I.0 Introduction

The DOE Hydrogen Program (the Program) has conducted comprehensive and focused efforts to enable the widespread commercialization of hydrogen and fuel cell technologies in diverse sectors of the economy. 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. In addition to DOE's Office of Energy Efficiency and Renewable Energy (EERE), the Program includes activities in the DOE Offices of Fossil Energy (FE), Nuclear Energy (NE), and Science (SC).

In Fiscal Year (FY) 2010, Congress appropriated approximately $244 million for the DOE Hydrogen 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. The goals, objectives, and targets of each of the applied research programs are identified in the multi-year program plans for EERE, FE, and NE; and the basic research areas addressed by the Office of Science are described in *Basic Research Needs for the Hydrogen Economy–Report of the Basic Energy Sciences Workshop on Hydrogen Production, Storage, and Use*. 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 are summarized below. More detail can be found in the sub-program chapters of this report.

PROGRAM PROGRESS AND ACCOMPLISHMENTS

Hydrogen Production

The FY 2010 Hydrogen Production activities 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 portable power, stationary power, backup power, specialty vehicles, and transportation. The goal of the Program's production portfolio is to develop low-cost, high-efficiency hydrogen production technologies from diverse, domestic sources, including renewable resources, coal (with carbon sequestration), and nuclear energy. The main objective is to reduce the cost of hydrogen dispensed at the pump to a cost competitive with gasoline. Important FY 2010 accomplishments in the major production technology pathways are summarized below:

Biomass and Bio-Derived Liquids: The National Renewable Energy Laboratory (NREL) demonstrated hydrogen production by auto-thermal reforming of bio-oil using a bench-scale reactor system and achieved hydrogen production of 7.3 g/100 g bio-oil (potentially 9.6 g/100 g bio-oil after water-gas shift) with 93% bio-oil to gas conversion. Argonne National Laboratory (ANL) completed an analysis of the economic feasibility of hydrogen production from glycerol derived as a byproduct of the biodiesel industry–estimating the cost of hydrogen for a base case set of conditions at $4.86/kg, where the price of glycerol was assumed to be $1.07/gallon. United Technologies Research Center demonstrated nearly 100% conversion of wood, using an inexpensive base metal catalyst, and completed a study to better understand the impact of base concentration on H_2 yield and selectivity.

Electrolysis: Giner Electrochemical Systems reduced hydrogen embrittlement in titanium/carbon cell-separators, demonstrated enhanced dimensionally stable membrane (DSM™) performance, and projected a decrease in overall capital cost of their electrolyzer stack from >$2,500/kW in 2001 to $463/kW in 2010. In addition, NREL completed an independent review of wind electrolysis, estimating the levelized cost range for state-of-the-art electrolysis to be $4.90–$5.70 per gallon gasoline equivalent (gge) of hydrogen for forecourt refueling stations (including compression, storage and dispensing), and \$2.70–3.50/gge for central electrolysis operations (at the plant gate, excluding all delivery and dispensing costs).

Solar Thermochemical Hydrogen Production: The University of Colorado optimized formulations for hercynite materials, which are more stable and generate hydrogen at lower temperature than the traditional ferrites; they also completed a techno-economic analysis indicating that atomic-layer-deposition of ferrite materials on 100 m^2/g supports with an oxidation/reduction cycle every five minutes will meet the DOE 2015 cost targets. In addition, ANL initiated a development and testing project for new membrane materials for the CuCl electrolyzer in the hybrid copper chloride cycle, and demonstrated that a decrease in the reactor pressure reduces the amount of steam required ($H_2O/CuCl_2$ ratios reduced by more than 30%, from 20–23 to 11–15) for >90% yield of the desired Cu_2OCl_2 product.

Photoelectrochemical and Biological Production: Directed Technologies, Inc. (DTI) completed separate technoeconomic boundary analyses of photoelectrochemical (PEC) solar hydrogen production and biological hydrogen production, projecting cost ranges of \$2.50–\$10/gge H_2 for PEC and \$3-\$12/gge H_2 for biological production, based on the current state of these technologies. Stanford University achieved the first-ever demonstration of bandgap tailoring in photoactive MoS_2 nanoparticles–increasing the MoS_2 bulk bandgap from 1.2 eV up to 1.8 eV, a more optimal value for PEC water splitting. University of California, Berkeley, developed methods to minimize the size of chlorophyll antennae used in photosynthesis by decreasing the expression of the Truncated-Light-Antenna genes, thereby substantially improving solar light energy utilization efficiencies in plants and microalgal cultures from the 2000 baseline of 3% up to 25%. In addition, NREL, in collaboration with Pennsylvania State University, designed, constructed, and tested a 2.5-L bench-scale prototype microbial electrolysis cell that produced hydrogen gas at a rate up to 1,250 mL/d, demonstrating the usefulness of this design.

Fossil Energy–Hydrogen from Coal: Eltron Research Inc., Southwest Research Institute® (SwRI®), and Worcester Polytechnic Institute (WPI) developed membrane separation technologies that achieve a hydrogen recovery rate of 90% with nearly 100% H_2 purity, while simultaneously enabling 90–95% CO_2 capture at high pressure, minimizing CO_2 compression costs.

Hydrogen Delivery

Hydrogen Delivery sub-program activities continued to focus on developing technologies to reduce the cost and increase the energy efficiency of hydrogen delivery, to enable the widespread use of hydrogen as an energy carrier. Three potential delivery pathways are being considered: gaseous hydrogen (trucks or pipelines), liquid hydrogen (trucks), and novel solid or liquid hydrogen carriers (trucks or pipeline). FY 2010 accomplishments in the major delivery activities are summarized below:

Pipelines: Savannah River National Laboratory (SRNL) completed a life-cycle management plan for fiber reinforced composite (FRC) pipelines, completed a review of existing FRC design specifications and standards and initiated environmental and flaw tolerance testing of FRC. Also, Sandia National Laboratories (SNL) examined the fracture properties of X52 pipeline steel in high-pressure hydrogen gas to evaluate the reliability of current pipeline steel for transmission.

Tube Trailers and Bulk Storage: Lincoln Composites completed an assembly that includes an International Organization for Standardization (ISO) frame, four pressure vessels, and relevant plumbing. The American Bureau of Shipping approved the entire ISO assembly for manufacture. In addition, Lawrence Livermore National Laboratory (LLNL) designed a pressure vessel that when incorporated into a trailer could deliver hydrogen at a cost below \$1/gge (not including forecourt expenses).

Compression and Liquefaction: Concepts ETI Inc. completed a preliminary design of a six-stage H_2 pipeline compressor capable of delivering 240,000 kg H_2/day at 1,250 psig. In addition, five subsystems of a 290 K to 120 K active magnetic regenerative liquefier prototype were designed, fully assembled, and successfully tested by Prometheus Energy.

Analysis: ANL upgraded the Hydrogen Delivery Scenario Analysis Model to evaluate three new delivery pathways, two different station configurations for 700-bar dispensing, and an option permitting user selection of station configuration. Also, NREL upgraded the Hydrogen Rail Components Model with 700-bar and cryo-compressed dispensing and higher tube-trailer delivery pressure, of up to 480 atm.

Hydrogen Storage

In FY 2010 the storage sub-program continued to make research and development (R&D) progress on advanced storage technologies for on-board vehicle applications.[1] Investigations have continued to focus on development of materials within the three classes of hydrogen storage materials: hydrogen adsorbents, reversible metal hydrides and chemical hydrogen storage materials. There has also been an increased effort on advancing the state of the art in system engineering for materials-based vehicular storage systems through the Hydrogen Storage Engineering Center of Excellence (HSECoE). Progress has also continued on cryo-compressed physical storage.

Metal Hydride Center of Excellence (MHCoE): Over the five-year life of the MHCoE, more than 80 distinct materials have been investigated; work on about 75% of these has been discontinued, based on criteria developed by the MHCoE, such as reversible capacities, absorption thermodynamics, and kinetics. Work at the University of Hawaii and Sandia-Livermore National Laboratory has demonstrated 12 wt% reversibility from $Mg(BH_4)_2$ using severe re-hydrogenation conditions of 900+ bar H_2 pressure and 400°C. The formation of the stable $Mg(B_{12}H_{12})$ intermediate has been found to be the reason that extreme hydrogenation pressures are needed. Under mild conditions, the group found they could obtain 2.4 wt% with partial cycling of $Mg(BH_4)_2$ without formation of the $Mg(B_{12}H_{12})$ intermediate. This preliminary work has been shown to extend to other metal borohydrides as well. Work has continued to progress at SRNL in developing a route for electrochemical formation of alane (AlH_3) from aluminum metal and hydrogen gas in an electrolyte solution. In FY 2010, an electrocatalytic additive was found that increased the rate of alane production approximately 1.8 times.

Hydrogen Sorption Center of Excellence (HSCoE): Through FY 2010, the HSCoE has identified approximately 210 materials, of which approximately 80% are no longer being investigated due to their failure to meet gravimetric or volumetric capacity targets. The Center has published its Materials Go/No-Go Recommendation Report (NREL), which is available through the DOE Web site at: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/hscoe_recommendation_feb_10.pdf.

Additionally, through collaborative center work, boron-substituted carbon materials were synthesized and demonstrated to have increased hydrogen binding energy (isosteric heats of 9–11 kJ/mol) as a function of coverage, agreeing with theory predictions. Several new sorbent materials were synthesized, including: Duke University's polyether-etherketone (PEEK) material, which was found to have greater than 5 wt% excess hydrogen capacity; Texas A&M University's PCN-68 framework material with 5,109 m^2/g surface area and 7.2 wt% excess hydrogen capacity; and Caltech's Cs and Rb-intercalated graphite with narrow "slit-pore" geometries of 5.3 to 5.8 Å, which were shown to have a near constant isosteric heat of adsorption of 14 and 12 kJ/mol H_2, respectively.

Chemical Hydrogen Center of Excellence (CHCoE): The CHCoE has investigated about 130 distinct chemical compositions over its five-year life. Research on approximately 95% of these has ended due to issues related to storage capacities, hydrogen release temperatures, kinetics, and spent fuel regeneration efficiency. FY 2010 advancements in chemical hydrogen storage materials included Los Alamos National Laboratory's (LANL's) development of a "one-pot" spent ammonia borane (AB) regeneration process with an overall yield of 90%; demonstration by Pacific Northwest National Laboratory (PNNL) of a new AB first-fill process with higher purity and yield and completion of a reactor scale-up capable of providing 100-gram batches of high purity AB to center partners; and the University of Pennsylvania achieving over 6x rate enhancements with reduced borazine formation and up to 11.4 wt% H_2-release from 80/20 (w/w)AB/ionic-liquid mixtures at 110°C. Additionally, high release rates for liquid AB at temperatures as low as 70°C with non-platinum group metal catalysts were demonstrated by LANL.

Hydrogen Storage Engineering Center of Excellence (HSECoE): FY 2010 was the first full year of effort for the HSECoE. The focus of FY 2010 was to develop preliminary complete system models for the three material classes using data for well-characterized representative materials from each class.

[1] U.S. Department of Energy Hydrogen Program Records #9017: On-Board Hydrogen Storage Systems – Projected Performance and Cost Parameters, www.hydrogen.energy.gov/program_records.html

The Center also developed fuel cell power plant and vehicle models and coupled the models together so that on-board hydrogen storage system performance impacts on vehicle and power plant performance can be readily determined. The model development and coupling was carried out collaboratively primarily by Ford, General Motors, NREL, PNNL, SRNL, and United Technologies Research Center. LANL developed and demonstrated a novel acoustic fuel gauge sensor for use with materials-based storage systems.

In addition to the advancements made within the four Centers, the Storage sub-program continued to advance physical storage systems using compressed and cryo-compressed hydrogen. At Oak Ridge National Laboratory (ORNL), work was initiated to develop new melt-spin precursor preparation processes that could lead to projected cost savings of up to 50% of the carbon fiber precursor costs, potentially leading to a 25% reduction in final carbon fiber costs. ANL and TIAX LLC completed their technical assessments of compressed gas storage tank systems for automotive applications and their final report will be available through the DOE Web site. LLNL has continued progress on cryo-

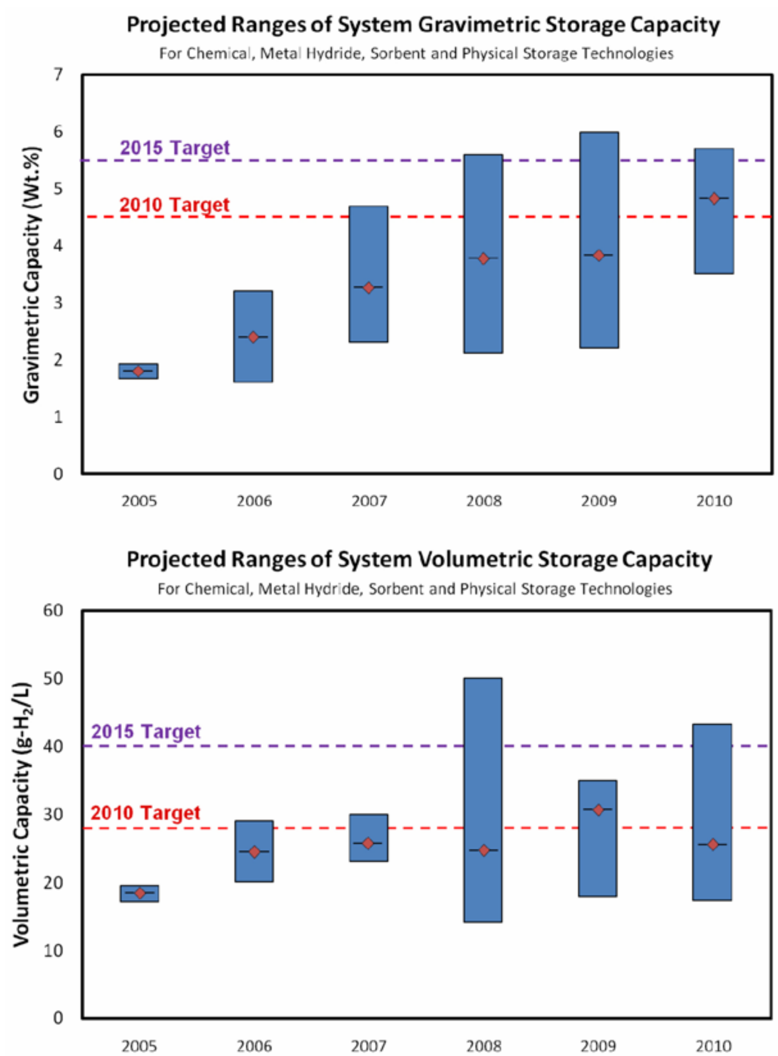

FIGURE 1. Estimates of gravimetric and volumetric capacities projected for on-board storage systems that can supply 5.6 kg of usable hydrogen as compared to DOE targets (based upon engineering analyses). Note that the plotted data points are the average values for all systems analyzed during each year while the bars correspond to the range of maximum and minimum values obtained in each year. Also note that systems with predicted capacities exceeding the gravimetric or volumetric targets do not meet other targets.

compressed systems. An LLNL generation-3 tank design with 5.6 kg of usable H_2 has been projected by ANL to be capable of meeting the 2015 gravimetric and volumetric targets, with greater than 5.5 wt% and 42 g/L capacities.

Fuel Cells

The Fuel Cells sub-program has made continued progress toward meeting 2010 and 2015 targets through advancements achieved in both catalysis and membrane R&D. Technological advances in several component areas have led to significant improvements in performance and durability, with decreased cost. Progress has also been demonstrated in the sub-program's efforts to develop fuel cell systems for combined heat and power (CHP) applications.

The cost of a hydrogen-fueled 80-kW_e fuel cell power system projected to high volume production (500,000 units/year) has been estimated to be $51/kW (assuming 2010 technology), as shown in Figure 2.[2] Cost reduction was a result of simplified architecture and reduction in stack component costs through ongoing R&D efforts. The cost of the fuel cell stack has been estimated to be $25/kW (assuming 2010 technology).

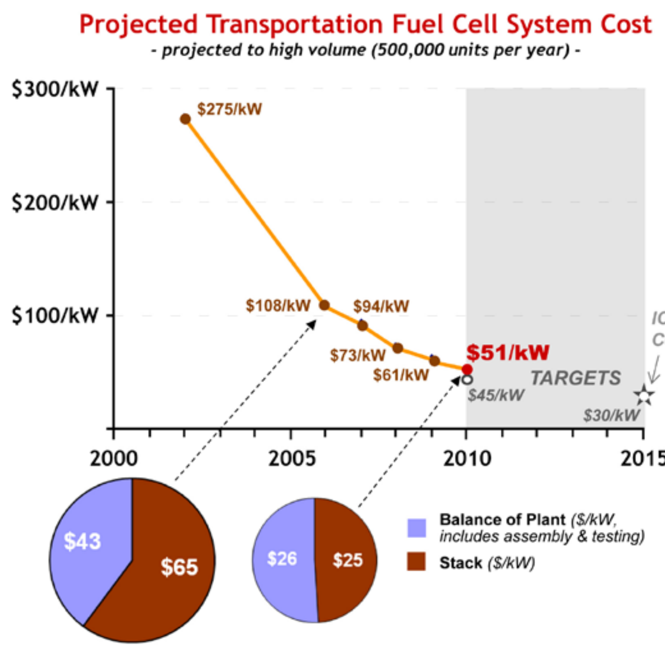

FIGURE 2. Modeled High-Volume Cost of an 80-kW Fuel Cell System (based on 500,000 units/year)

In FY 2010, advancements in platinum group metal (PGM)-based catalysts resulted in significant progress toward improvement of fuel cell performance and reduction in cost through minimization of PGM loading. In FY 2010, 3M increased PtCoMn mass activity 30%, reaching 0.24 A/mg_{PGM} at 0.9 V, and demonstrated Pt_3Ni_7 alloy with mass activity of 0.40 A/mg_{PGM}.

3M operated a membrane over 5,000 hours with load cycling using a membrane electrode assembly (MEA) based on a non-stabilized 20-µm membrane and catalyst loading of 0.15 mg_{PGM}/cm^2, meeting the DOE 2010/2015 durability target of 5,000 hours.[3] (The 7,300 hours reported previously was with a higher PGM loading.) With the use of chemical stabilizers in the membrane, 3M exceeded the 200-hour DOE target for stability under open-circuit voltage hold in H_2/air by more than 300%.

In FY 2010, Brookhaven National Laboratory (BNL) improved its core-shell catalyst by using an interlayer of Au to separate the Pt shell from the PdCo core. Rotating disk electrode (RDE) testing of the new catalyst has demonstrated mass activity as high as 1.10 A/mg_{PGM} and specific activity as high as 1,170 $µA/cm^2$ at 0.9 V,[4] suggesting a high probability of meeting DOE MEA-level and stack-level targets of 0.44 A/mg_{PGM} and 720 $µA/cm^2$. RDE testing of an early Pt/Pd/C catalyst yielded 0.35 A/mg_{Pt}. A Pt_{ML}/Pd/C core-shell catalyst delivered significantly better oxygen reduction reaction performance than a PtPd/C alloy with the same composition and identical performance as Pt/C, but with one fourth as much Pt at 0.90 V.

[2] U.S. Department of Energy Hydrogen Program Record #10004, www.hydrogen.energy.gov/program_records.html; costs are based on projections to high-volume manufacturing (500,000 units/year).
[3] Mark K. Debe, "Advanced Cathode Catalysts and Supports for PEM Fuel Cells," 2010 Annual Merit Review Proceedings, 2010, http://www.hydrogen.energy.gov/pdfs/review10/fc001_debe_2010_o_web.pdf.
[4] Piotr Zelenay, "Advanced Cathode Catalysts," 2010 DOE Hydrogen Program Review. http://www.hydrogen.energy.gov/pdfs/review10/fc005_zelenay_2010_o_web.pdf

Continued work at LANL on PGM-free catalysts yielded significant performance improvements in FY 2010, with current density as high as 60 A/cm^3 measured at 0.80 V (iR-free) during fuel cell testing with an Fe-cyanamide-C catalyst, representing a 64x improvement over the past two years. Progress also continues on PGM-free polyaniline-based catalysts at LANL, with activity as high as 31 A/cm^3 measured at 0.80 V, a 36x improvement over the past two years.[4]

3M developed new polymer electrolyte membranes with higher proton conductivity and improved durability under hotter and drier conditions, compared with previously produced membranes, as shown in Figure 3.[5] The new multi acid side-chain polymer membranes have better mechanical properties than conventional single acid side chain perfluorosulfonic acid membranes. In FY 2010, 3M developed innovative polymers in which side chains contain both sulfonic acid and sulfonamide groups.

The Fuel Cells sub-program also includes work on systems other than polymer electrolyte membrane (PEM) fuel cells, and progress is being made in these areas as well. For example, DOE is funding distributed energy and CHP systems based on several technologies. Acumentrics Corporation continues to develop micro-CHP systems based on tubular solid oxide fuel cell (SOFC) technology. In FY 2010, Acumentrics achieved a 24% increase in system power density, enabling a 33% reduction in stack volume and a 15% reduction in stack weight.[6]

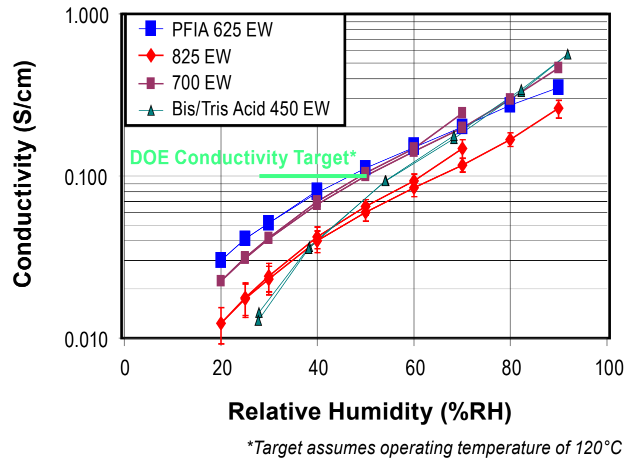

FIGURE 3. Conductivity of 3M Ionomers at 80°C

Manufacturing R&D

FY 2010 saw a number of cost and process advancements in the manufacturing of fuel cells and storage systems. W.L. Gore demonstrated, using their cost model, that a new 3-layer MEA process has the potential to reduce MEA cost by 25%. Quantum and Boeing demonstrated advanced filament winding and fiber placement processes that reduce storage system costs by 10%. BASF developed a predictive model and evaluated the impacts of electrode variation and defects on MEA performance using a new on-line X-ray fluorometer. Ballard developed a process model for controlling gas diffusion layer (GDL) coating conditions resulting in significant improvement in quality yields and GDL cost reduction of 53%. NREL developed and tested an iR-based test stand for defects such as pinholes, shorts, and variations in electrode thickness.

Basic Research

The Office of Basic Energy Sciences (BES) within the DOE Office of Science supports fundamental scientific research addressing critical challenges related to hydrogen storage, hydrogen production, and fuel cells. This basic research complements the applied R&D projects supported by other offices in the Program.

Progress in any one area of basic science is likely to spill over to other areas and bring advances on more than one front. The subjects of basic research most relevant to the Program's key technologies are:

- **Hydrogen Storage:** Nanostructured materials; theory, modeling, and simulation to predict behavior and design new materials; and novel analytical and characterization tools.

[5] Steven Hamrock, 3M, "Membranes and MEA's for Dry, Hot Operating Conditions," 2010 DOE Hydrogen Program Review. http://www.hydrogen.energy.gov/pdfs/review10/fc034_hamrock_2010_o_web.pdf
[6] Norman Bessette, "Development of a Low Cost 3-10kW Tubular SOFC Power System," 2010 DOE Hydrogen Program Review. http://www.hydrogen.energy.gov/pdfs/review10/fc032_bessette_2010_o_web.pdf

- **Fuel Cells:** Nanostructured catalysts and materials; integrated nanoscale architectures; novel fuel cell membranes; innovative synthetic techniques; theory, modeling, and simulation of catalytic pathways, membranes, and fuel cells; and novel characterization techniques.
- **Hydrogen Production:** Longer-term approaches such as photobiological and direct photochemical production of hydrogen.

By maintaining close coordination between basic science research and applied R&D, the Program ensures that discoveries and related conceptual breakthroughs achieved in basic research programs will provide a foundation for the innovative design of materials and processes that will lead to improvements in the performance, cost, and reliability of fuel cell technologies and technologies for hydrogen production and storage. This is accomplished in various ways–for example, through monthly coordination meetings between the participating offices within DOE, and at the researcher level by having joint meetings with participation from principal investigators who are funded by the participating offices.

Technology Validation

The Technology Validation sub-program has been focused on conducting learning demonstrations that emphasize co-development and integration of hydrogen infrastructure with hydrogen fuel cell-powered vehicles to permit industry to assess progress towards technology readiness. These activities include fuel cell vehicle and infrastructure demonstrations, stationary power demonstrations, and projects that integrate renewable power generation and hydrogen production. The Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project[7] (also known as the "National Hydrogen Learning Demonstration"), launched in April 2004, brought together four teams of industry partners to operate fuel cell vehicles and all essential hydrogen infrastructure elements to evaluate progress and to identify challenges encountered when hydrogen and fuel cell technologies are operated in real-world environments. The teams were led by Chevron and Hyundai-Kia, Mercedes-Benz North America and BP, Ford and BP, and GM and Shell, with additional participation from hydrogen suppliers, fuel cell suppliers, utility or gas companies, fleet operators, system and component suppliers, small businesses, universities, and government entities.

Through the National Hydrogen Learning Demonstration, the Program has deployed 152 fuel cell vehicles and collected data from 24 hydrogen fueling stations. These vehicles have traveled over 2.8 million miles, and the fueling stations have produced or dispensed over 130,000 kg of hydrogen (not all of the hydrogen dispensed has been used in Learning Demonstration vehicles). Vehicles and infrastructure in these demonstrations have validated the status of several key technologies in integrated systems under real-world operating conditions, including vehicular fuel cell efficiency of 53 to 59 percent, projected durability of 2,500 hours (nearly 75,000 miles) for automotive fuel cell systems, and a range of more than 250 miles between refueling. The Technology Validation activity has collected and analyzed data from a total of nine fuel cell buses operated in revenue transit service at five sites in the United States. These buses have shown fuel economies 39 to 141 percent higher than conventional diesel buses and compressed natural gas buses, and they have traveled more than 395,000 miles.

In FY 2011 the final two National Learning Demonstration projects (GM and Mercedes-Benz North America) will conclude and publish final reports. In addition, the Hydrogen Energy Station at Fountain Valley, California, which will co-produce power, heat, and hydrogen, is expected to be fully operational in FY 2011. Data will be collected on power and heat generation, hydrogen production, and vehicle refueling.

Safety, Codes and Standards

The Safety, Codes and Standards sub-program continues to support critical R&D to establish key requirements and close knowledge gaps in safety, codes and standards to enable the commercialization of hydrogen and fuel cell technologies. Building on work from previous years, the sub-program continues to facilitate collaborative activities among relevant stakeholders in an effort to harmonize domestic and international regulations, codes, and standards.

[7] For more information on the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, see: www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/fleet_demonstration.html.

The sub-program developed a strong technical basis for a risk-informed approach to update bulk gas storage separation distances in the 2010 edition of National Fire Protection Association (NFPA) 55. Experimental and modeling studies were used to develop new, technically defensible separation distances, which were in some cases reduced by as much as 50%. The sub-program also completed testing to enable the deployment of 100-MPa stationary storage tanks. The sub-program facilitated the development of requirements for forklift tank life-cycle testing used by the Canadian Standards Association Hydrogen Powered Industrial Truck Committee. In cooperation with the Education sub-program, the Safety, Codes and Standards sub-program continued to deploy an advanced-level, prop-based course to support first-responder training; this course has successfully reached over 300 first responders in California.

The sub-program expanded its Web-based safety information tools in FY 2010 including the *Technical Reference for Hydrogen Compatibility of Materials* and *Hydrogen Safety Training for Researchers*, which highlights best practices for the safe use of hydrogen in a research setting.

Working with an international team of experts, the sub-program conducted an intensive testing, modeling, and analytical effort to provide data that established a scientific basis for hydrogen fuel quality specifications for PEM fuel cell road vehicles under the ISO and the Society of Automotive Engineers. This effort included a round-robin test of a single-cell PEM fuel cell among laboratories in Japan, the European Commission, and the United States to establish interchangeability of data among the laboratories.

Education

The Education sub-program facilitates hydrogen and fuel cell demonstrations and supports commercialization by providing technically accurate and objective information to key target audiences both directly and indirectly involved in the use of hydrogen and fuel cells.

To support early market outreach, the Education sub-program implemented several end-user, state and local government, and safety and code official education activities in FY 2010. Carolina Tractor and Equipment Inc. conducted hydrogen education sessions with hands-on forklift demonstrations at material handling dealerships, customer sites, community colleges, and regional green business expos to educate potential end-users about the benefits of fuel cell forklifts. As evidence of the project's success, one site has decided to acquire over 100 fuel cell forklifts as a result of their experience with the demonstration units. Seven state and local government outreach projects focused on states with an active hydrogen and fuel cell presence to develop case studies, best practices, and technical assistance resources; these will be used to help decision-makers identify and assess opportunities for future deployment. Many groups have been using these education resources to work directly with state agencies to implement policies, programs, and best practices that can support the growth of hydrogen and fuel cell markets in the local economy. PNNL expanded first responder education by hosting several sessions of an advanced-level, hands-on prop course for firefighters and registering the Web-based "Introduction to Hydrogen Safety for First Responders" on the Training Finder Realtime Affiliate Network (TRAIN) Web site, a central repository for health training courses.

University and secondary education projects introduced future scientists, engineers, technicians, and end-users to hydrogen and fuel cell technologies. Five university projects–at California State University, Los Angeles; Michigan Technological University; the University of North Dakota; Humboldt State University; and the University of Central Florida–targeted a broad student audience through general education courses, specialized science and engineering courses, minor and concentration programs, curriculum modules, internships, labs, lab kits, and textbook chapters. In their second year, these projects are finalizing development of curricula and have moved into teaching, reviewing, and refining the course materials. "H2 Educate!," a set of lesson plans and activities for middle school teachers and students, continued to be disseminated through one-day teacher training workshops across the country. The companion effort for high schools, "HyTEC," deployed a six-unit science curriculum and laboratory kit on hydrogen and fuel cells through professional development workshops and science teacher conferences across the country.

Market Transformation

To ensure that the benefits of its efforts are realized in the marketplace, the Program continues to facilitate the growth of early markets for fuel cells used in portable, stationary, and specialty-vehicle applications. Market transformation activities are helping to reduce the cost of fuel cells by enabling economies of scale through early market deployments and by overcoming a number of barriers, including the lack of operating performance data, the need for applicable codes and standards, and the need for user acceptance.

The development of niche-market applications for hydrogen fuel cells has been identified as the quickest way to achieve early market penetration. A study conducted for the Program by the Battelle Memorial Institute, *Identification and Characterization of Near-Term Direct Hydrogen PEM Fuel Cell Markets,*[8] identifies fuel cells to power forklifts and to provide backup power for telecommunications and emergency response communications as promising near-term opportunities.

In FY 2010, the Program provided approximately $15 million for market transformation activities, to accelerate the deployment of fuel cells in early market applications. Specific FY 2010 projects included the deployment of nearly 100 lift trucks and a primary power system at Department of Defense sites and 14 hydrogen fuel buses at federal facilities across the country. These projects provide valuable data on the status of the technologies in real-world operation and information that will be used to validate the benefits of the technologies and potential needs for further R&D.

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 2010 included an update of the Macro-System Model (MSM) to include infrastructure and resource analysis for various regions and a variety of hydrogen production pathways. The Fuel Cell Power Model was upgraded to include business and financial analysis useful to multiple entities such as building owners, fuel cell vendors, station owners, utilities, and fleet operators.

Infrastructure analysis identified potential synergies between fuel cells for stationary power generation and transportation applications, particularly in the early phases of market adoption of hydrogen for light-duty fuel cell vehicles. Widespread deployment of combined heat, hydrogen, and power (CHHP) could address the problem of hydrogen availability in the early stages of transition to fuel cell vehicles. Analyses have indicated that the practice of producing hydrogen from CHHP systems could give rise to smaller stations with higher capital utilization and lower hydrogen cost, supplementing the supply of hydrogen from distributed natural gas–based steam methane reforming (SMR). Analysis conducted by NREL with the Fuel Cell Power model predicts that hydrogen produced from a stationary fuel cell would have a lower cost than hydrogen produced from an SMR system at low volumes, as shown in Figure 4.

ANL enhanced well-to-wheels analysis capabilities by modifying the Greenhouse gases, Regulated Emissions and Energy use in Transportation model to include analysis of criteria pollutant emissions from stationary fuel cells for combined heat, power and/or hydrogen generation (CHP/CHHP). The analysis estimates that fuel cell systems for CHP and CHHP emit significantly less carbon monoxide, particulate matter, and nitrogen oxides (NOx) than conventional generation technologies. For example, phosphoric acid fuel cells and molten carbonate fuel cells (MCFCs) emit at least 80% less NOx than other conventional generation technologies without after treatment.

[8] For a brief summary of early market opportunities for PEM fuel cells, see the Program's fact sheets on forklifts and backup power: www1.eere.energy.gov/hydrogenandfuelcells/education/pdfs/early_markets_forklifts.pdf and www1.eere.energy.gov/hydrogenandfuelcells/education/pdfs/early_markets_backup_power.pdf; for the full report by the Battelle Memorial Institute, see: www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pemfc_econ_2006_report_final_0407.pdf.

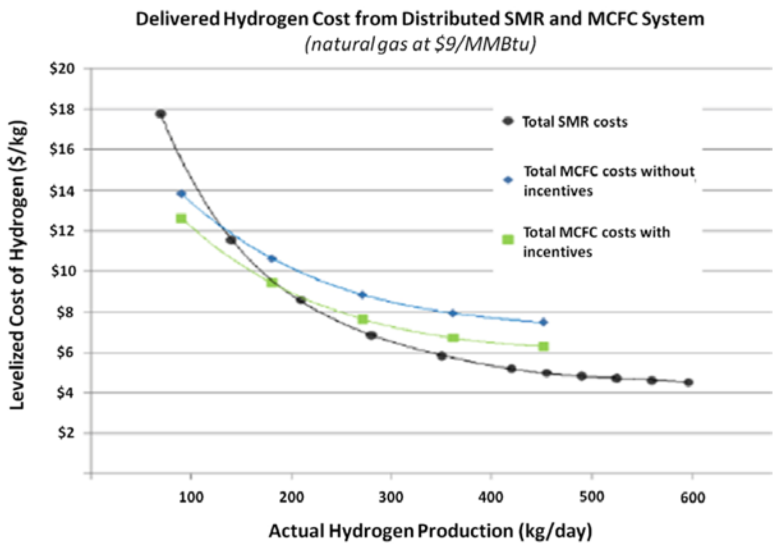

FIGURE 4. Delivered Hydrogen Cost from Distributed SMR and Molten-Carbonate Fuel Cell (MCFC) Systems (Source: NREL)

OTHER PROGRAM ACTIVITIES

American Recovery and Reinvestment Act Projects

The American Recovery and Reinvestment Act (Recovery Act or ARRA) has been a critical component of the Program's efforts to accelerate the commercialization and deployment of fuel cells in the market. With approximately $41.9 million from the Recovery Act and $54 million in cost-share funding from industry participants–for a total of nearly $96 million–this funding is supporting the deployment of nearly 1,000 fuel cell systems in emergency backup power, material handling, and CHP applications.[9] Twelve projects were competitively selected to develop and deploy a variety of fuel cell technologies including polymer electrolyte, solid oxide, and direct-methanol fuel cells in stationary, portable, and specialty vehicle applications. To date, a total of at least 36 direct jobs have been created or retained as a result of these projects. The Program exceeded its 2010 target by deploying 206 fuel cell-powered lift trucks and installing fuel cells for backup power at 24 cell tower sites. An additional 75 portable fuel cells–handheld power generators for consumer electronics–are being sent to users as test units.

These projects will help build a competitive domestic supply base, decrease costs, and demonstrate the economic and performance benefits of fuel cells as competitive options for stationary, portable, and specialty vehicle applications. These advances will lead to reductions in carbon emissions, the creation of jobs, and a broadening of the nation's clean energy technology portfolio.

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 EERE's Fuel Cell Technologies (FCT) Program by tracking the commercial products and technologies developed with the support of the Program. The *FY 2010 Pathways to Commercial Success Report* shows that 198 patents have been issued and 28 products have been commercialized as a result of research funded by the FCT Program in the areas of fuel cells and hydrogen production, delivery, and storage (Figure 5).[10]

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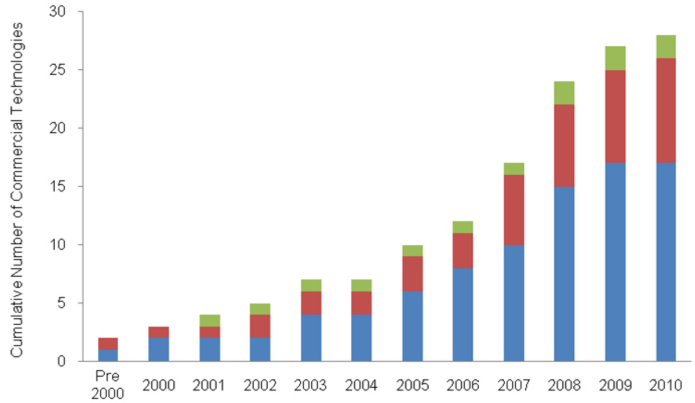
[9] Fuel Cell Market Transformation Recovery Act Projects, http://www1.eere.energy.gov/hydrogenandfuelcells/recovery.html.
[10] FY 2010 Pathways to Commercial Success Report. http://www1.eere.energy.gov/hydrogenandfuelcells/fc_publications.html#fc_general



	Pre 2000	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Storage	0	0	1	1	1	1	1	1	1	2	2	2
Production/Delivery	1	1	1	2	2	2	3	3	6	7	8	9
Fuel Cell	1	2	2	2	4	4	6	8	10	15	17	17
Total	2	3	4	5	7	7	10	12	17	24	27	28

FIGURE 5. Cumulative Number of Commercial Technologies on the Market

INTERNATIONAL ACTIVITIES

International Partnership for Hydrogen and Fuel Cells in the Economy

The United States is a founding member of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), which includes 17 member countries (Australia, Brazil, Canada, China, France, Germany, Iceland, India, Italy, Japan, New Zealand, Norway, the Republic of Korea, the Russian Federation, South Africa, the United Kingdom, and the United States) and the European Commission. The IPHE is a forum for governments to work together to advance worldwide progress in hydrogen and fuel cell technologies. IPHE also offers a mechanism for international R&D managers, researchers, and policymakers to share program strategies.

In FY 2010, DOE hosted the IPHE Steering Committee meeting in Washington, D.C., at which the secretariat was transferred from Canada to Germany. Germany and China also hosted two additional joint Steering Committee and Implementation & Liaison Committee meetings. In November 2010, the IPHE released an overview of the global technical and commercialization progress of hydrogen and fuel cell technologies titled, *2010 Hydrogen and Fuel Cell Global Commercialization and Development Update*.

IPHE–in collaboration with DOE, the California Fuel Cell Partnership (CaFCP), and NREL–coordinated the IPHE Infrastructure Workshop on February 25–26, 2010, to examine the key drivers and gaps to early market infrastructure development for light-duty vehicles. This interactive workshop engaged more than 80 professionals–representing a wide variety of stakeholders and expertise–in developing creative and practical solutions for establishing hydrogen infrastructure in the near term. Responding to the strategic issues and information gaps discussed during the workshop, the Program plans to conduct a rigorous assessment of challenges and needs–both from an R&D and business case perspective–to develop the appropriate strategy for vehicle and infrastructure rollout. For more information on the IPHE, visit www.iphe.net.

International Energy Agency

The United States is also involved in international collaboration on hydrogen and fuel cell R&D through participation in the International Energy Agency (IEA) implementing agreements, where it is a member of both the Advanced Fuel Cells Implementing Agreement (AFCIA) and the Hydrogen Implementing Agreement (HIA). These agreements provide a mechanism for member countries to share the results of research, development, and analysis activities in their respective areas.

The AFCIA currently comprises six annexes: Molten Carbonate Fuel Cells, Polymer Electrolyte Fuel Cells, Solid Oxide Fuel Cells, Fuel Cells for Stationary Applications, Fuel Cells for Transportation, and Fuel Cells for Portable Power. The participating countries are Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, South Korea, the Netherlands, Mexico, Sweden, Switzerland, Turkey, and the United States. The implementing agreement was recently extended from 2009 to 2013. Information about the IEA AFCIA is available at www.ieafuelcell.com.

The IEA HIA is focused on RD&D and analysis of hydrogen technologies. It includes ten tasks covering safety, hydrogen production, hydrogen storage materials, hydrogen delivery, and systems analysis including: Hydrogen Safety, Biohydrogen, Fundamental and Applied Hydrogen Storage Materials Development, Small-Scale Reformers for On-Site Hydrogen Supply, Wind Energy and Hydrogen Integration, High-Temperature Production of Hydrogen, Water photolysis, Near-Market Routes to Hydrogen by Co-Utilization of Biomass with Fossil Fuel, and Large Scale Hydrogen Delivery Infrastructure and Global Hydrogen Systems Analysis. The United States participates in all of these tasks. Members of the HIA are Australia, Canada, Denmark, the European Commission, Finland, France, Germany, Greece, Iceland, Italy, Japan, South Korea, Lithuania, the Netherlands, New Zealand, Norway, Spain, Sweden, Switzerland, Turkey, United Nations Industrial Development Organization-International Center for Hydrogen Energy Technologies, and the United States. In the past year, new tasks or annexes in hydrogen delivery infrastructure and global systems analysis have been initiated. A new task, Distributed and Community Hydrogen for Remote Communities, is under definition and is expected to start in FY 2011. Information about the IEA HIA is available at www.ieahia.org.

EXTERNAL COORDINATION, INPUT, AND ASSESSMENT

Hydrogen and Fuel Cell Technical Advisory Committee (HTAC)

HTAC was created in 2006 to advise the Secretary of Energy on issues related to the development of hydrogen and fuel cell technologies and to provide recommendations regarding DOE's programs, plans, and activities, as well as on the safety, economic, and environmental issues related to hydrogen and fuel cells. HTAC members include representatives of domestic industry, academia, professional societies, government agencies, financial organizations, and environmental groups, as well as experts in the area of hydrogen safety.

HTAC met three times between August 2009 and August 2010. In March 2010, HTAC released its second annual report, which summarizes hydrogen and fuel cell technology domestic and international progress in RD&D projects; commercialization activities; and policy initiatives. More information about HTAC, including the annual reports, is available at: http://www.hydrogen.energy.gov/advisory_htac.html

Federal Agency Coordination—the Interagency Task Force and the Interagency Working Group

The Hydrogen and Fuel Cell Interagency Working Group (IWG), co-chaired by DOE and the White House Office of Science and Technology Policy, meets monthly to share expertise and information about ongoing programs and results, to coordinate the activities of federal entities involved in hydrogen and fuel cell RD&D, and to ensure efficient use of taxpayer resources.

In August 2010, the IWG launched an updated Web portal, www.hydrogen.gov. The site serves as an information and government news source on hydrogen and fuel cells and a portal to participating agency activities. The IWG also completed a draft Interagency Action Plan with an expected release in FY 2011 in preparation for the reconvening of the Interagency Task Force.

National Academy of Sciences

The National Research Council (NRC) of the National Academies provides ongoing technical and programmatic reviews and input to the Hydrogen Program. The NRC has conducted independent reviews of both the Program[11] and the R&D activities of the FreedomCAR and Fuel Partnership.[12,13] In 2010, the NRC completed its Phase III review of the Partnership. Key outcomes of the review are documented in the report, *Review of the Research Program of the FreedomCAR and Fuel Partnership: Third Report*,[14] in which the committee expressed an overall opinion that the Partnership "is effective in progressing toward its goals," and that "there is evidence of solid progress in essentially all areas, even though substantial barriers remain." In this report, the committee also recognized "three primary alternative pathways" for reducing petroleum consumption and greenhouse gas emissions in the transportation sector: (1) improved internal combustion engine vehicles coupled with greater use of biofuels, (2) expanded use of plug-in electric vehicles and battery electric vehicless, and (3) hydrogen fuel cell vehicles.

In 2010, the NRC's Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies released the report, *Transitions to Alternative Transportation Technologies–Plug-In Hybrid Electric Vehicles*.[15] This report followed the committee's 2008 report, *Transitions to Alternative Transportation Technologies–A Focus on Hydrogen*. These reports were required by the Energy Policy Act section 1825 to compare hydrogen fuel cell vehicles to alternate advanced vehicle technologies. A key conclusion of the latest report is that a diverse approach to RD&D and market transformation–comprising a portfolio of efforts in hydrogen, batteries, and biofuels–will "enable the greatest reduction in oil use."

FY 2010 Annual Merit Review and Peer Evaluation

The Annual Merit Review (AMR) took place June 7–11, 2010, providing an opportunity for the Program to obtain an expert peer review of the projects it supports and to report its accomplishments and progress. For the second time, this meeting was held in conjunction with the annual review of DOE's Vehicle Technologies Program. During the AMR, reviewers evaluate the Program's projects and make recommendations; DOE uses these evaluations, along with other review processes, to make project funding decisions for the upcoming fiscal year. The review also provides a forum for promoting collaborations, the exchange of ideas, and technology transfer. This year, over 1,700 people attended the review and 349 projects were presented, of which 216 were peer-reviewed. There were 198 contributing reviewers; the report compiling their comments is available at http://www.hydrogen.energy.gov/annual_review.html. In 2011, the AMR will be held May 9–13 in Arlington, Virginia.

IN CLOSING...

The Program will continue to pursue a broad portfolio of RD&D activities for fuel cell applications across multiple sectors. Efforts will span the full spectrum of technology readiness, including: early market applications that are already viable or are expected to become viable in the next few years, such as forklifts, backup power, and portable power applications; mid-term markets that are expected to emerge in the 2012–2015 timeframe, such as residential combined-heat-and-power systems, auxiliary power units, fleet vehicles, and buses; and longer-term markets that are expected to emerge in the 2015–2020 timeframe, including light-duty passenger vehicles and other transportation applications. The Program will also continue to pursue activities to enable commercialization and stimulate the markets for hydrogen and fuel cells as they achieve technology readiness. Supporting these markets will not only help to achieve the economic, environmental, and energy security benefits that fuel

[11] National Research Council and National Academy of Engineering, Committee on Alternatives and Strategies for Future Hydrogen Production and Use, The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs, (Washington, D.C.: National Academies Press, 2004).

[12] National Research Council of the National Academies; Committee on Review of the FreedomCAR and Fuel Research Program, Phase 1; Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences, Transportation Research Board; *Review of the Research Program of the FreedomCAR and Fuel Partnership: First Report*, (Washington, DC: National Academies Press, 2005).

[13] National Research Council of the National Academies; Committee on Review of the FreedomCAR and Fuel Research Program, Phase 2; Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences, Transportation Research Board; Review of the Research Program of the FreedomCAR and Fuel Partnership: Second Report, (Washington, DC: National Academies Press, 2008).

[14] The full report is available from: http://www.nap.edu/catalog.php?record_id=12939.

[15] The full report is available from: http://books.nap.edu/catalog.php?record_id=12826.

cells provide in those specific applications, but it will complement the Program's longer-term R&D efforts by helping to increase current sales and manufacturing volumes, providing essential cost reductions–through economies of scale–for many of the same technologies that will be used in longer-term applications. Supporting earlier markets can also reduce many non-technological barriers to the deployment of hydrogen and fuel cell technologies and lay the groundwork for the larger infrastructure and supply base that will be needed for fuel cell vehicles. The Program released its draft strategic plan in October 2010 (www.eere.energy.gov/hydrogenandfuelcells/pdfs/program_plan2010.pdf); the final version will be released in FY 2011.

We are pleased to present the U.S. Department of Energy's *2010 Hydrogen Program Annual Progress Report*. The report is divided into chapters and is organized by technology area (e.g., fuel cells, hydrogen storage, etc.). Each chapter opens with an overview written by a DOE technology development manager that summarizes the progress and accomplishments of the previous fiscal year. The projects outlined in this document represent the work of the many innovative scientists and engineers supported by DOE. They are the ones responsible for the progress and technical accomplishments reported this year's *Annual Progress Report*. We would like to recognize them for their hard work, commitment, and continued progress.

Sunita Satyapal
Program Manager
Hydrogen Program
Fuel Cell Technologies Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy