

## I.0 Introduction

The DOE Hydrogen Program (the Program) has conducted comprehensive and focused efforts to enable the widespread commercialization of fuel cells 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 barriers facing the development and deployment of 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 the DOE Offices of Nuclear Energy, Fossil Energy, and Science.

In Fiscal Year 2009, Congress appropriated \$269 million for the DOE Hydrogen Program. The Program is organized into distinct sub-programs focusing on specific areas of research and development (R&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, the Office of Fossil Energy, and the Office of Nuclear Energy; 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](http://www.hydrogen.energy.gov/program_plans.html).

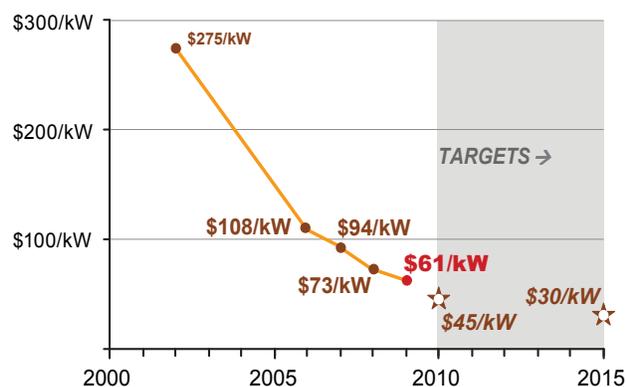
In the past year, the Program made substantial progress toward its goals and objectives. Highlights of the Program's accomplishments are summarized in the following.

### PROGRAM PROGRESS AND ACCOMPLISHMENTS

#### Fuel Cells

The Fuel Cell Sub-Program has made significant advances in reducing the high-volume cost of fuel cell systems; improving membrane performance under hot, dry operating conditions; and characterizing fuel cell materials and components. In FY 2009, an independent review panel validated the Program's assessment that the high-volume cost of fuel cells was reduced by 23%, from \$94/kW in 2007 to \$73/kW in 2008. Moreover, the panel approved of DOE's cost analysis methodology and concluded that a range of \$60/kW to \$80/kW is a "valid estimation of the potential manufactured cost for an 80-kW<sub>net</sub> fuel cell system, based on 2008 technology."<sup>1</sup> Based on further progress during the past year, primarily by reducing platinum (Pt) loading and improving power density, the FY 2009 cost assessment showed that the high-volume fuel cell system cost is \$61/kW, as indicated in Figure 1.

High catalyst cost associated with the use of Pt and other platinum group metals (PGMs) limit potential cost reductions. As a result, strong focus is given to reducing the loading of these metals in the stack, while maintaining performance. One example of progress is the development of innovative



**FIGURE 1.** DOE-funded R&D has resulted in significant cost reductions of fuel cells, achieving \$61/kW as the projected high-volume cost of an 80 kW<sub>net</sub> automotive fuel cell system based on state-of-the-art technology in FY 2009.

<sup>1</sup> *Fuel Cell System Cost for Transportation—2008 Cost Estimate*, National Renewable Energy Laboratory, May 2009, <http://hydrogen.doedev.nrel.gov/pdfs/45457.pdf>.

PGM-based nanostructured catalysts by Brookhaven National Laboratory, achieving low Pt-loading and high activity. The performance of these catalysts compares favorably with that of the baseline Pt/C catalyst (Figure 2). In FY 2009, Los Alamos National Laboratory (LANL) developed two paths toward high-performance fuel cell cathodes that use no Pt or PGMs. Results showed a five-fold and an eleven-fold improvement over the best performing non-noble catalyst of the past year. In 2009, 3M continued to play a significant role in fuel cell system cost reduction, demonstrating a new baseline membrane electrode assembly (MEA) with a 40% decrease in loading from 2008. The 3M MEA exceeded—by more than 30%—DOE's lifetime targets for minimal surface area and performance loss under open-circuit voltage hold tests.

Major progress was also made this year in the development of high-temperature membranes capable of operating at low relative humidity (RH). Giner Electrochemical Systems demonstrated a perfluorosulfonic acid (PFSA) membrane with conductivity at least 2.5 times that of Nafion<sup>®</sup> under hot, relatively dry conditions, exceeding the DOE 2009 conductivity milestone of 0.1 S/cm at 120°C and 50% RH.

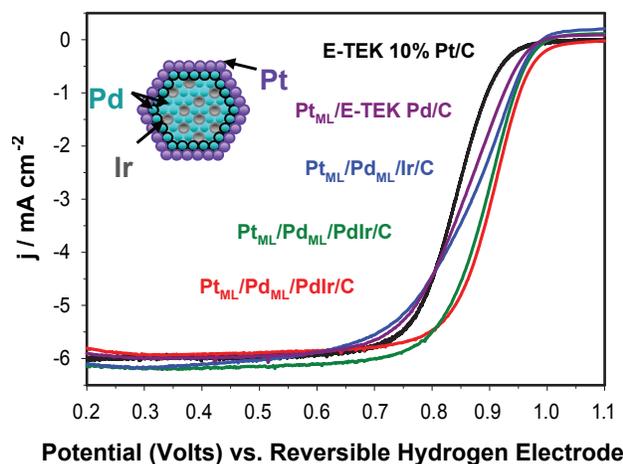
LANL researchers examined the effects of impurities on fuel cell performance and durability, finding that sub-ppm levels of H<sub>2</sub>S in hydrogen fuel caused significant performance loss, with degradation occurring due to catalyst poisoning in both the anode and the cathode. The ability of a contaminant in the anode inlet to cause degradation of the cathode demonstrates the important role of contaminant crossover in performance degradation.

In FY 2009, the Fuel Cell Sub-Program expanded its focus—which had been primarily on longer-term transportation applications—to include more nearer-term applications of fuel cells including distributed power (primary and backup), portable power, auxiliary power units, material handling equipment, and specialty vehicles. Fuel cell technology already provides sufficient performance and durability to be competitive with alternative technologies in some of these applications, while in others, some improvements are still required.

## Hydrogen Storage

In FY 2009, the Storage Sub-Program continued to make progress in all three classes of materials under investigation—hydrogen sorbents, reversible metal hydrides, and chemical hydrogen storage. These achievements involved improvements in operational properties, not just in storage capacity.

An initial down-select process by the Chemical Hydrogen Storage Center of Excellence (CoE) examined about 120 materials and combinations of materials, resulting in approximately 85% being discontinued, allowing resources to be focused on improving the kinetics and capacities for hydrogen release through the use of catalysts and other additives. A detailed cost estimate for the regeneration of one of the key materials studied, ammonia borane (AB), indicated a cost of \$7–8/kg H<sub>2</sub> for large-scale production. Costs were found to be driven by capital equipment recovery costs and the cost of utilities. Development of an approach using hydrazine to form the BH<sub>3</sub>-containing species may regenerate decomposed AB in just one or two steps, reaching thermodynamic efficiencies of 83%.



**FIGURE 2.** The Program is developing innovative nanostructured catalysts as a means of improving fuel cell performance while reducing cost. Pd-interlayer core/shell nanoparticles developed at Brookhaven National Laboratory have electrocatalytic activity superior to that of conventional Pt/C catalysts, but use less than 1/3 of the platinum.<sup>2</sup>

<sup>2</sup>P. Zelenay, "Advanced Cathode Catalysts," *2009 Annual Merit Review Proceedings*, DOE Hydrogen Program, 2009, [www.hydrogen.energy.gov/pdfs/review09/fc\\_21\\_zelenay.pdf](http://www.hydrogen.energy.gov/pdfs/review09/fc_21_zelenay.pdf).

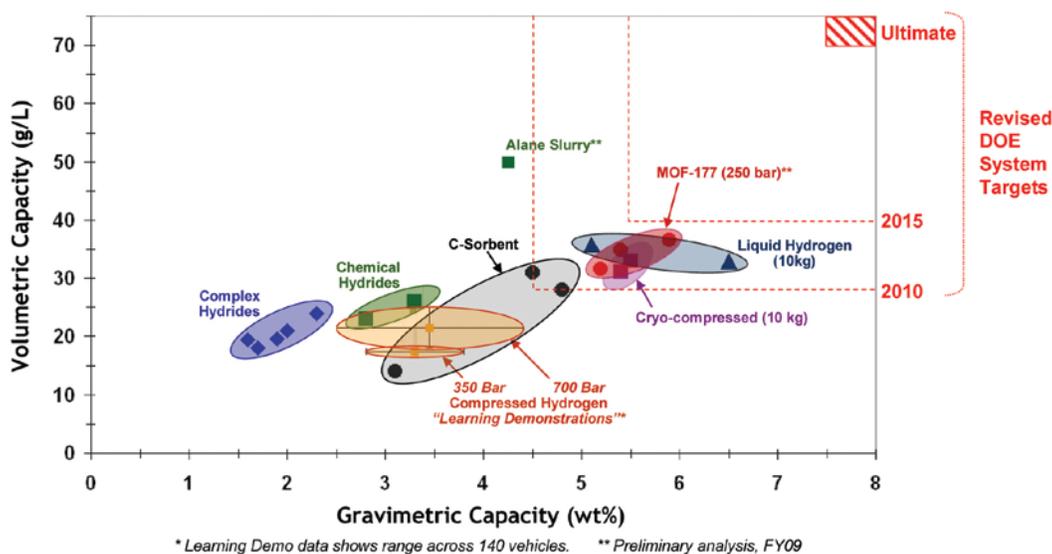
Progress continued on increasing the hydrogen release rates from several ionic liquid/AB mixtures at temperatures below 120°C along with a total release that exceeded 10 wt%.

The Metal Hydride CoE continued a materials down-select process, with down-select decisions based on material reversible capacity, sorption thermodynamics, and kinetics. One achievement in this area was the electrochemical synthesis of high yields of pure alane ( $\text{AlH}_3$ ) that avoids expensive thermodynamic routes for its reversible regeneration, making the hydride a more viable storage candidate. The University of Hawaii, along with HRL Laboratories, developed a low-temperature homogenous organometallic approach to incorporate about five times higher amounts of  $\text{MgH}_2$  into carbon aerogels than was achieved via molten Mg metal. Additionally, in FY 2009 the aluminoborane compound,  $\text{AlB}_4\text{H}_{11}$ , was found to start releasing hydrogen at 125°C and desorb 10.5 wt%  $\text{H}_2$  by heating to 325°C, suggesting that this material and related species may be good candidates for on-board hydrogen storage.

The Hydrogen Sorption CoE completed a down-select process that resulted in one third of the materials being continued. Research efforts from Rice University, Air Products, and the National Renewable Energy Laboratory were devoted to gaining a better understanding of the mechanisms for the hydrogen spillover effects of metal particles on sorbent surfaces to improve both kinetics and storage capacity. Caltech explored layered carbon structures as a means to increase the hydrogen sorption enthalpy and demonstrated an increase from the nominal range of 4–6 kJ/mole to 8.5–13 kJ/mole, thus retaining 50% of the liquid nitrogen temperature capacity at 195 K.

In addition to the advancements made by the CoEs, the Storage Sub-Program furthered technology in the areas of compressed and cryogenic tanks and materials properties and testing. Composite tank systems with 350-bar and 700-bar compressed gas storage were analyzed, and the tank designs were revised accordingly. Lawrence Livermore National Laboratory designed and fabricated a cryogenic vessel for cryo-compressed hydrogen storage with promising cost results compared to conventional liquid hydrogen. As part of an international cooperative program, research groups in Canada, Germany, and Japan (along with U.S. partners) are assessing the chemical reactivity and safety aspects of representative hydrogen storage materials. The U.S. partners' activities in this cooperative effort included Savannah River National Laboratory developing models assessing potential release scenarios, Sandia National Laboratories investigating risk mitigation strategies, and United Technologies Research Center (UTRC) performing failure mode effects analysis.

In FY 2009, working in conjunction with the Hydrogen Storage Technical Team, the Storage Sub-Program released revised performance targets for on-board storage systems, consistent with the



**FIGURE 3.** In FY 2009, storage targets were revised and the three Storage Centers of Excellence continued to make progress in the down-selection of materials.

multi-year plans developed in 2003 which called for a reassessment of targets as more real-world data became available (Figure 3). When revising the targets, two key assumptions were maintained: targets are to be based on the application requirements, not the projected capabilities of storage technologies; and targets must allow for sufficient fuel storage for a driving range greater than 300 miles, without compromising passenger/cargo space or vehicle performance for the majority of light-duty vehicles. A key new assumption was that there would be differences in vehicle architecture between fuel cell and gasoline internal combustion engine (ICE) vehicles. In addition, real-world fuel cell vehicle fleet data were considered when establishing assumptions for fuel requirements, fuel economy, and weight and volume constraints; instead of the expected improvements over gasoline ICE vehicles that had been assumed earlier. Revised cost targets will be released in the future. The complete revised hydrogen storage performance targets can be found at: [www1.eere.energy.gov/hydrogenandfuelcells/storage/pdfs/targets\\_onboard\\_hydro\\_storage.pdf](http://www1.eere.energy.gov/hydrogenandfuelcells/storage/pdfs/targets_onboard_hydro_storage.pdf).

## Hydrogen Production

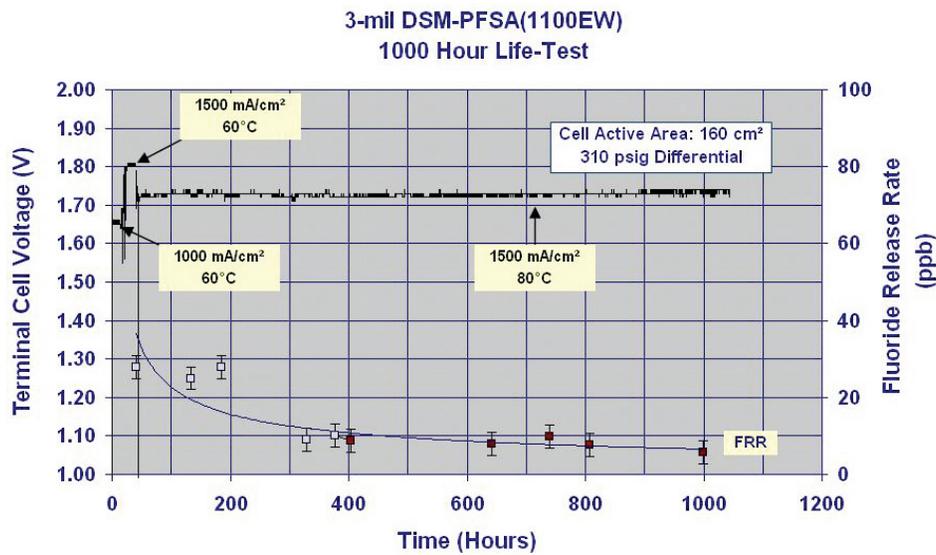
**Renewable-Based Hydrogen.** Advances in biofuel-reforming technology continued to reduce the cost of bio-derived hydrogen. Pacific Northwest National Laboratory demonstrated a significant increase in hydrogen yields by optimizing catalyst formulations and reaction conditions for vapor phase reforming at low pressure. Researchers at UTRC announced greater than 95% conversion of cellulosic biomass with 74% hydrogen selectivity. These high-yield processes bring hydrogen from biomass and bio-derived liquids closer to the 2014 cost targets of \$3.30/gasoline gallon equivalent (gge) and \$3.80/gge, respectively.

Technoeconomic analyses were performed on solar hydrogen production pathways. One study that was completed focused on several high-temperature thermochemical cycles, which resulted in the down-selection of the ZnO cycle and the identification of critical tasks for the remaining cycles, allowing resources to be applied effectively. In another study, Directed Technologies, Inc. (DTI) examined the photoelectrochemical direct water splitting pathway. With costs ranging from \$4 to \$10/gge for this approach, the analysis identified several viable pathways to meet the production cost targets. DTI also completed a separate boundary level technoeconomic analysis for hydrogen production costs from four different biological processes, again finding several production pathways that can meet long-term hydrogen production cost targets.

Significant increases were achieved in the productivity of photosynthetic organisms (microalgae and plants), with direct benefits for employing photosynthesis for hydrogen, biodiesel, or biomass production. Researchers at the University of California, Berkeley, achieved 15% solar energy conversion efficiency in a photosynthetic organism, a substantial improvement over the 3% efficiency measured in naturally existing organisms. This effort entails application of biotechnology approaches to reduce the size of (or “truncate”) light-harvesting chlorophyll antennae. Truncated chlorophyll antennae reduce shading of cells deeper in the mass culture, resulting in greater sunlight utilization efficiency and improved photosynthetic productivity. Genes identified in this work can be applied to other photosynthetic organisms and can benefit the production of biofuels in addition to hydrogen.

Another pathway for renewable-based hydrogen is electrolysis using power from renewable energy sources. Giner Electrochemical Systems demonstrated 1,000-hour single-cell membrane activity, and from this research, they projected an electrolyzer membrane lifetime of 45,000 to 55,000 hours (Figure 4). Researchers at Giner are also testing a new biphenyl sulfone membrane that is less than half the cost of their current membranes. Under nominal operating conditions, these membranes show 75% efficiency (lower heating value) for a single cell. Long-term durability tests are planned.

**Hydrogen from Coal.** Progress was made toward 2010 hydrogen separation targets, with Eltron Research, Inc. and Southwest Research Institute® demonstrating membranes in bench-scale tests, that have the ability to meet all of the Office of Fossil Energy’s targets. The Eltron membrane cost estimates would make it competitive with conventional technology. Southwest Research Institute® has produced a self-supported Pd-Cu alloy membrane with a thickness (5 microns) that is 1/5 of the 2007 state-of-the-art. This demonstrated progress was echoed by preliminary economic analysis that shows membranes have the potential for lower electricity cost, higher thermal efficiency, and improved CO<sub>2</sub> capture compared to conventional technologies.



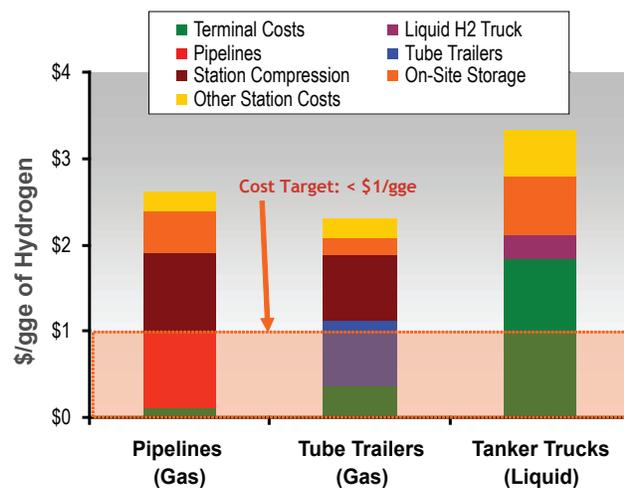
**FIGURE 4.** Giner Electrochemical Systems PFSA membrane demonstrating 1,000-hour single membrane activity.

**Nuclear Hydrogen.** In FY 2009 Idaho National Laboratory operated their integrated laboratory-scale high temperature electrolysis unit for 45 days. This demonstration achieved a peak output of 5,650 liters per hour at 12-kWe input. Savannah River National Laboratory (SRNL) developed new operating methods that demonstrated electrolyzer operation without limitations caused by sulfur build-up.

**Hydrogen Delivery**

Researchers continued to make major advances in modeling hydrogen delivery infrastructure through the Hydrogen Delivery Scenario Analysis Model (HDSAM), finding only a 15% increase in the gaseous hydrogen fueling costs of a high pressure cascade system at 700 bar versus 350 bar. Cryo-compressed fueling was also added to the model, and analysis using HDSAM showed that hydrogen station costs for cryo-compressed fueling, using a cryopump, were 70% lower than station costs for fueling 700-bar vehicles using booster compressors. A version of the Hydrogen Rail Components Model was developed as an add-on to HDSAM, with preliminary analysis suggesting rail delivery as a viable low-cost option for long-distance transport.

Researchers were also successful in making progress in a variety of delivery technologies, including fiber reinforced polymer (FRP) pipelines and gaseous tube trailers. SRNL concluded a testing regimen on FRP pipelines and found positive results for hydrogen compatibility and blow-down testing. Leakage rate tests measured a rate of 0.02%, exceeding the DOE 2017 target of less than 0.5%. Advances in tube-trailer technologies included the successful testing of manufacturing procedures for 600-kg hydrogen tanks and innovative tube-trailer designs using high-strength, low-cost glass fiber, with triple the capacity of conventional tube-trailers.



**FIGURE 5.** These modeled high-volume costs of hydrogen delivery assume current technology, with a potential 2030 market penetration of 25% and hydrogen delivered 62 miles from a production plant to Los Angeles.

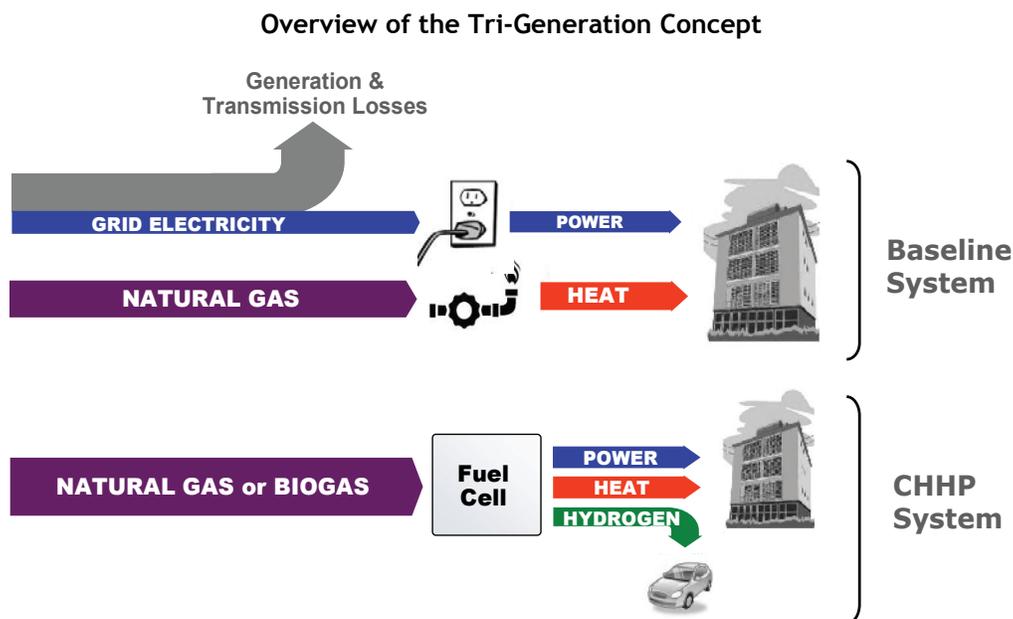
In FY 2009, continued progress was made in the areas of compression and liquefaction, essential technologies for reducing hydrogen delivery costs. Significant cost savings for early markets could be attained through the use of mass-produced compressor components. Researchers at Concepts NREC are developing a centrifugal compressor for hydrogen made from off-the-shelf components designed for natural gas service. In liquefaction, Prometheus Energy is working on an innovation called the Active Magnetic Regenerative Liquefier, which utilizes magnetic cooling, and could reduce energy consumption by 50% and reduce the liquefaction capital costs by 30%. Prototype development began in 2009.

### Systems Analysis

The Systems Analysis Sub-Program continued to focus on the development of core models for hydrogen analysis and on conducting resource, infrastructure, well-to-wheels (WTW), and hydrogen quality analysis for different hydrogen production and delivery pathways. Significant progress was made in FY 2009 in the areas of early market analysis, the development and updating of analysis models, and analysis of the environmental impacts of hydrogen.

For example, Oak Ridge National Laboratory performed a sensitivity analysis to examine the potential effects on fuel cell vehicle market penetration of not meeting the Program's on-board hydrogen storage targets. The analysis showed a reduction from 95% to 50% vehicle penetration rates by 2050 if storage costs were \$17/kWh versus the storage target of \$2/kWh. Another important cost factor is hydrogen quality. Argonne National Laboratory developed a model to analyze the impact of hydrogen quality on fuel cell performance and the hydrogen production costs associated with meeting the required hydrogen quality specifications—the results showed a cost increase of less than \$0.05/gge.

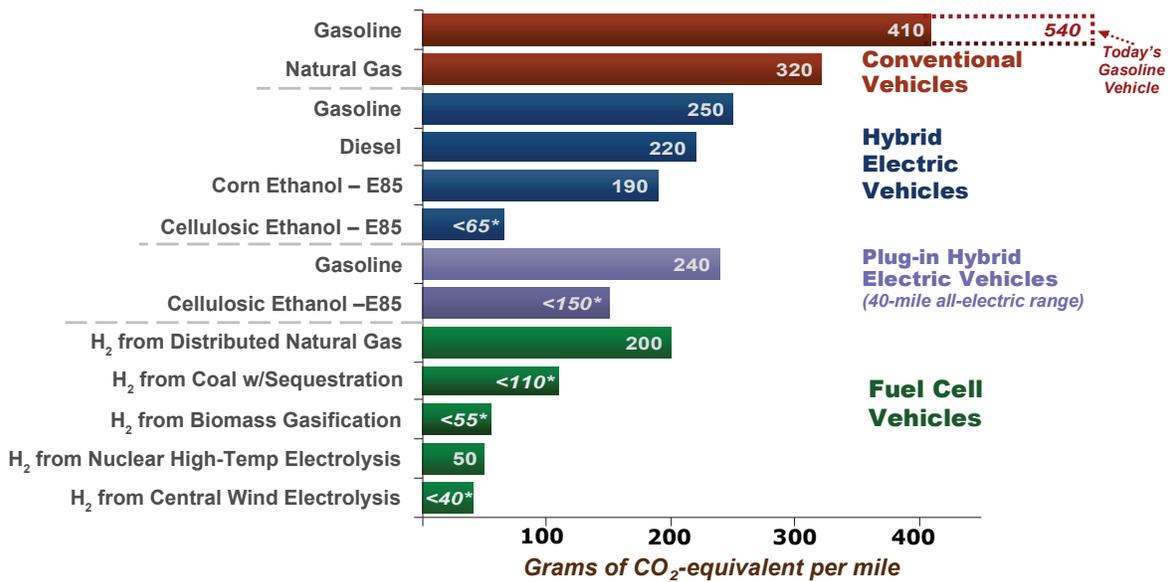
Industry, academia, and national laboratories peer-reviewed the H2A Stationary Power Model, which addresses combined heat and power generation for proton exchange membrane, phosphoric acid, and molten carbonate fuel cells. Features of the model include analysis of power, heat, and hydrogen fuel costs based on capital equipment costs, feedstock prices, operating climate conditions, as well as heat and power loads.



**FIGURE 6.** Tri-generation of electricity, heat, and hydrogen (also called CHHP – combined heat, hydrogen and power) can achieve market penetration in areas of high electric prices, moderate natural gas prices and emerging demand for hydrogen for transportation fuel.

### Well-to-Wheels Greenhouse Gas Emissions

(life cycle emissions, based on a projected state of the technologies in 2020)



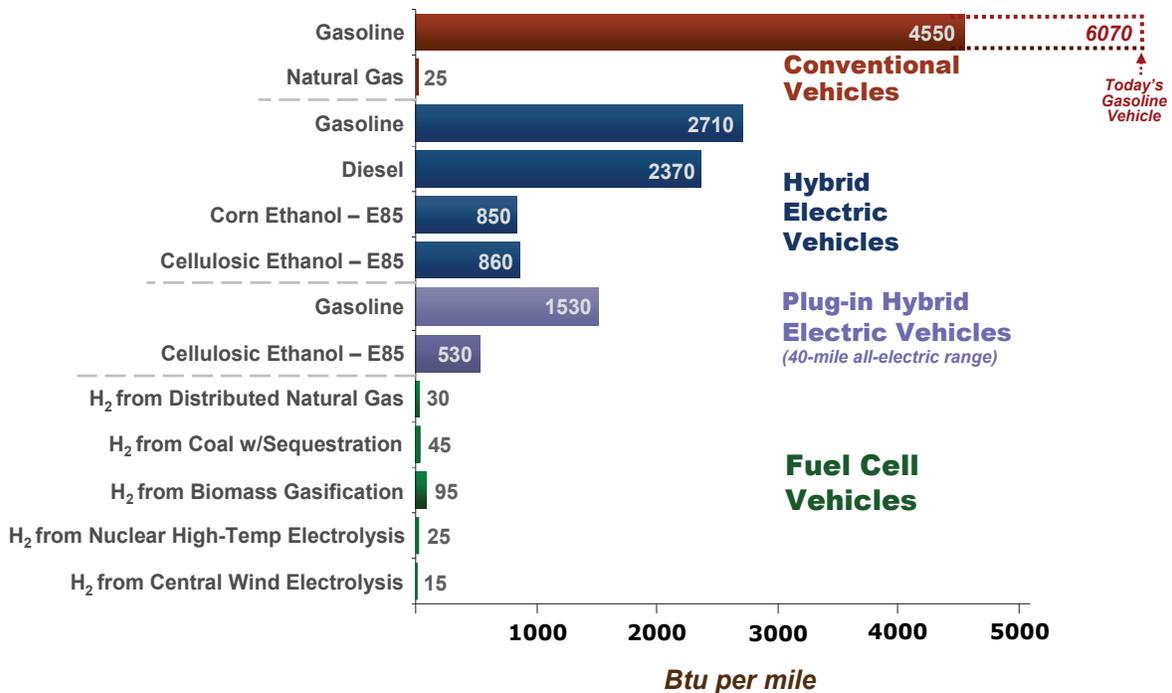
\*Net emissions from these pathways will be lower if these figures are adjusted to include:

- The displacement of emissions from grid power-generation that *will* occur when surplus electricity is co-produced with cellulosic ethanol
- The displacement of emissions from grid power-generation that *may* occur if electricity is co-produced with hydrogen in the biomass and coal pathways, and if surplus wind power is generated in the wind-to-hydrogen pathway
- Carbon dioxide sequestration in the biomass-to-hydrogen process

FIGURE 7. (above) and FIGURE 8 (below): WTW analysis shows the potential for reductions in greenhouse gas emissions and petroleum consumption through the use of a number of technologies DOE is developing, including fuel cell vehicles using hydrogen from several production pathways. These results are documented in Program Record #9002, [www.hydrogen.energy.gov/program\\_records.html](http://www.hydrogen.energy.gov/program_records.html).

### Well-to-Wheels Petroleum Energy Use

(based on a projected state of the technologies in 2020)



The Macro-System Model (MSM) links existing and emerging models to simulate the performance and evolution of hydrogen infrastructure. In FY 2009, the MSM was used in analysis to support decision-making and was updated to include HyDRA, the resources model; HyPro, the infrastructure model; and HDSAM, the updated delivery model. One of the existing models, GREET, used for WTW analysis, was modified to include conventional and alternative-fuel plug-in hybrid electric vehicles, through coordination across programs within DOE. These enhanced analysis capabilities increase the ability to accurately assess the entire portfolio of vehicles and ensure consistent, transparent and most up-to-date assumptions across technologies. Similarly, greenhouse gas emissions using various electrical sources such as the U.S. grid or the California grid can be compared using the WTW analysis.

### Manufacturing R&D

The key goals of Manufacturing R&D are to reduce the cost of producing fuel cell systems and hydrogen technologies and to enable increases in manufacturing rates and capacities. A number of advances were achieved in FY 2009: UltraCell created a specification for leak-testing and analyzed fuel cell stack manufacturing methods; Ballard down-selected a tool to measure the weight of gas diffusion layer coatings, demonstrating a means of achieving six-sigma quality standards; and researchers at Rensselaer Polytechnic Institute (RPI) demonstrated a reduction in cycle time for joining electrodes to sub-gaskets, from one minute with thermal bonding to one second with ultrasonic welding (Figure 9).

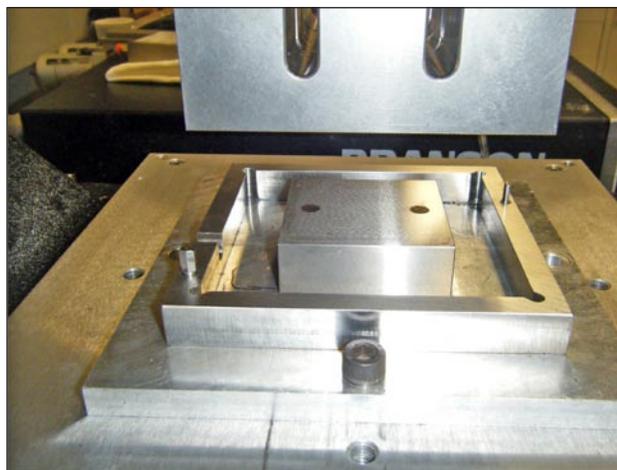


FIGURE 9. RPI's work on ultrasonic welding for MEA pressing.

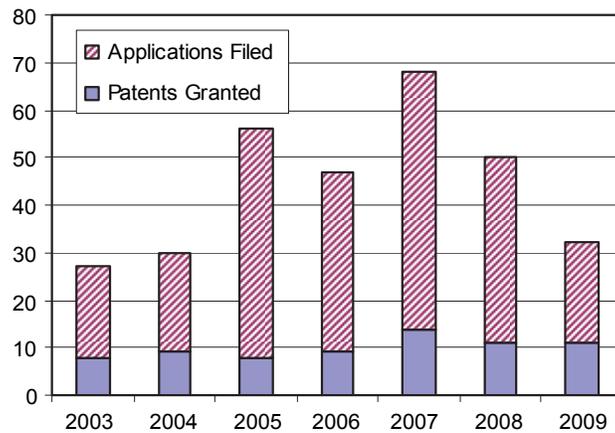
### Basic Research

In FY 2009, the Office of Science, Basic Energy Sciences (BES) continued to make progress in basic research for hydrogen and fuel cell technologies, with projects continuing in hydrogen storage, nanoscale catalysts, membranes, hydrogen production, and bio-inspired hydrogen research. Researchers funded by BES have learned how to tune hydrogen binding to metal-organic framework materials with exposed transition metal sites by influencing their magnetic spin state, utilized their understanding of crystal growth to tailor the synthesis of highly efficient crystals for photo generation of hydrogen, and created a bio-hybrid catalyst for hydrogen production using self-assembled carbon nanotubes linked to [FeFe] hydrogenase. At the FY 2009 Annual Merit Review and Peer Evaluation Meeting, researchers funded by the Office of Basic Energy Sciences on the topic of hydrogen storage presented their work through 14 oral and 11 poster presentations to help further coordination between the applied and basic research communities. The Office of Science also announced 46 Energy Frontier Research Centers (EFRCs) with a planned commitment of \$777 million over five years. Some of the EFRC efforts are relevant to the mission of the Hydrogen Program, and further coordination is planned in FY 2010.

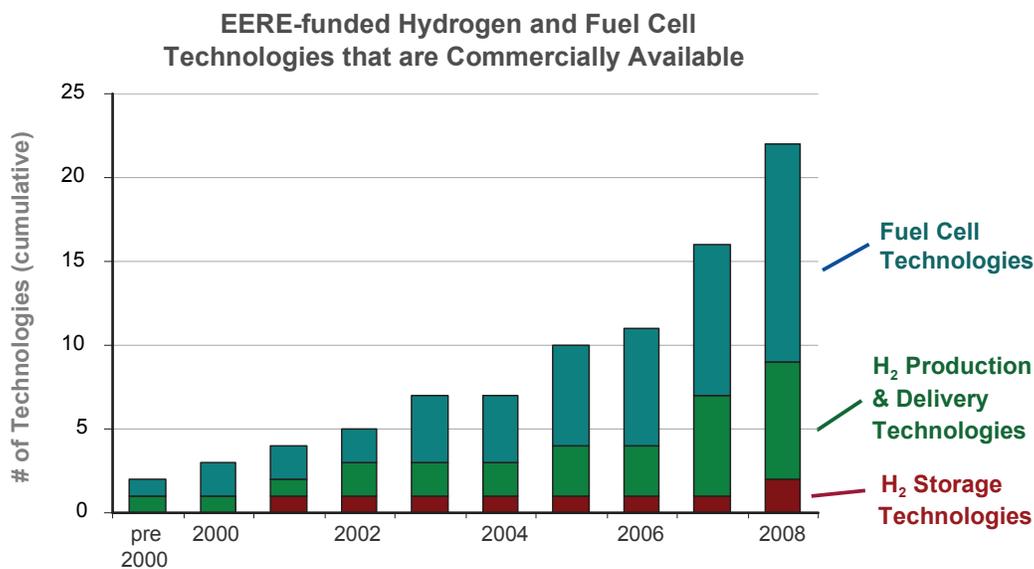
### Tracking the Commercialization of Technologies

One indicator of the robustness and innovative vitality of a research and development program is the number of patents applied for and granted. Each year, the DOE Hydrogen Program tracks the number of patents that are filed by or awarded to projects it sponsors. In FY 2009, 11 new patents were issued for discoveries or technologies developed in DOE Hydrogen Program projects; 21 more applications were filed or are in the process of being awarded, based on information provided by researchers in their Annual Progress Reports (Figure 10). In addition, the Program commissioned a

study of EERE-funded projects over the last several years to determine the number of patents as well as commercial and near-commercial technologies resulting from EERE funding (see Figure 11).



**FIGURE 10.** Patents granted to and applications filed by projects funded by the DOE Hydrogen Program.



**FIGURE 11.** DOE is tracking the commercial success of hydrogen and fuel cell technologies developed by EERE-funded projects. Complete results will be documented in a report by Pacific Northwest National Laboratory, *Pathways to Commercial Success: Technologies and Products Supported by the Hydrogen, Fuel Cells and Infrastructure Technologies Program*.

## NEW PROJECTS SELECTED AND NEW SOLICITATIONS ISSUED

In FY 2009, the DOE Hydrogen Program competitively selected new projects to address key barriers in the development of hydrogen and fuel cell technologies. These included:

- Twenty-eight projects (approximately \$113M; \$129M with cost share over five years) in fuel cell technologies to develop novel catalysts, explore innovative concepts in materials and components, identify degradation mechanisms and mitigation strategies, understand the effects of water transport, and improve materials and packaging for portable-power fuel cells.

- Twelve projects (\$41.9M over two years; \$114.3M with cost share) to support the deployment of nearly 1,000 fuel cell systems for emergency backup power and material handling applications (e.g., forklifts), as well as the demonstration of fuel cells for residential combined heat and power, auxiliary power units, and portable applications. These projects were funded under the American Recovery and Reinvestment Act of 2009.
- Initiation of the competitively selected Hydrogen Storage Engineering Center of Excellence (\$40M over five years) to provide a coordinated approach to the engineering R&D of on-board storage and refueling systems.

## INTERNATIONAL ACTIVITIES

### International Partnership for the Hydrogen Economy

The United States is a founding member of the International Partnership for the Hydrogen Economy (IPHE), which includes 16 member countries (Australia, Brazil, Canada, China, France, Germany, Iceland, Italy, Japan, New Zealand, Norway, South Korea, Russia, 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 technology research, development, and deployment. IPHE also offers a mechanism for international R&D managers, researchers, and policymakers to openly share program strategies.

Since its inception, the IPHE has endorsed a total of 31 collaborative projects that cover a broad range of topics including hydrogen production, hydrogen storage, fuel cell technology, demonstration of fuel cell technology in light-duty vehicles and buses, and the socio-economic impacts of hydrogen production. In 2008, the IPHE published the “Hydrogen and Fuel Cell Brief for Policymakers” and initiated three new global IPHE projects focusing on Hydrogen Highways, Renewable Hydrogen Production, and an International Youth Competition.

The IPHE’s priorities are follows:

- Accelerating the market penetration and early adoption of hydrogen and fuel cell technologies and supporting infrastructure.
- Encouraging policy and regulatory actions to support widespread deployment.
- Raising the profile of hydrogen with policy-makers and the public.
- Monitoring hydrogen, fuel cell, and complementary technology developments.

For more information, please visit [www.iphe.net](http://www.iphe.net).

### International Energy Agency

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

The IEA AFC currently comprises six tasks: 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 HIA is also in the process of defining a new task on Large Scale Hydrogen Infrastructure and Mass Storage. The participating countries are Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, South Korea, the Netherlands, Norway, Mexico, Sweden, Switzerland, Turkey, the United Kingdom, and the United States. The United States participates in all of the AFC’s tasks except Fuel Cells for Portable Power. The implementing agreement was recently extended from 2008 to 2013. Information about the IEA Advanced Fuel Cells Implementing Agreement is available at [www.ieafuelcell.com](http://www.ieafuelcell.com).

The IEA HIA is focused on RD&D and analysis of hydrogen technologies. It includes nine tasks: Integrated Systems Evaluation & Analysis, 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, Advanced Materials for Hydrogen from Waterphotolysis, and Near-Market Routes to Hydrogen by Co-Utilization of Biomass with Fossil Fuel. 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, the United Kingdom, and the United States.

As part of the Integrated Systems Evaluation task, the IEA HIA completed a number of case studies<sup>3</sup> in hydrogen systems that synthesized lessons learned and technology operating experience. These case studies, including a proposed hydrogen power station with carbon capture in the United Kingdom, the EPACOP project (Expérimentation de 5 Piles A Combustible sur sites OPérationnels) in France to test proton exchange membrane fuel cells under “real world” conditions for residential and commercial applications, and a hydrogen house in Italy, provide the DOE Program insight into progress made by other member countries.

## OTHER PROGRAM ACTIVITIES

### Market Transformation

In FY 2009, the Program increased its focus on a new activity - “market transformation” - to help promote the widespread commercialization of fuel cell power systems. The goals of this effort are to increase opportunities for market expansion, gather valuable data from the operation of fuel cells in integrated systems in real-world conditions, eliminate non-technical barriers such as codes and standards, accelerate user acceptance, help companies bridge the “valley of death” between development and commercialization, and enable agencies to meet energy efficiency goals. The Program actively collaborates with other agencies to facilitate federal deployment of fuel cells in key early markets (including specialty vehicles, material handling equipment, backup/remote power, and prime power for critical applications), as well as integrated renewable hydrogen production projects. Federal agency partnerships are supported by the Hydrogen and Fuel Cell Interagency Working Group and Task Force.

By purchasing fuel cells to meet their energy needs, federal agencies can play a role in reducing technology cost, developing and sustaining a domestic supplier base and in increasing public awareness of the technologies. The Program continues to collaborate with federal agencies to deploy fuel cells at federal sites across the country. The Program initiated projects to install 43 emergency backup power systems at the Federal Aviation Administration and Department of Defense (DOD) sites, and collaborated with the Defense Logistics Agency (DLA) to deploy 40 material handling units. Plans are in place for DLA’s installment of 60 more units at three additional sites across the country. The Program is also planning to deploy up to 75 emergency backup power units in collaboration with the Army Construction Engineering Research Laboratory, the National Park Service, the Ohio National Guard, and several other DOD sites. In addition, the DOE National Laboratories are performing feasibility studies examining the installation of stationary fuel cell systems at their facilities. Studies will be completed at the National Renewable Energy Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, Argonne National Laboratory, Sandia National Laboratories, Thomas Jefferson National Accelerator Facility, and the Y12 National Security Complex.

### American Recovery and Reinvestment Act Projects

The Program initiated new projects in FY 2009 under the American Recovery and Reinvestment Act (Recovery Act). Twelve projects will receive \$41.9 million of Recovery Act funds for the deployment of more than 1,000 fuel cells for emergency backup power and material handling applications (e.g.,

<sup>3</sup> IEA HIA Web site, [www.ieahia.org/page.php?s=d&p=casestudies](http://www.ieahia.org/page.php?s=d&p=casestudies).

forklifts), as well as the demonstration of fuel cells for residential combined heat and power, auxiliary power units, and portable applications.

These deployments will have significant near-term impact, creating jobs in fuel cell manufacturing, installation, maintenance and support service sectors. Industry participants have reinforced their commitment by proposing approximately \$72.4 million in cost-share—bringing total project funding to nearly \$114.3 million.

### Hydrogen Quality

The quality of hydrogen fuel is expected to play a large role in the ultimate performance, durability, and cost of fuel cell systems. Higher quality fuel allows for lower fuel cell system costs, while higher fuel quality requirements correlate to higher lifecycle costs for hydrogen production, purification, distribution, storage, and detection systems. To quantify these relationships and to develop a roadmap to define R&D priorities in this cross-cutting area, DOE established the Hydrogen Quality Working Group, which includes participants from the automotive and energy industries, the national laboratories, and the DOE Hydrogen Program.

The Hydrogen Quality Working Group continues to develop and refine models and tools to analyze the tradeoffs for hydrogen production and fuel cell performance based on various levels of hydrogen quality. The Working Group has developed a model of the pressure-swing adsorption hydrogen purification system and assessed the effect of allowable CO concentrations on hydrogen production costs. While reducing CO concentration in hydrogen fuel is not expected to significantly impact the cost of hydrogen production, the cost of measuring CO concentrations at the proposed low levels of 0.1 ppm can increase the dispensed cost of hydrogen significantly. Work continues to develop this model further and to seek experimental verification of the results.

### Coordination with Vehicle Technologies Program

In FY 2009, three key activities—Technology Validation; Education; and Safety, Codes and Standards—were funded through EERE’s Vehicle Technologies Program and closely coordinated with the Office of Hydrogen, Fuel Cells and Infrastructure Technologies. The Technology Validation activity continued its Learning Demonstration with 140 hydrogen fuel cell vehicles and 20 hydrogen stations. The Program has now demonstrated more than 2.2 million miles of real-world driving and more than 90,000 kg of hydrogen dispensed since its inception. Data shows efficiencies of 53-58%, a driving range of up to 254 miles, and durability of roughly 2,000 hours. The Safety, Codes and Standards activity continued to make progress in facilitating the development of codes and standards and conducting the underlying safety research to ensure the safety of hydrogen and fuel cell technologies. The Education activity continued its efforts in state and local government outreach; education related to early deployment; and university programs. More details on these three activities can be found at: [http://www1.eere.energy.gov/vehiclesandfuels/resources/proceedings/2009\\_merit\\_review.html](http://www1.eere.energy.gov/vehiclesandfuels/resources/proceedings/2009_merit_review.html).

**FIGURE 12.** Recovery Act projects and proposed funding to deploy fuel cells. DOE funding has supported R&D resulting in the success of the fuel cell suppliers involved in all these projects.

Company	Application
Delphi Automotive	Auxiliary Power
FedEx Freight East	Specialty Vehicle
GENCO	Specialty Vehicle
Jadoo Power	Backup Power
MTI MicroFuel Cells	Portable Power
Nuvera Fuel Cells	Specialty Vehicle
Plug Power, Inc. (1)	CHP
Plug Power, Inc. (2)	Backup Power
Polyfuel, Inc./UNF	Portable Power
ReliOn Inc.	Backup Power
Sprint Communications	Backup Power
Sysco of Houston	Specialty Vehicle

CHP - Combined Heat and Power

## EXTERNAL COORDINATION, INPUT, AND ASSESSMENT

### DOE Utilizes Expertise from the Stakeholder Community and Government Partners

**Hydrogen and Fuel Cell Technical Advisory Committee.** The Hydrogen and Fuel Cell Technical Advisory Committee (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 safety, economic, and environmental issues related to hydrogen. 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.

The HTAC met three times between August 2008 and August 2009. As required by the Energy Policy Act of 2005, the Secretary's biennial report to Congress is scheduled for release in 2010, describing HTAC's recommendations, addressing how DOE will implement those recommendations, and providing an explanation for those recommendations that will not be implemented.

**Federal Agency Coordination—the Interagency Task Force and the Interagency Working Group.** The Interagency Task Force (ITF), consisting of senior-level representatives from 15 agencies, plays a critical role in supporting and enhancing the market introduction of new technologies by focusing on federal leadership in early adoption of fuel cell technologies. This year, the ITF convened once to discuss agency demonstration and deployment activities and plans. As a result of the transition to the new administration, new appointees to each participating agency must be identified. The next meeting will be held once the new appointees have been confirmed.

Underpinning the ITF, the staff-level 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. The IWG's public Web site, [www.hydrogen.gov](http://www.hydrogen.gov), serves as a portal to information about all federal hydrogen and fuel cell activities, programs, and news.

**National Academy of Sciences.** The National Research Council (NRC) of the National Academies provides ongoing technical and programmatic advice to the DOE Hydrogen Program. The NRC has conducted independent reviews of both the Program<sup>4</sup> and the research and development activities of the FreedomCAR and Fuel Partnership.<sup>5,6</sup> The NRC's two reviews of the Partnership to date have offered recommendations on the Partnership's technical direction, strategies, funding, and management. In parallel with the second review of the Partnership, the NRC also conducted a study to determine the investments in R&D, demonstrations, government actions, education, and infrastructure that will be required for the development of fuel cell technologies and for the successful transition from petroleum- to hydrogen-fueled vehicles in a significant percentage of the U.S. vehicle market by 2020, along with potential reductions in oil use and CO<sub>2</sub> emissions.<sup>7</sup> While the study also investigated the impact of alternative measures such as improved fuel economy, increased penetrations of hybrid vehicles and the use of biomass-derived fuels, plug-in hybrid vehicles were originally not taken into consideration.

<sup>4</sup> 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).

<sup>5</sup> 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, D.C.: National Academies Press, 2005).

<sup>6</sup> 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, D.C.: National Academies Press, 2008).

<sup>7</sup> National Research Council of the National Academies; Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies; Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences; *Transitions to Alternative Transportation Technologies: A Focus on Hydrogen*, (Washington, D.C.: National Academies Press, 2008).

The NRC has initiated a follow-on study to investigate the potential impact of plug-ins, to be released in late 2009. As part of these efforts, the NRC has met with battery developers, original equipment manufacturers, utilities and analysts to gather information on the technology.

DOE has addressed the recommendations from all of the NRC's reviews and incorporated many of them into the Program and Partnership activities. Currently, the NRC is conducting the Phase III review of the Partnership, to review technical goals, evaluate progress, and examine research activities.

**FY 2009 Annual Merit Review and Peer Evaluation.** In addition to soliciting feedback from these expert and stakeholder groups, the DOE Hydrogen Program holds an Annual Merit Review, which provides an opportunity for the Program to obtain an expert peer review of the projects it supports and to report its accomplishments and progress. In 2009, DOE held this review from May 18–22, 2009, in Arlington, Virginia, for the first time in conjunction with the annual review of DOE's Vehicle Technologies Program. Over 1,500 people attended the review, and 256 projects were presented, of which 216 were peer-reviewed.<sup>8</sup> The Review also provides a forum for promoting collaborations, the exchange of ideas, and technology transfer. Reviewers evaluate the Program's projects and make recommendations to the principal investigators and to the Program. DOE uses these evaluations to make project funding decisions for the upcoming fiscal year. This year, there were 189 contributing reviewers—the report compiling their comments is available at [www.hydrogen.energy.gov/annual\\_review.html](http://www.hydrogen.energy.gov/annual_review.html). The next review will be held June 7–11, 2010, in Washington, D.C.

## IN CLOSING...

We are pleased to present the U.S. Department of Energy's *FY 2009 Hydrogen Program Annual Progress Report*. The report is divided into chapters and 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 this fiscal year. The 256 projects outlined in this document represent the work of the many innovative scientists and engineers supported by the Hydrogen Program. It is they who are responsible for the progress reported herein and the technical accomplishments outlined above. We thank them for their hard work, commitment and continued progress.



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<sup>8</sup> Not all of the projects presented were reviewed, because projects from the DOE Office of Science are reviewed through a process managed by the Office of Science that involves different evaluation criteria and projects that have ended are not reviewed.