# UNITED STATES

**Dr. Eric L. Miller**

U.S. Department of Energy (DOE)

Office of Energy Efficiency and Renewable Energy

Fuel Cell Technologies Program

## INTRODUCTION AND BACKGROUND

The Department of Energy Hydrogen and Fuel Cells Program (the Program) conducts comprehensive efforts to enable the widespread commercialization of hydrogen and fuel cell technologies in diverse sectors of the economy. The Program is coordinated across the Department of Energy (DOE or the Department), including activities in the offices of Energy Efficiency and Renewable Energy (EERE), Science (SC), Nuclear Energy (NE), and Fossil Energy (FE), and it is aligned with DOE's strategic vision and goals—its efforts will help to secure U.S. leadership in clean energy technologies and advance U.S. economic competitiveness and scientific innovation. With emphasis on applications that will most effectively strengthen our nation's energy security and improve our stewardship of the environment, the Program engages in research, development, and demonstration (RD&D) of critical improvements in the technologies, as well as diverse activities to overcome economic and institutional obstacles to commercialization. The Program addresses the full range of challenges facing the development and deployment of hydrogen and fuel cell technologies by integrating basic and applied research, technology development and demonstration, and other supporting activities.

## UPDATE ON MEMBER'S ENERGY FRAMEWORK

In fiscal year (FY) 2011, Congress appropriated approximately $150 million for the DOE Hydrogen and Fuel Cells Program. The Program is organized into distinct sub-programs focused on specific areas of RD&D, as well as other activities to address non-technical challenges. More detailed discussions of Program activities and plans can be found in EERE's Fuel Cell Technologies Program Multi-Year RD&D Plan; FE's Hydrogen from Coal RD&D Plan; and SC's Basic Research Needs for the Hydrogen Economy. All of these documents are available at www.hydrogen.energy.gov/program_plans.html. In the past year, the Program made substantial progress toward its goals and objectives. Highlights of the Program's accomplishments in hydrogen related RD&D are documented in the US DOE Hydrogen and Fuel Cells Program 2011 Annual Progress Report[1], and summarized below.

## HYDROGEN RD&D SPECIFICS

### HYDROGEN PRODUCTION

The FY 2011 Hydrogen Production sub-program continued to focus on developing technologies that enable the long-term viability of hydrogen as an energy carrier for a diverse range of end-use applications, including stationary power, backup power, specialty vehicles, transportation, and portable power. In FY 2011, the sub-program continued to make progress in several key areas, including autothermal reforming of bio-derived

## VITAL STATISTICS

**Population**[1]

313,847,465 (July 2012 est.)

**Territory**[1]

Total Area: 9,826,675 km$^2$

Land: 9,161,966 km$^2$

Water: 664,709 km$^2$

**Capital**

Washington, DC

**GDP1**

$15.04 trillion (2011 est.)

**GDP/capita1**

$48,100 (2011 est.)

**Recent average GDP Growth**[1]

1.5% real growth rate (2011 est.)

**Electricity**[1]

**Production**

3.953 trillion kWh (2009 est.)

**Consumption**

3.741 trillion kWh (2009 est.)

**Energy Production**[2]

(Quadrillion Btu, 2010)

**Fossil Fuels**

58,527

*Coal: 22.077*

*Natural Gas (dry): 22.095*

*Crude Oil: 11.669*

*NGPL: 2.686*

Nuclear Electric Power

8.441

**Renewable Energy**

8.084

**Total Production**

75,031

**Energy Consumption**[2]
*(Quadrillion Btu, 2010)*

**Fossil Fuels**
81.425

**Nuclear Electric Power**
8.441

**Renewable Energy**
8.049

**Total Consumption**
98.003

**Energy Imports**[2]
*(Quadrillion Btu, 2010)*

**Petroleum**
25.290

**Total Imports**
29.792

1 https://www.cia.gov/library/publications/the-world-factbook/geos/us.html

2 http://www.eia.doe.gov/emeu/aer/overview.html

liquids, electrolysis, photoelectrochemical (PEC) hydrogen production, and biological hydrogen production. In the area of bio-derived liquids, increases in process efficiency from 47% to 62% and increases in yield from 7.4g to 10.1g hydrogen per 100g bio-oil were achieved for bench-scale tests of catalytic steam reforming of pyrolysis oil as a result of improvements in catalyst performance through the use of a 0.5% Pt/Al2O3 BASF catalyst. Progress in the area of electrolysis included demonstration of a proton exchange membrane (PEM) electrolyzer incorporating advanced low-cost membrane electrode assemblies (MEAs) with chemically etched supports. Due to improvements in MEAs and flow fields and reductions in catalyst loading, the projected capital cost of electrolyzer stacks was reduced to less than $400/kW, representing a cost reduction of more than 10% relative to 2010 projections. In the area of photoelectrochemical (PEC) hydrogen production, the Program demonstrated exceptional stability in quantum-confined $MoS_2$ nanoparticle photocatalysts with bandgaps optimized at 1.8eV, showing stable operation over 10,000 voltage cycles of accelerated lifetime testing. In complementary work, novel macroporous scaffolds, which are transparent and conductive, were developed as electrode substrates to support PEC photocatalyst materials, such as MoS2, in high-efficiency devices. Finally, in the area of biological hydrogen production, the gene mutation responsible for the decrease in chlorophyll antenna size, previously observed to increase light utilization efficiency to 15% from 3% in wild-type organisms, was identified and characterized. Efforts to identify the mutation responsible for light utilization of up to 25% are ongoing, along with R&D to optimize hydrogen production in microalgal cultures.

## HYDROGEN DELIVERY

Hydrogen Delivery sub-program activities continued to focus on reducing the cost and increasing the energy efficiency of hydrogen delivery, to enable the widespread use of hydrogen as an energy carrier. In FY 2011, the sub-program continued to make progress in all major areas, including the following examples. A design trade study for a 5,000 pounds per square inch (psi) vessel was completed; this showed a projected 33% increase in capacity at 15°C and ~10% reduction in capital cost (on a per kilogram of transported hydrogen basis). In addition, burst testing on fiber reinforced polymer (FRP) pipe with 40% through-wall flaws was also completed and demonstrated a 3x margin above the rated pressure for the pipe. Researchers also showed that industry-standard compression fittings will meet Department of Transportation (DOT) requirements for joint leakage between pipe segments. FY 2011 also saw the development of a two-stage electrochemical hydrogen compressor that achieved 420 bar of compression.

## HYDROGEN PRODUCTION AND DELIVERY COST STATUS

As shown in Figure 1, significant progress has been made in cost reductions for several hydrogen production pathways in recent years. The Hydrogen Threshold Cost[2] shown in the plots represents the cost at which hydrogen fuel cell electric vehicles are projected to become competitive on a cost-per-mile basis with competing vehicles (gasoline hybrid-electric vehicles) in 2020. Natural gas reforming already meets the threshold cost criteria, and several of the other near-term technologies, particularly at the low end of the major feedstock cost, continue to approach the threshold.

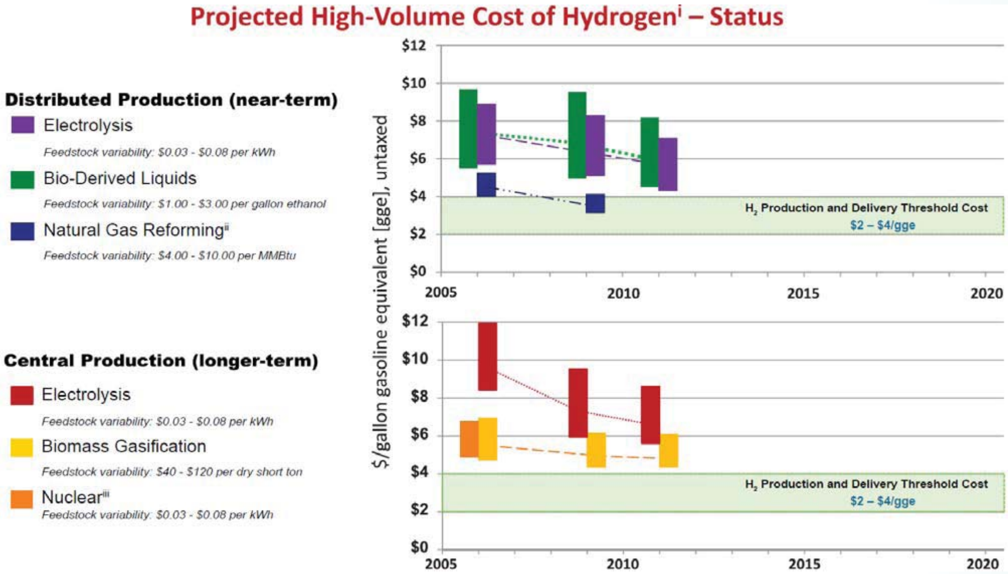


Figure 1: Hydrogen production and delivery cost status shown for near term pathways with sensitivities to major feedstock costs.

*Notes: (i) Costs shown include all delivery and dispensing costs, but do not include taxes. A cost of $1.80 for forecourt compression, storage, and dispensing is included for distributed technologies, and $2.60 is included as the total cost of delivery (including transportation, compression, storage, and dispensing) for centralized technologies. All delivery costs are based on the Hydrogen Pathways Technical Report (NREL, 2009). Projections of distributed costs assume station capacities of 1,500 kg/ day, with 500 stations built per year. Projections of centralized production costs assume capacities of ≥50,000 kg/day. Cost ranges for each pathway are shown in 2007 dollars, based on high-volume projections from H2A analyses, reflecting variability in major feedstock pricing and a bounded range for capital cost estimates. (ii) DOE funding of natural gas reforming projects was completed in 2009 due to achievement of the threshold cost. Incremental improvements will continue to be made by industry. (iii) High-temperature electrolysis activities are ongoing under the Next Generation Nuclear Plant Program.*

## HYDROGEN STORAGE

In FY 2011, the Hydrogen Storage sub-program's materials-discovery projects developed a number of new materials and improved the performance of other materials. Key accomplishments in FY 2011 include: characterization of high surface area sorbents with specific surface areas greater than 6000 $m^2$ per gram and excess hydrogen sorption capacities exceeding 8% by weight at 77 K; demonstration of cycling of $Mg(BH4)^2$ at hydrogen capacities greater than 12% by weight under high-temperature and high-pressure conditions; demonstration of alane slurry with 60% capacity by weight and with kinetics exceeding non-slurried alane; and determination that thermal stability of ionic liquids is dominated by choice of cation. The Hydrogen Storage Engineering Center of Excellence (HSECoE) completed a baseline assessment of storage system models for reversible metal hydrides, cryo-sorbents, and both solid- and liquid-phase off-board regenerable chemical hydrogen storage material systems. The HSECoE assessed these models against the full set of DOE onboard storage targets. Also in FY 2011, the sub-program increased its emphasis on reducing the cost of compressed hydrogen gas storage tanks by initiating new efforts on low-cost, high-strength carbon fiber. Inexpensive storage vessels for compressed hydrogen gas are considered the most likely near-term hydrogen storage solution for the initial commercialization of FCEVs, as well as for other early market applications.

## TECHNOLOGY VALIDATION

The Technology Validation sub-program demonstrates, tests, and validates hydrogen and fuel cell technologies and uses the results to provide feedback to the Program's R&D activities. The Technology Validation sub-program has been focused on conducting learning demonstrations that emphasize co-development and integration of hydrogen infrastructure with fuel cell electric vehicles (FCEVs) to permit industry to assess progress toward technology readiness. As the vehicle and infrastructure demonstrations are coming to a close, the sub-program is increasing its focus on other areas, such as combined hydrogen, heat, and power (tri-generation or CHHP) as well as stationary power applications. A major accomplishment in FY 2011 was demonstrating the world's first fuel cell energy station that produces electric power and hydrogen from wastewater treatment gas. The energy station provides hydrogen as a transportation fuel to the public and electric power to the wastewater treatment facility; it also has the potential to operate in "trigeneration" (or combined-heat-hydrogen-and-power) mode, if waste heat from the fuel cell is captured and provided to the facility. The energy station began operation at the Orange County Sanitation District's facility in Fountain Valley, California, sending the first hydrogen to a fueling station for FCEVs in February 2011. The combined co-production efficiency of hydrogen and power was 54% at the energy station, exceeding DOE's target of 50% for FY 2011.

## SAFETY, CODES, AND STANDARDS

The Safety, Codes, and Standards sub-program continued to support critical R&D to establish key requirements and address knowledge gaps in safety, codes and standards. Building on work from previous years, the sub-program continued to facilitate collaborative activities among relevant stakeholders in an effort to harmonize domestic and international regulations, codes, and standards (RCS). Significant accomplishments include the development of NFPA 2: Hydrogen Technologies Code, which consolidates all building codes and requirements for hydrogen installations in the United States into a single document. NFPA 2 also includes a Qualitative Risk Assessment (QRA) introduced by DOE for separation distances for hydrogen bulk storage. Another achievement was the development of an international hydrogen fuel specification standard (ISO TC 197 WG 12), which was led by the United States and ensures performance and durability of PEM fuel cells. In addition, a final draft of a Global Technical Regulation (GTR) for hydrogen-fueled vehicles has been submitted to the UN Economic Commission for Europe. The sub-program also took a leadership role in international coordination by co-organizing the International Conference on Hydrogen Safety in California with Sandia National Laboratories.

## EDUCATION

To support early market outreach, the Education sub-program implemented several end-user, state and local government, and safety and code official education activities. Videos were developed to be aired on TV and posted online to YouTube and other sites, including the development of two segments for Motorweek entitled "Hydrogen and Fuel Cells Emerging Markets" and "Vehicles and Infrastructure Update." In FY 2011, the sub-program also organized, publicized, and facilitated ten webinars on hydrogen and fuel cell topics of interest to state policymakers, local leaders, and end users, including: "The Top 5 Fuel Cell States: Why Local Policies Mean Green Growth," "Hydrogen and First Responders," "Financing Fuel Cell Installations," and others.

## SYSTEMS ANALYSIS AND INTEGRATION

Systems Analysis supports decision-making by providing a greater understanding of technology gaps, options, and risks. Analysis is also conducted to assess cross-cutting issues, such as integration with the electrical sector and use of renewable fuels. Particular emphasis is given to assessing stationary fuel cell applications, fuel quality impacts on fuel cell performance, resource needs, and potential infrastructure options. Accomplishments in FY 2011 include the development of a hydrogen cost threshold in the range of $2–$4/gge (in 2007 dollars) to assist DOE in focusing and prioritizing R&D options. The cost threshold represents the cost at which hydrogen fuel cell electric vehicles (FCEVs) are projected to become competitive on a cost-per-mile basis with the competing fuel/vehicle combination—gasoline in hybrid-electric vehicles (HEVs). A graphical representation of the hydrogen threshold, relative to current projected production and delivery costs was shown in figure 1 in the "Hydrogen Production and Delivery Cost Status" section. In addition, infrastructure analysis revealed that synergies between fuel cells for stationary power generation and transportation could be realized in the early phases of market adoption of hydrogen for light duty fuel cell vehicles. Model results that indicate hydrogen produced from combined-heat-hydrogen-and-power (CHHP) systems could result in smaller stations with higher capital utilization and lower hydrogen cost; this hydrogen could supplement hydrogen supplied from distributed natural gas–based steam methane reforming, particularly for the early years of FCEV penetration scenarios where hydrogen demand and station sizes are initially small.

## TRACKING THE COMMERCIALIZATION OF TECHNOLOGIES

One indicator of the robustness and innovative vitality of an R&D program is the number of patents applied for and granted, and the number of technologies commercialized. The Program continued to assess the commercial benefits of Program funding by tracking the commercial products and technologies developed with the support of the EERE Fuel Cell Technologies Program[3]. DOE-funded R&D has resulted in more than 310 patents and more than 60 emerging technologies while 30 hydrogen and fuel cell technologies have entered the market.[2] DOE also tracks the impact of its funding in terms of industry revenues and investment—for example, $70 million in funding for specific projects that were tracked was found to have led to more than $200 million in industry revenues and investment.

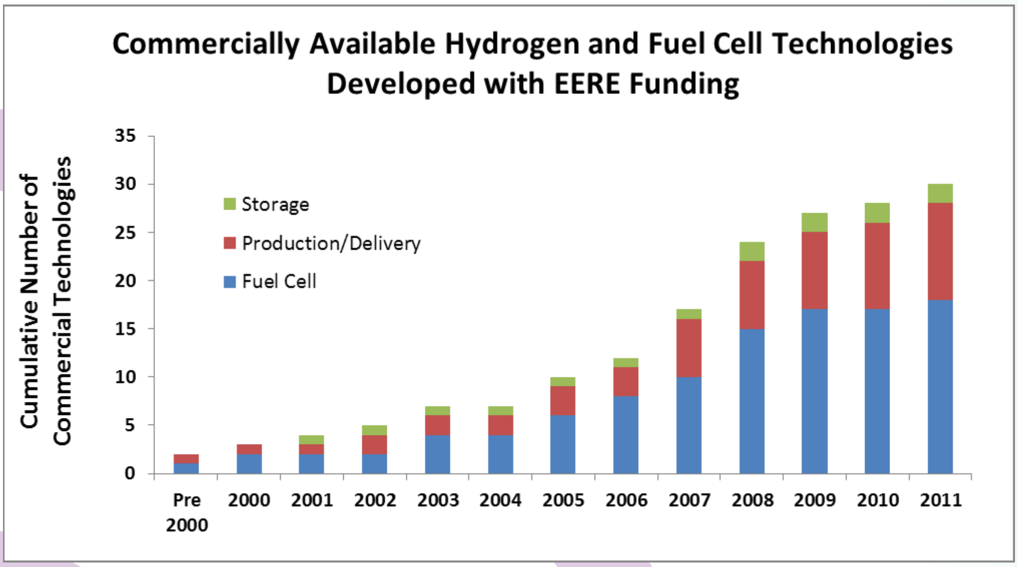


Figure 2: Cumulative Number of Commercially Available Technologies Developed with Funding from the Fuel Cell Technologies Program.

## ENDNOTES

Satyapal, Sunita, Program Manager, DOE EERE Fuel Cell Technologies, Introduction to the 2011 Annual Progress Report for the DOE Hydrogen and Fuel Cells Program: http://www.hydrogen.energy.gov/pdfs/progress11/i_introduction_2011.pdf

DOE Hydrogen and Fuel Cells Program Record #11012: http://hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.pdf

Pacific Northwest National Laboratory, Pathways to Commercial Success: Technologies and Products Supported by The Fuel Cell Technologies Program, 2011: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pathways_2011.pdf

## REFERENCES

### DOE EERE-FCT WEBSITES:

http://www.eere.energy.gov/topics/hydrogen_fuel_cells.html

http://www.hydrogen.energy.gov/

http://www.hydrogen.energy.gov/roadmaps_vision.html

http://www.hydrogen.energy.gov/annual_progress.html

http://www.hydrogen.energy.gov/annual_review.html

## CONTACT INFORMATION

Eric L. Miller
Fuel Cell Technologies Program
U.S. Department of Energy, EE-2H
1000 Independence Ave., SW
Washington, DC 20585
eric.miller@ee.doe.gov
Tel.: 202-287-5829
BB: 202-431-3075
Fax: 202-586-9811