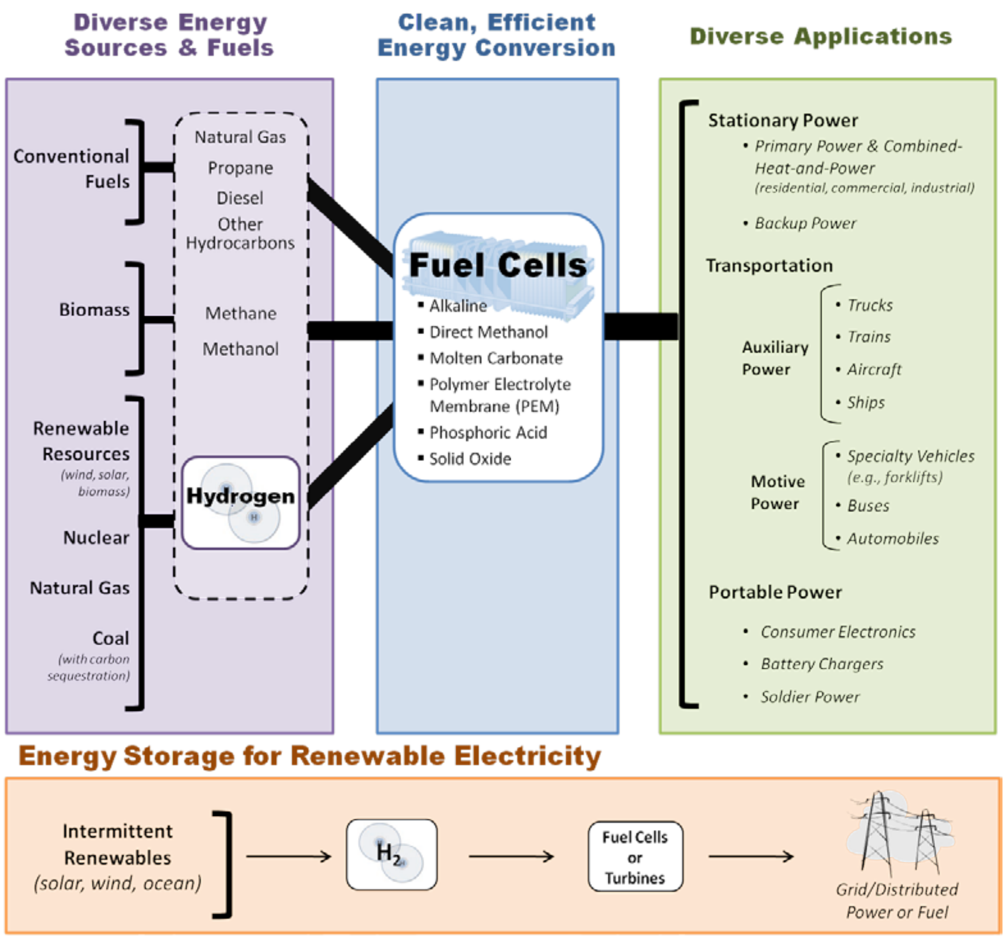

Figure 1.2 Fuel cells and hydrogen can be used for diverse applications.

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.

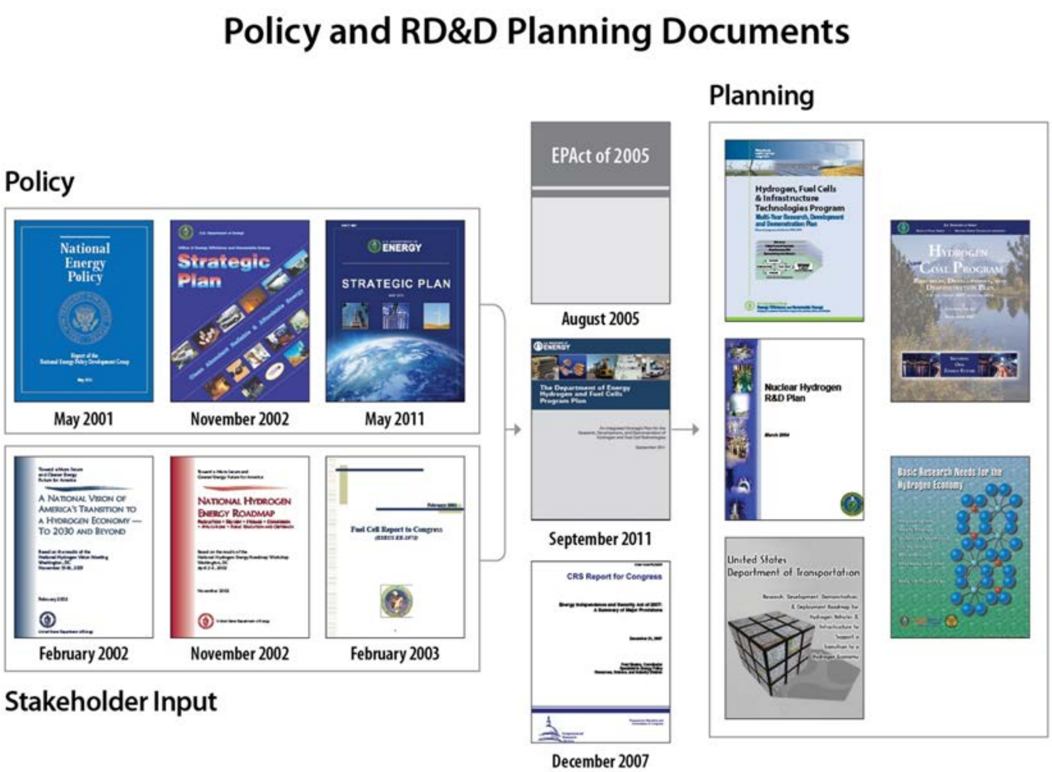

Figure 1.3 Policy and RD&D planning documents

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

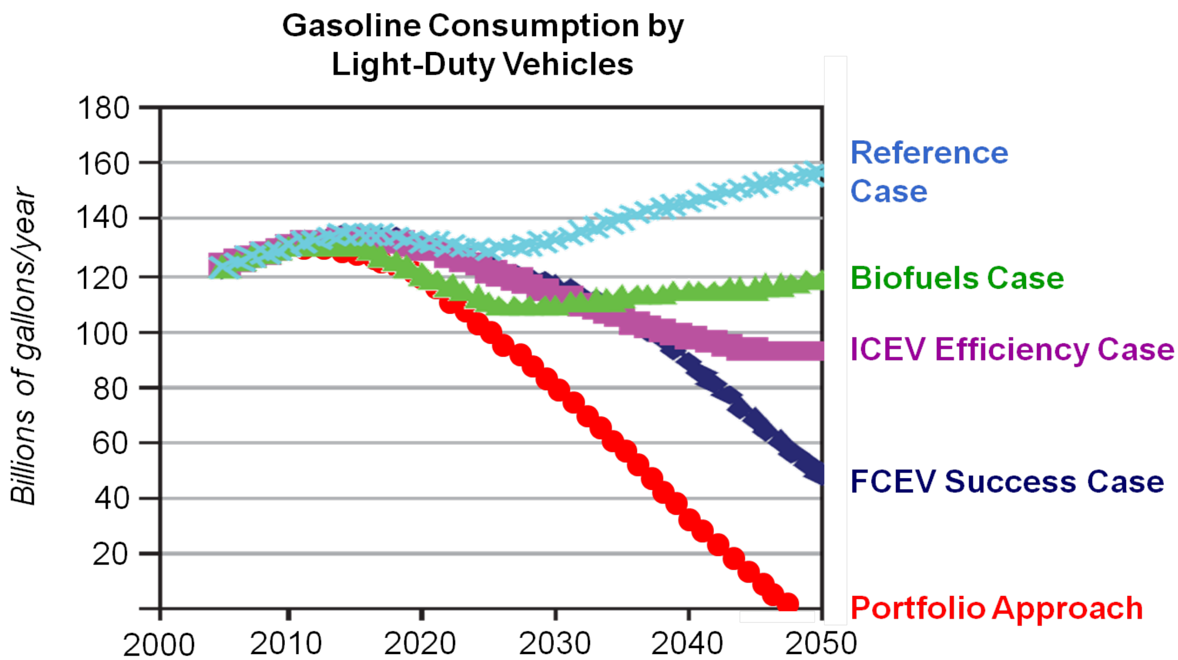

Figure 2.1.1.1. Reduced Oil Consumption. Significant reductions in the nation's consumption of oil could be achieved through the use of fuel cells—making substantial gains toward the long-term goal of independence from imported oil. The portfolio approach shown here assumes a significant introduction 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]

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[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.

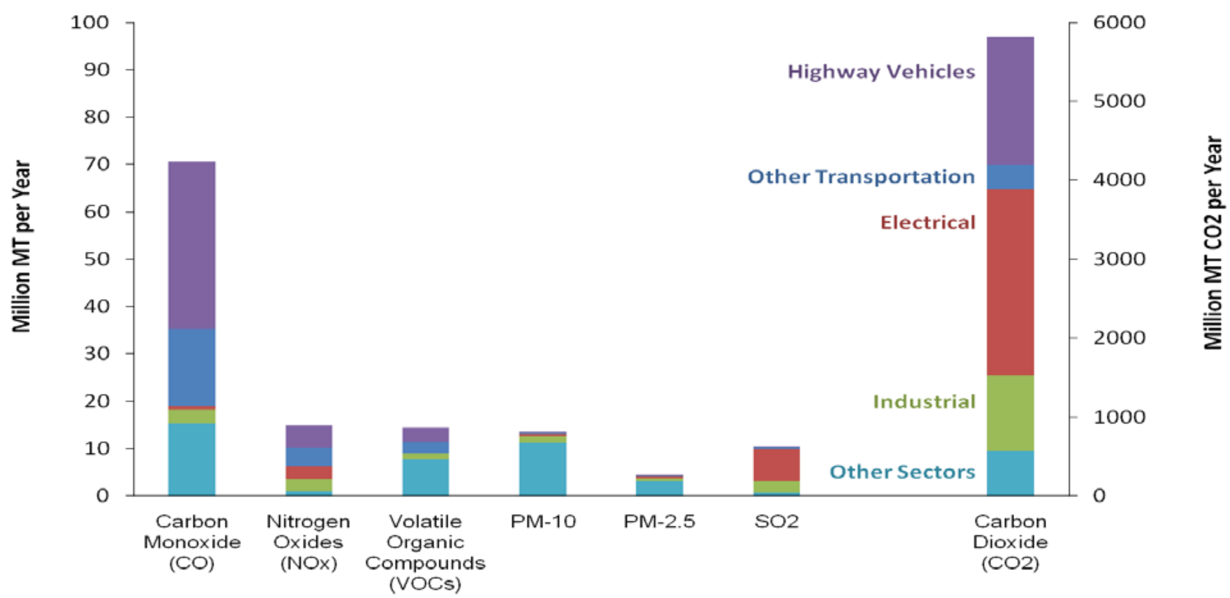

Figure 2.1.2.1 Emissions from Fossil Fuels in the United States. Fossil fuels are major contributors to air pollution and greenhouse gas emissions.[6] Fuel cells can convert conventional fossil fuels and low- to zero-carbon renewable fuels into usable energy with significantly reduced emissions.

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/.

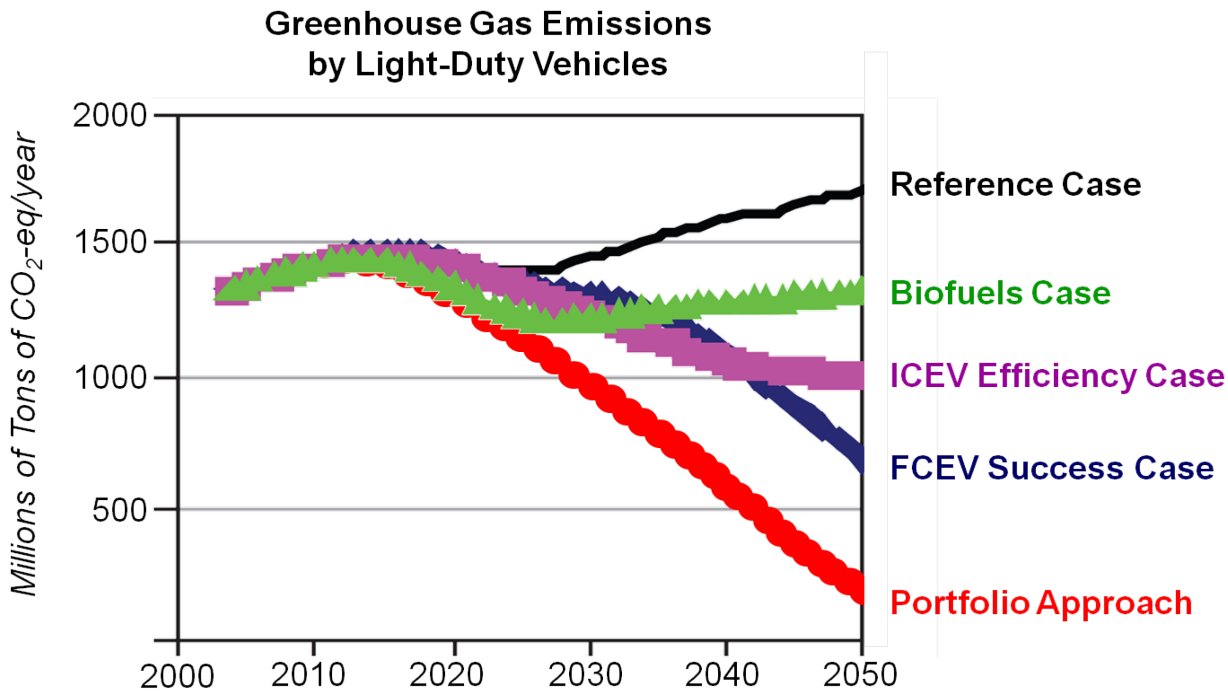

Figure 2.1.2.2. Reduced Greenhouse Gas Emissions. Significant reductions in greenhouse gas emissions could be achieved through the use of fuel cells—making substantial gains toward the goal of 80% reduction in CO_2 emissions[8] by 2050. The portfolio approach shown here assumes a significant introduction 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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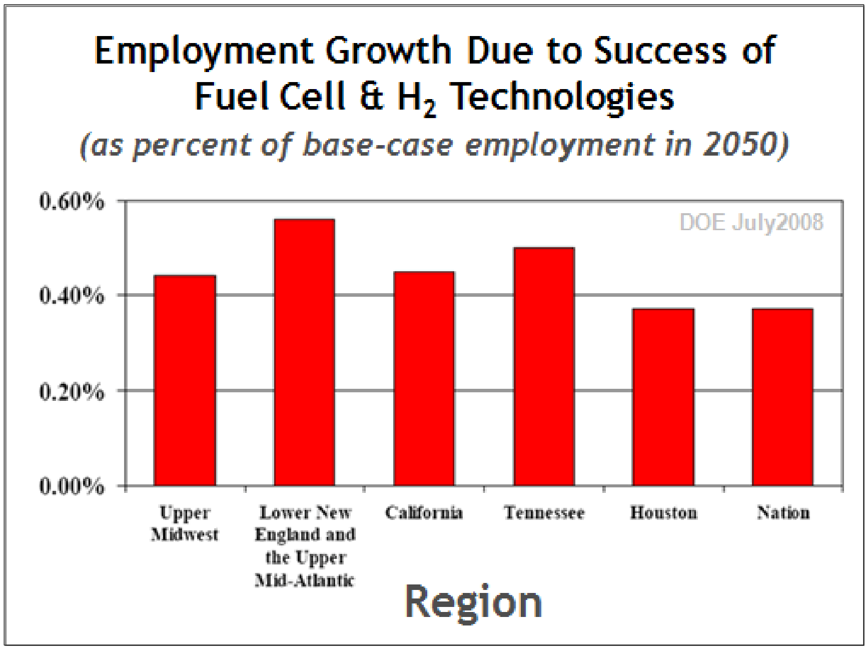
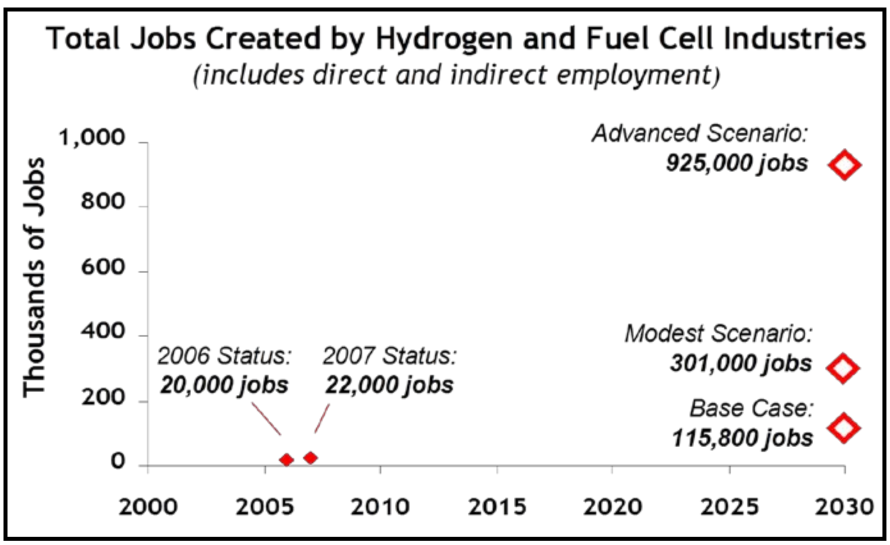
[10] "Effects of a Transition to a Hydrogen Economy on Employment in the United States—Report to Congress." U.S. Department of Energy, July 2008, www.hydrogen.energy.gov/pdfs/epact1820_employment_study.pdf. Key assumptions include: By 2035, fuel cell electric vehicles ramp up to 89% of light-duty vehicle (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.

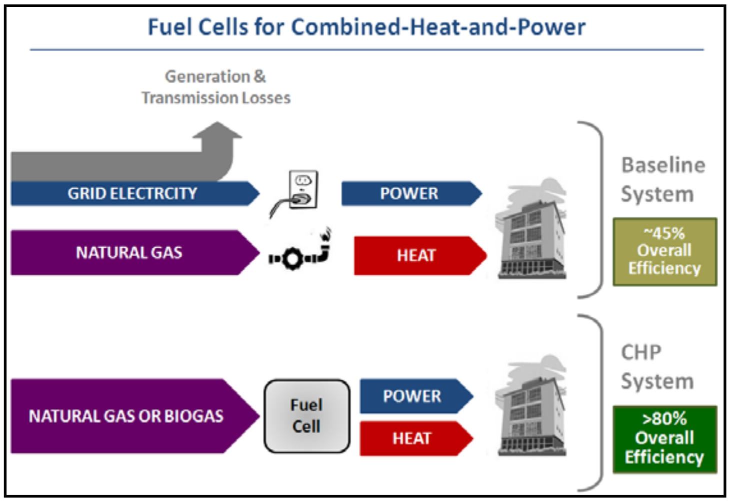


Figure 2.2.1. Fuel Cells for CHP Systems. Fuel cells in CHP installations can provide dramatic improvements in efficiency over conventional grid power and on-site natural gas heat.

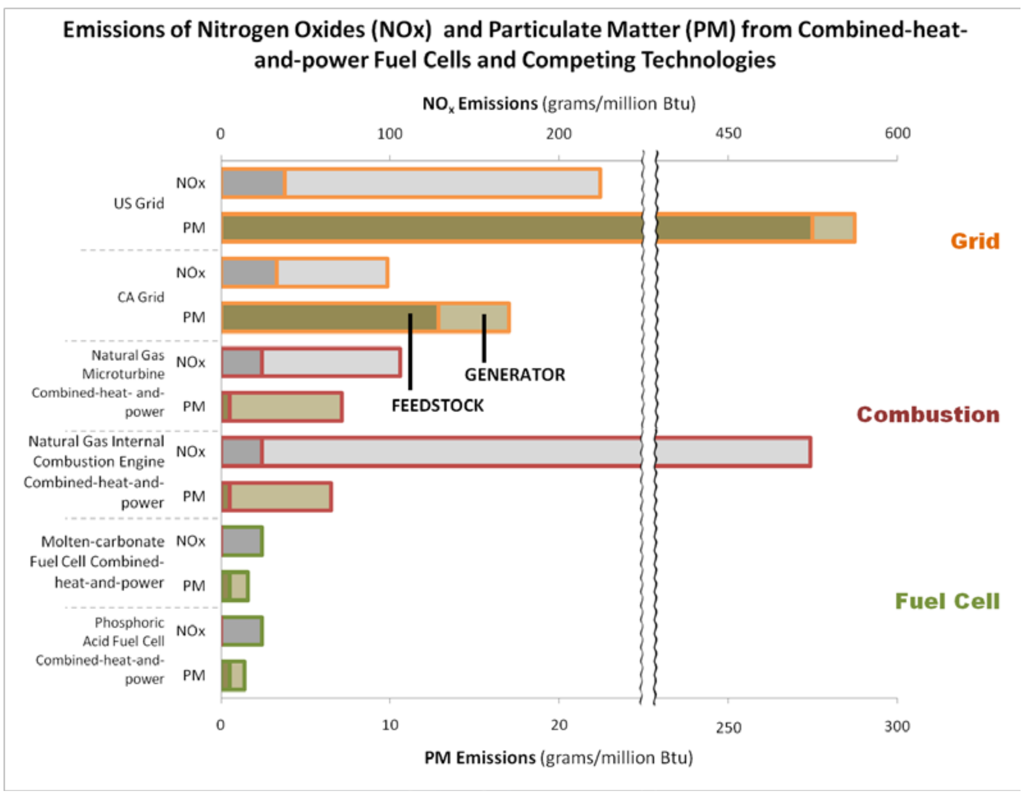
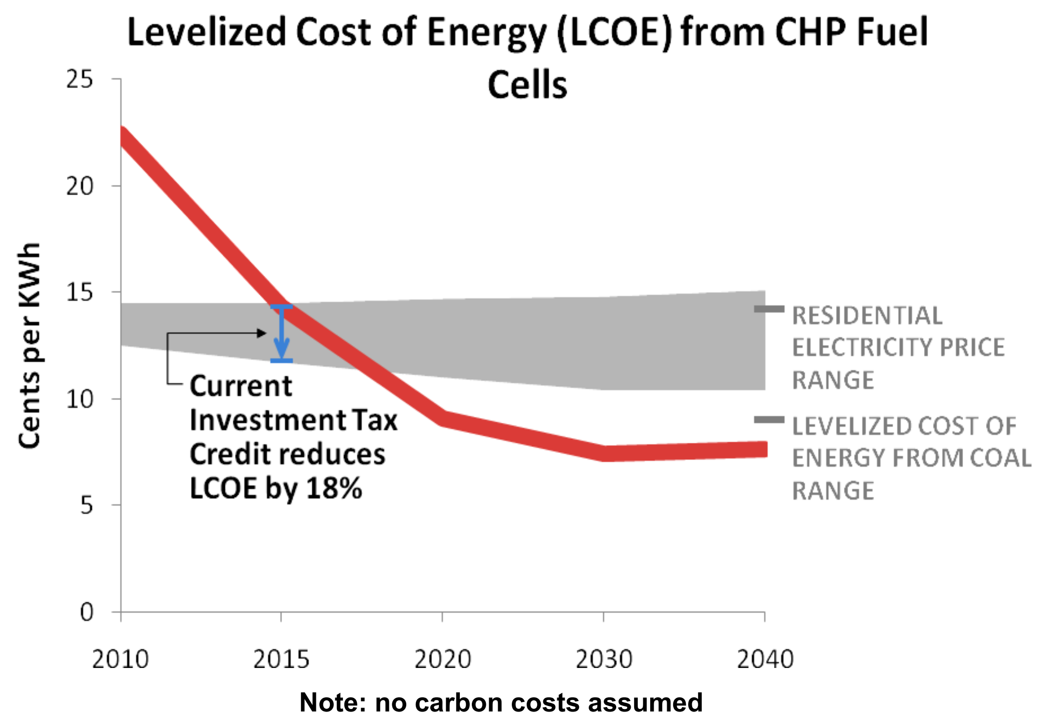


Figure 2.2.2. Criteria Pollutant Emissions from Generating Heat and Power. Fuel cells emit about 75 – 90% less NOx and about 75 – 80% less PM than other CHP technologies, on a life-cycle basis. In addition, similar to other CHP technologies, fuel cells can provide more than 50% reduction in CO_2 emissions,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



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

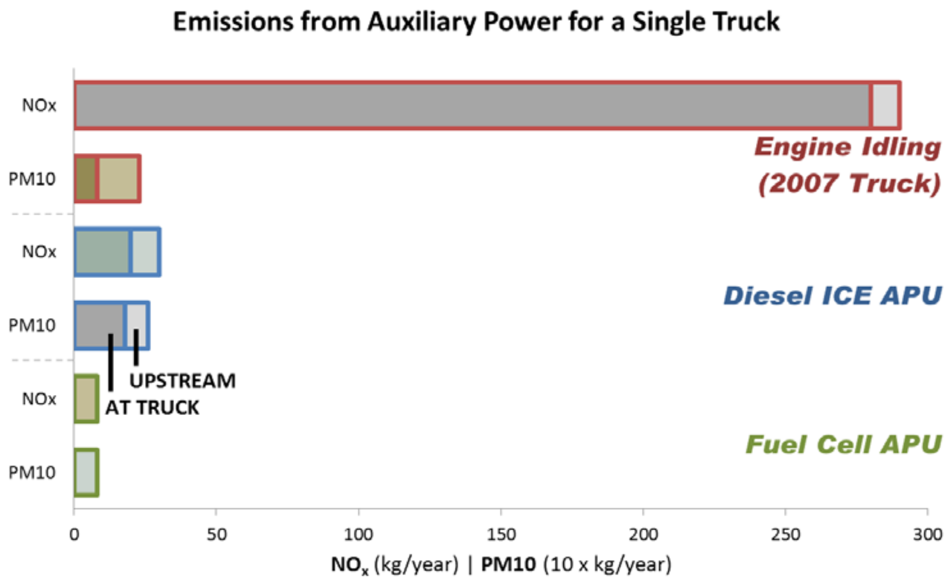

Figure 2.2.4. Emissions of Criteria Pollutants from Auxiliary Power for Trucks. Fuel cell auxiliary power units (APUs) can achieve significant reductions in criteria pollutant emissions over diesel internal combustion engine APUs and truck engine idling, while still using the truck's existing supply 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.

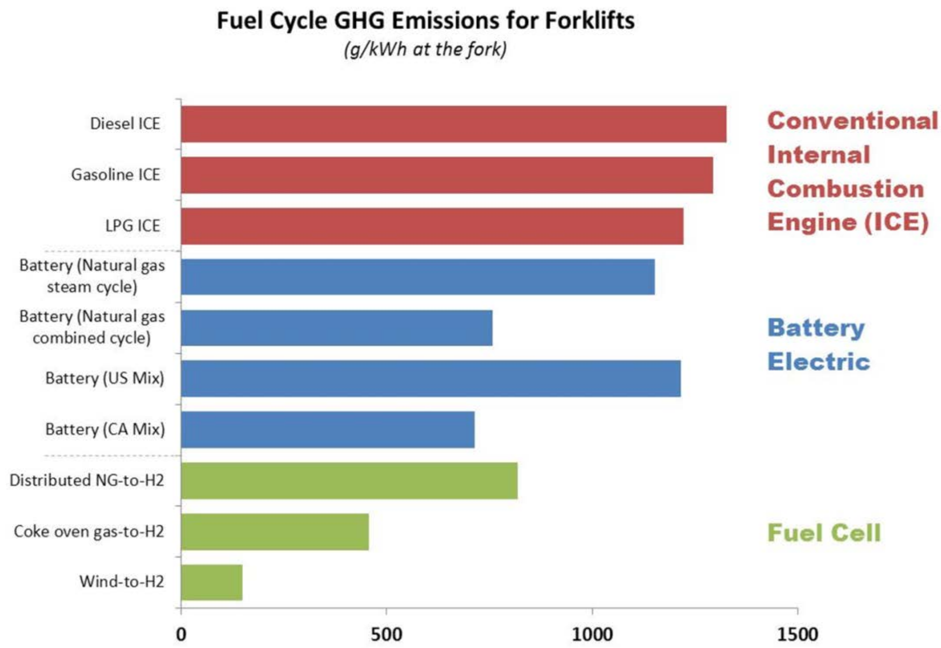

Figure 2.2.5. Greenhouse Gas Emissions from Forklifts. Specialty vehicles (including forklifts, lift trucks, and others) have become a key early market for fuel cells, where hydrogen and fuel cells can offer substantial reductions in emissions and significant benefits to the end-user in terms of economics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

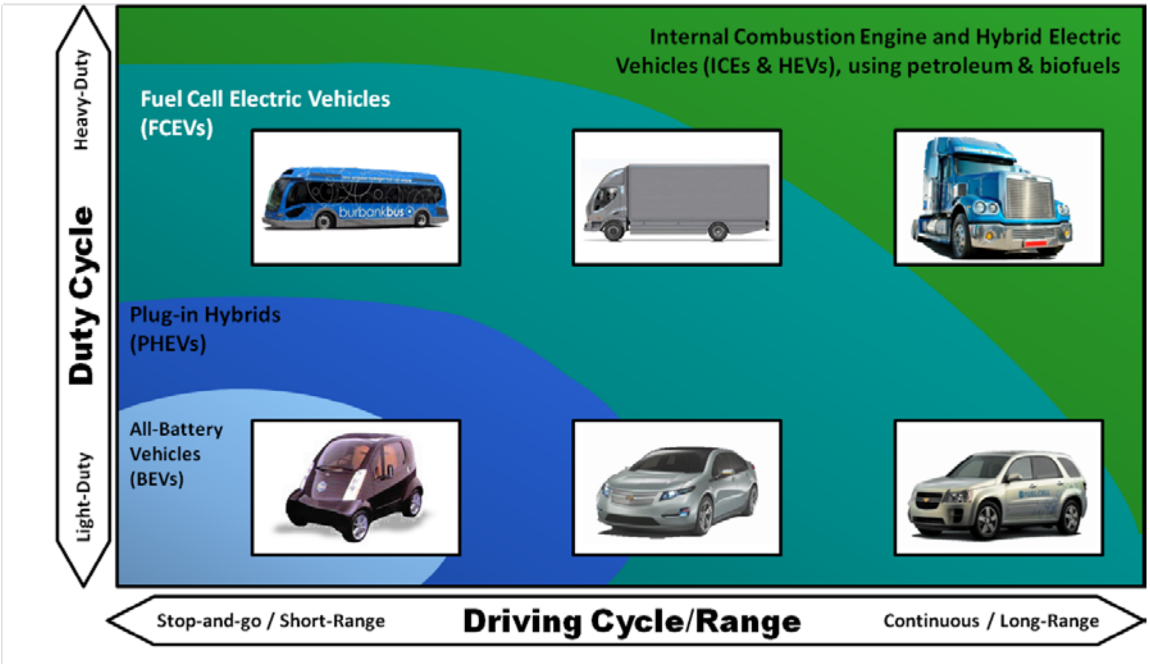

Figure 2.2.6. Diverse Technologies for Transportation Needs. A diverse portfolio of vehicle technologies will be required to meet the full range of driving cycles and duty cycles in the nation's vehicle fleet. Fuel cells play a central role, enabling longer driving ranges and heavier duty cycles for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

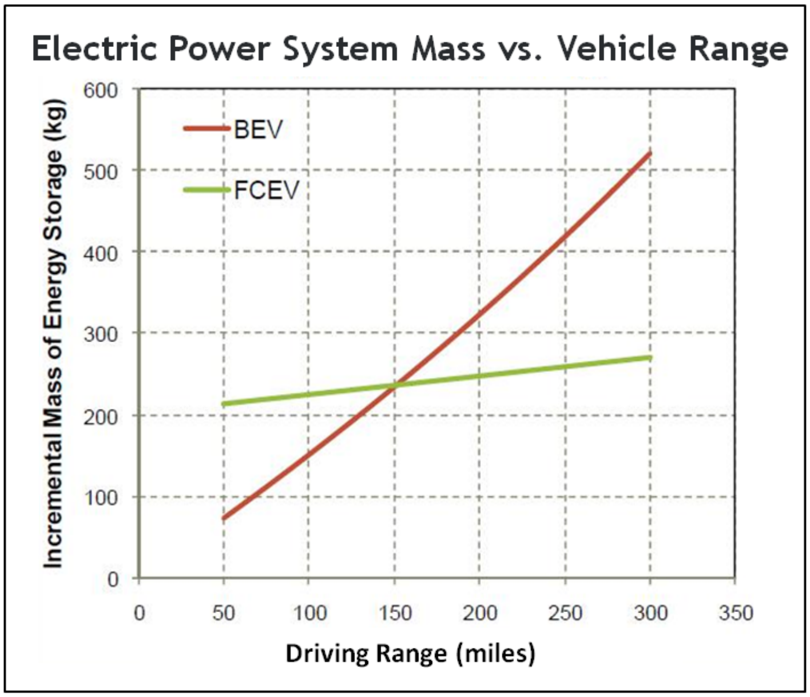

Figure 2.2.7.Range and Mass of Energy Storage Systems for Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs)[36] Battery system mass is preferable for short driving ranges (<150 miles), but FCEVs have much lower system mass (including the fuel cell and hydrogen storage systems)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

[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).

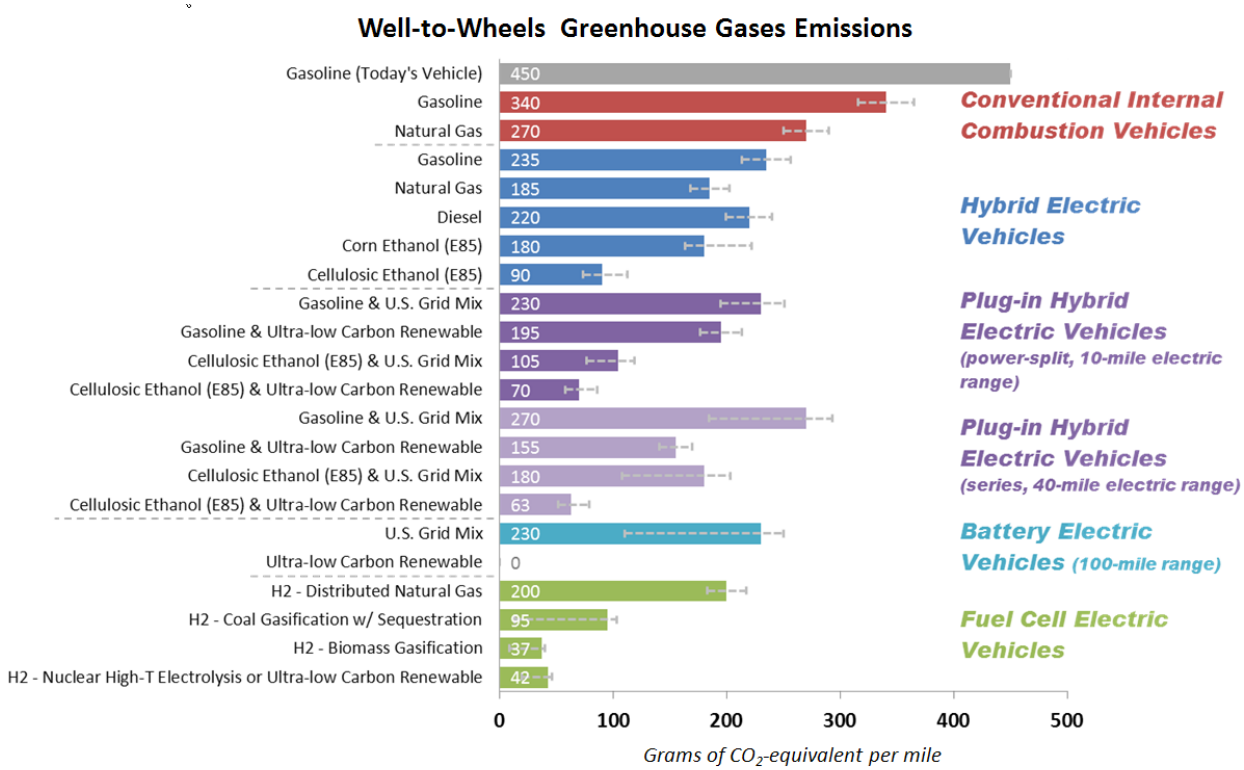

Figure 2.2.8. Well-to-Wheels Analysis of Greenhouse Gas Emissions. Substantial reductions in greenhouse gas emissions are possible through the use of a variety of advanced transportation technologies and fuels, including FCEVs using hydrogen from a variety of sources. Notes: (1) analysis based on a mid-sized 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]

[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

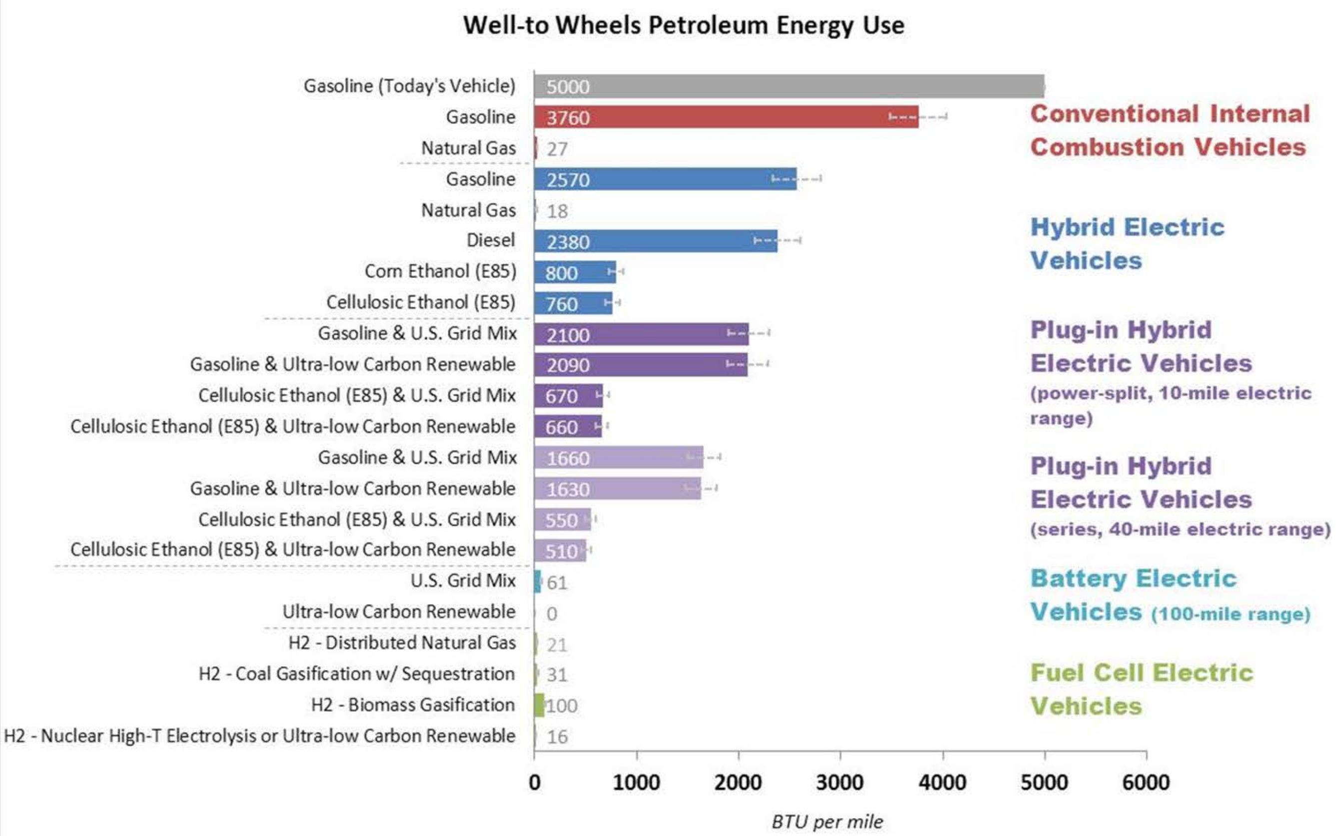

Figure 2.2.9. Well-to-Wheels Analysis of Petroleum Use. Notes: (1) analysis based on a mid-sized car; (2) assumes the state of the technologies expected in 2035–2045; (3) ultra-low carbon renewable electricity includes wind, solar, etc.; (4) the life-cycle effects of vehicle manufacturing and infrastructure 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]

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[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.

[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.*

3.0 Technical Plan

This section of the Plan provides a detailed outline of the various activities occurring within the technical sub-programs of the Fuel Cells Technologies Program (FCT Program). The technical sub-programs of the FCT Program are as follows:

3.1 Hydrogen Production

3.2 Hydrogen Delivery

3.3 Hydrogen Storage

3.4 Fuel Cells

3.5 Manufacturing R&D

3.6 Technology Validation

3.7 Hydrogen Safety, Codes and Standards

3.8 Education and Outreach

3.9 Market Transformation

For each section, a brief introduction is followed by the specific goal and objectives of each sub-program. The remainder of the section presents the sub-program's strategy for achieving success and measuring progress. This begins with an overview of the technical approach and review of the current activities within the sub-program. Next, each section lays out specific targets that will lead toward the objectives, the barriers to achieving these targets, and the specific tasks and milestones used to direct their efforts and gauge their progress.

Activities within each sub-program must be coordinated and integrated to achieve the technology readiness goals of the FCT Program. Interrelationships among all sub-programs, including Systems Analysis and Systems Integration, are represented in Figure 3.0.1. Specific inputs and outputs among sub-programs are identified in the milestone charts and tables in each section. Systems Analysis and Systems Integration (see Chapters 4 and 5) will be used to identify, analyze, and evaluate these complex interdependencies and to guide decision making for the FCT Program Manager. Program Management and Operations are covered in Chapter 6.

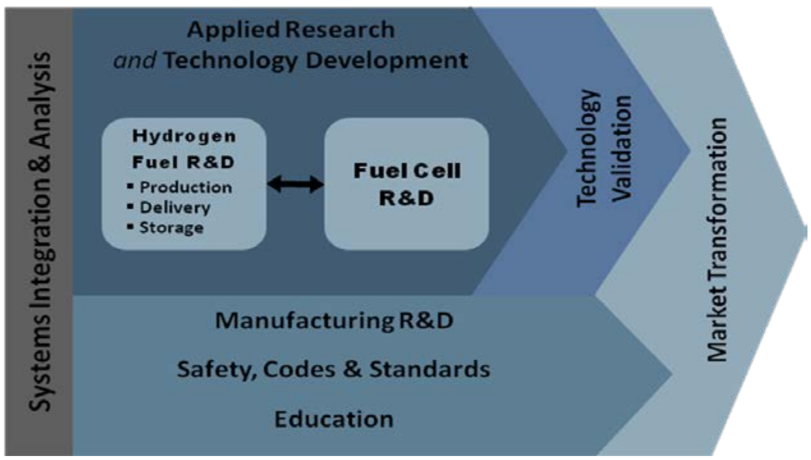

Figure 3.0.1. Fuel Cell Technologies Program Interrelationships

Each sub-program is also actively involved in coordination activities with the DOE Hydrogen and Fuel Cells Program, which includes hydrogen and fuel cell research and development efforts within DOE's Offices of Energy Efficiency and Renewable Energy (EERE), Nuclear Energy, Fossil Energy, and Science. Some EERE Programs sponsor research on technologies that can be used to produce or use hydrogen. EERE includes the following programs:

- Wind and Water Power Program
- Geothermal Technologies Program
- Solar Energy Technologies Program
- Biomass Program
- Vehicle Technologies Program
- Building Technologies Program
- Federal Energy Management Program
- Weatherization and Governmental Program
- Advanced Manufacturing Office

Hydrogen can play a key role in the realization of several of these technologies, and will benefit from the relevant research and development taking place. Advanced electrolysis technologies, conversion of biomass to hydrogen, polymer electrolyte membrane fuel cell development, and application of hydrogen for stationary energy needs are examples of areas in which collaboration among the FCT Program and other EERE Programs is vital to achieving the technical targets identified in this chapter.