2011 ANNUAL REPORT of The Hydrogen and Fuel Cell Technical Advisory Committee

Hydrogen and Fuel Cell Technical Development and Commercialization Activity

Hydrogen and fuel cells (HFC) offer significant economic, environmental, and energy-security benefits in industrial, residential, transportation, and utility applications. Fuel cells are energy efficient, clean, and fuel flexible and have the potential to replace the internal combustion engine in vehicles and to provide power in stationary and portable power applications. The Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) prepared this Annual Report to summarize notable advances in global HFC research, development, and demonstration (RD&D) efforts in 2011 and to identify key challenges to more widespread adoption of these technologies as part of an integrated strategy to meet the United States' long-term energy goals.


A hydrogen fuel cell forklift

Technical Advances

Significant progress in a variety of HFC technologies was made in 2011. Over the past year, fuel cell markets for stationary generation, backup power, and material-handling applications continued to expand as the operational effectiveness and efficiency of HFC technologies increased, adding more value for customers. Automotive applications progressed as RD&D programs lowered the cost of fuel cells and validated performance and durability in real-world applications. Global automakers continue to work toward a 2015 timeframe for introducing fuel cell electric passenger vehicles into the commercial market.

There have also been advances in the production, delivery, and storage potential of hydrogen. For example, the delivered cost of hydrogen was further decreased, with hydrogen from steam reforming of methane (SMR) now in the price-range of gasoline on a per mile basis. HTAC has launched a study of the potentially significant role that hydrogen could play in enabling increased use of renewable energy sources.

Remaining Challenges

U.S. public investment in HFC RD&D, including American Recovery and Reinvestment Act (ARRA) funding, has contributed substantially to the commercial readiness of HFC technologies, but further investments are needed to address the remaining challenges to allow more widespread adoption.

Some HFC technologies must continue to improve performance and reduce cost to be competitive with the capabilities and cost of incumbent technologies. The cost of safe, lightweight, low-volume hydrogen storage systems must come down, although automakers are preparing to incorporate current high-pressure tanks in their 2015 vehicle introductions. The cost to produce and deliver clean hydrogen to end users must be further reduced and include construction of hydrogen fueling stations for consumer use. Finally, there is a need to improve emission-free methods of hydrogen production.

> It is important to note that the use of hydrogen is not new. Hydrogen, in vast quantities, has been used safely for decades in petroleum refining, chemical and metallurgical applications, the food industry, and the space program. The U.S. currently produces and safely uses more than 9 million tons of hydrogen each year. Hydrogen has become part of our nation's long-term energy strategy because in addition to its traditional uses, it can also be used as a transportation fuel and to provide electricity and heat to buildings.

Non-technical barriers to broader adoption must also be addressed, such as the public's unfamiliarity with HFC systems and a prevailing misconception that hydrogen is unsafe and unreliable. Furthermore, current regulations and standards do not always reflect real-world use of HFC technologies and need to be standardized, not only in the United States but worldwide. This is particularly important as global competition for clean energy technologies intensifies and the United States risks losing its competitive edge.

Meeting Goals

During the course of the year, HTAC reviewed the progress being made by the U.S. Departments of Energy's (DOE's) Hydrogen and Fuel Cells Program and other industrial- and government-sponsored HFC RD&D activities both in the United States and overseas. Progress toward the cost-competitive goals for hydrogen and fuel cells has continued with some goals already met and some close to being met. Table 1 summarizes the goals, the status in 2006, and the current status. It is clear from this table that, while the goals set by DOE and industry are indeed challenging, the current state of the art has moved to a point where, with growing production volume, the aggressive targets are close to being achieved.

Table 1. Summary of DOE/Industry Fuel Cell and Hydrogen Production and Storage Goals

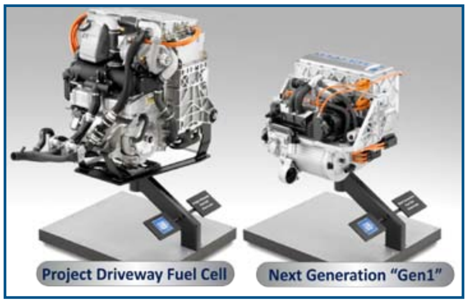
Issue	Goal	2005/2006 Status	Current Status
Automotive fuel cells			
Cost[1]	\$30/kW	\$108/kW (at 500,000 units/year)[2] (\$144/kW at 30,000 units/year)[3]	\$49/kW (at 500,000 units/year)[2] (\$82/kW at 30,000 units/year)[4]
Durability	5,000 hours (150,000 miles)	950 hours (28,500 miles)[5] 2,000 hours (lab)[6]	2,500 hours (75,000 miles)[7] 3,700 hours (lab)[8]
Hydrogen production (dispensed, untaxed)			
Cost[1]	\$2–\$4/gge[9]	\$4–\$10/gge distributed \$5–\$12/gge centralized[10]	\$3–\$8/gge distributed \$4–\$9/gge central[11] \$9–\$11/gge (first adopters)[12]
Hydrogen storage (on vehicle) [13]			
High pressure tanks[14]	2.3 kWh/L 2.5 kWh/kg	350 bar: 0.6 kWh/L 2.0 kWh/kg	700 bar: 0.8 kWh/L 1.7 kWh/kg
Materials-based systems	2.3 kWh/L 2.5 kWh/kg	0.7–1.0 kWh/L[15] 0.5–1.1 kWh/kg	1.6–2.2 kWh/L 1.2–1.6 kWh/kg[16]
Driving range	> 300 mile range[17]	125 miles/fill[18]	250[19]–430[20] miles/fill
Stationary power (100 kW–3 MW)			
Cost[21]	\$1,000/kW (natural gas) \$1,500/kW (biogas)	\$6,000/kW (natural gas)[22]	\$3,500/kW(natural gas) \$5,500/kW(biogas)[23]
Durability	80,000 hours	20,000–60,000 hours[24–25]	40,000–80,000 hours[26]

Technical Progress and Demonstration Activities

Major technical progress is being made in the hydrogen/fuel cell arena through partnerships among industry, academia, national laboratories, and federal and international agencies. This progress has moved the technologies much closer to the performance goals in Table 1. Deployments of buses and personal vehicles, both in the United States and internationally, is growing and shows impressive performance to date. Hydrogen delivery infrastructure is rather straightforward for fleet applications, but its growth is key to increased personal vehicle use. The following examples are validating the use of hydrogen and fuel cell technologies in real-world systems.

Fuel Cell Development

- **There has been a major reduction in the cost of polymer electrolyte membrane (PEM) fuel cells produced at high volume over the last decade (80% since 2002, 30% since 2009).** The 2011 analysis of this cost showed a projected decrease to $49/kW, within range of the $30/kW target. Although auto manufacturers are reluctant to reveal their anticipated production costs, the fact that supply chains are being activated in anticipation of 2015 first generation consumer market introductions suggests that they are confident that it is feasible to industrialize the technology.



Designs such as these automotive fuel cell engine systems for GM are progressing toward competitive solutions

- **Great progress continues to be made to lower the platinum group metal (PGM) content from more than 1g/kW to less than 0.2g/kW and is well on its way to the goal of 0.125g/kW.** In addition, progress continues on developing platinum-free technologies. However, as PGM loading and costs decrease, durability becomes more challenging.

Fuel Cell Cars and Buses

- **Auto manufacturers continue to expand their HFC demonstration fleets as they move toward their 2015 commercialization date. Currently, Toyota has 100 demonstration vehicles on the road, Honda 200, GM 115, and Hyundai, Daimler, and other auto manufacturers are ramping up.**
- **More than 3.5 million miles have now been traveled in real-world FCEVs as part of the DOE technology validation effort.**
- **Opel, a German automobile company, announced that its HydroGen4 vehicle fleet had passed the 2.4 million mile mark as part of the GM global fleet test.**
- **Hyundai Motor Company unveiled a third-generation FCEV with a 100 kW fuel cell, 700 bar storage, -25°C start capability, and a 400-mile range. Forty-eight of these vehicles were added to the Hyundai test fleet in 2011.**
- **In 2011, Mercedes began leasing the B-Class fuel cell vehicle to customers in Orange County and Los Angeles, California.**
- **Thirteen Japanese companies announced plans to install 100 hydrogen fueling stations by 2015 as part of a previously announced commitment to introduce FCEVs to consumers by 2015.**
- **Recent studies have shown that the fuel economy of hydrogen fuel cell buses is 42–139% better than the fuel economy of diesel and compressed natural gas buses.**
- **An Oakland, California public transit agency announced a fuel cell bus world record—10,000 hours of operation.**

Hydrogen Production and Distribution

- **To be competitive with existing technologies, the cost of high-volume hydrogen production must be within the range of $2–$4 per gallon gasoline equivalent (gge).** The use of natural gas reforming at high volume is projected to be close to that now, but the use of electrolysis or biomass still has about a factor of two to go, even at high volume.
- **The world's first tri-generation fuel cell and hydrogen energy station opened at the Orange County Sanitation District's wastewater treatment plant in Fountain Valley, California, and was co-funded by DOE.** The system, which produces combined hydrogen, heat, and power (CHHP) from biogas, will provide transportation fuel to the public and will supply 5–6% of the treatment plant's electric power needs.

- **The growth of successful hydrogen distribution systems in both stationary and vehicle applications is impressive, especially in fleet applications where there are now approximately 50 stations in the United States and more than 200 worldwide.** While the cost of delivering hydrogen for remote backup power systems remains high, there has been considerable progress in their deployment.

- **The United Kingdom's first public hydrogen vehicle refueling station opened at Honda's manufacturing facility in Swindon, and the first 700 bar hydrogen refueling station opened in Holstebro, Denmark.**

- **The first hydrogen fueling station on Long Island is now officially open and fueling two Toyota fuel cell sport utility vehicles.** The station is part of the town of Hempstead's Clean Energy Project in which the viability of hydrogen as an alternative fuel will be assessed.

Hydrogen fueling station in Hempstead, Long Island

- **Proton OnSite's renewable hydrogen station in Connecticut is fueling 10 Toyota Highlanders.**

- **A new £7.5 million (USD $12.1 million) demonstration program in the United Kingdom will help further accelerate the adoption of HFC technologies for everyday use.**

- **There is increasing interest in using existing gas pipeline infrastructure to deliver hydrogen-rich gas to end-use points.** A notable example is the Hawaiian Hydrogen Initiative between the Departments of Defense and Energy, General Motors on Oahu, and The Gas Company (TGC). In this initiative, TGC will produce and distribute hydrogen-rich gas blends, tap into its 1,100-mile utility pipeline system at key locations, and separate byproduct hydrogen to be used in fuel cell electric vehicles (FCEVs).

- **The first pipeline-fed hydrogen fueling station opened in Torrance, California. This station has two fueling islands and four dispensers, enabling up to four vehicles to fill at the same time.**

- **Proton OnSite has been awarded a $1.7 million second-phase contract with the U.S.** Army's Tank-Automotive Research Development and Engineering Center (TARDEC), to produce a large-capacity hydrogen refueling station in Hawaii that will fuel 16 GM Equinox vehicles.

One of the GM Equinox fuel cell cars being deployed in Hawaii

Commercial Deployments

Demonstration projects such as those described above help to address user acceptance issues and can accelerate the transition to widespread consumer uses. The most dramatic growth in market application of HFC technology has been in two areas: stationary backup power and the use of fuel cells on forklift trucks. These early HFC deployments reflect the benefit of displacing conventional fossil fuels or batteries for special applications, which leads to longer term performance and shorter down time for refueling, For example, it takes 8 hours to recharge a battery, but it only takes 3 minutes to refuel a fuel cell forklift. This results in greater productivity and a reduced need for additional batteries.

Following are some 2011 highlights of commercial deployment of HFC technologies.

Stationary Power

- **The world's largest fuel cell power plant was opened in Daegu City, South Korea.** The 11.2 MW facility will sell electricity to an electric utility and high-grade heat to the local municipality for their wastewater treatment plant under long term power purchase agreements.

- **A hydrogen PEM fuel cell system from Heliocentris has been installed in Meiningen, Germany, to provide backup power to the city's council offices.**

- **More than 50 MW of stationary fuel cells were either installed or purchased in the United States since April 2010, according to a new report, *State of the States: Fuel Cells in America 2011,* by Fuel Cells 2000, a non-profit fuel cell information resource.**

- **More than 1,000 backup fuel cells were shipped by ReliOn, Altergy, and IdaTech, including 382 as a result of ARRA funding.** Of these, 372 were used as backup power for communication towers by Sprint and AT&T.

- **Nedstack shipped a 1MW PEM fuel cell power plant to a Solvay chlorine plant in Belgium, and ACAL Energy installed a 1kW backup power system using its redox cathode technology at another Solvay plant in the United Kingdom.**

Fuel cells installed at the Solvay plant in Belgium

Fleet Vehicles

- **ARRA funding led to the deployment of a total of 504 fuel cell powered lift trucks, and to the planned deployment (without additional government funding) of over 500 additional fuel cell lift trucks by ARRA partners.** There are now more than 3,000 such trucks deployed or on order in the United States at firms such as FedEx, Coca-Cola, Wegmans, and Whole Foods.

- **In Canada, a 20-bus fleet powered by fuel cells and operated by British Columbia Transit in the resort town of Whistler surpassed 1 million miles of service by the end of 2011.**

Research and Development

As shown by the number of successful HFC system demonstrations and commercial deployments, great strides have been made in all areas of hydrogen use. However, continued R&D is required to meet the long-term goals shown in Table 1 and further increase the use of this promising technology. In 2011, DOE awarded $7 million to four independent studies to evaluate pathways for reducing both fuel cell and hydrogen storage system costs. Reducing system costs is a key to increase the value of these technologies and their widespread use. Following is an overview of HFC R&D conducted over the past year, organized into six research areas: hydrogen generation, storage, fuel cell development, stationary applications, compression, and research for enabling other renewable technologies.

Hydrogen Generation

Efforts to reduce the cost of delivered hydrogen focus on improving production pathways other than natural gas reforming. Pathways such as electrolysis and biomass still require a factor of two cost reduction at high volume to be competitive. Parallel efforts to reduce the accompanying greenhouse gas emissions for all methods continue.

Storage

Safe, high-pressure vehicle fuel tanks have been proven, but their cost remains about a factor of three too high (roughly $3,000 produced at high volume). Efforts to develop new lightweight materials continue to be actively pursued for high-pressure storage on board vehicles. For solid-state storage, many different materials are showing promise.

Fuel Cell Development

It is possible to reduce fuel cell costs through continued R&D in targeted areas, such as reducing or replacing platinum catalyst (which represents about a third of high-volume PEM fuel cell stack cost), lowering membrane costs, as well as reducing the cost and improving the durability of balance-of-plant components. Argonne National Laboratory, Brookhaven National Laboratory, and 3M have been developing innovative low and ultra-low platinum catalysts, while Los Alamos National Laboratory has been developing a no-platinum catalyst - all of which exhibit ex-situ activity levels that exceed, or are projected to exceed, DOE targets.

Compression

Compression is a major cost component of hydrogen fueling infrastructure. HyET, a Dutch company, announced that its electrochemical compressor technology has achieved 800 bar (11,600 psi) hydrogen compression from atmospheric pressure. In addition, the single-stage compressor has no moving parts, avoiding issues around friction and wear. The company is targeting applications for hydrogen filling stations. Air Products has demonstrated tube trailer delivery of hydrogen at high pressure to reduce the need for compression at the station.

Stationary Applications

While stationary fuel cell applications have made enormous progress toward long-term goals, R&D remains focused on reducing costs, increasing longevity, and improving mean time to failure.

Enabling Other Renewable Technologies

The use of hydrogen to store energy produced from wind and solar technologies is being investigated as a means of mitigating renewable energy's problems with variability. HTAC established a working group to investigate the merits of hydrogen storage as a cost-effective electrical energy stabilizing resource. This working group invited representatives from industry and the National Renewable Energy Laboratory to assist with this investigation. Using simplified economic simulation models designed to reflect real world (and DOE-target) technical and cost assumptions, this group is examining the circumstances under which hydrogen generation, storage, and electricity production might offer competitive solutions for enabling high penetrations (>50%) of solar and wind resources in existing electrical systems. While the working group's analysis is not complete, results to date appear promising and were reported to DOE and HTAC. This work will be refined through 2012. Some early findings conclude that electrolyzer stack efficiency is at the target level of about 70%, but the cost of hydrogen is about $5.30/gge and remains above the target of $2–$4/gge. R&D is needed to find ways to reduce equipment costs, including the electrolyzer, for hydrogen to be an economical alternative for storing energy from rapidly changing or otherwise curtailed wind-generated electricity (e.g., due to electric grid constraints) in areas where there are high penetrations of wind power.

63 MW Dry Lake Wind Power Project in Arizona

Policy, Codes, and Standards

In order to enable the FCEV market to grow substantially, an important step is to develop a policy that would foster more aggressive commercialization of FCEVs, as has been done with other innovative transportation technologies. Of particular importance would be policies and investments to support early introduction of hydrogen fueling infrastructure. One of the barriers to the growth of infrastructure is the current practice of permitting at the local level, which has led to inconsistent regulations. Development of more uniform codes would help reduce confusion about the permitting process.

As hydrogen and fuel cells begin to play a greater role in meeting the energy needs of our nation and the world, safety related to using hydrogen as a fuel remains a high priority. DOE and industry are working to develop and implement practices and procedures that will ensure safety in operating, handling, and using hydrogen and hydrogen systems. Components are built to meet strict manufacturer and published guidelines and undergo third-party testing for safety and structural integrity. However, there is an ongoing need to develop national and international safety codes and standards for such items as tank life cycle testing and leak detection.

Although there has been a continued record of hydrogen safety, additional education and training programs become more critical as the technology develops and the number of installations increases. Emergency personnel, particularly at the local jurisdictional level, must be prepared to handle potential incidents, and public education must be provided to familiarize users with simple hydrogen safety practices.

Financial Climate

While the progress of hydrogen and fuel cell technologies has been impressive, there is a concern about the financial situation going forward. The ARRA funds were a great stimulus to deployment and progress, especially in material handling and backup power applications. These funds were amplified by cost sharing with industry but are no longer available. With the federal budget under stress, a significant increase in funding for any area of federal investment seems problematic. Furthermore, the bankruptcy of some "green" firms may have a negative spillover effect on the DOE loan program for companies involved with renewable energy.

Nevertheless there are some positive signs. HTAC is encouraged by the congressional initiative to restore the DOE Fuel Cell Technologies Program budget for fiscal year (FY) 2012 to $104 million, slightly above the FY 2011 budget request of $100 million. Congress also provided $25 million for DOE's Solid State Energy Conversion Alliance (SECA) multi-megawatt solid oxide fuel cell program.

State budgets are also under duress, but a handful of states led by California, Connecticut, Hawaii, New York, and South Carolina, have been aggressively proceeding with funds for hydrogen and fuel cell applications.

Proton OnSite, which had been planning an ambitious East Coast "Hydrogen Highway," has revised its plans to focus initially on a cluster of hydrogen refueling stations around the Northeast, where early vehicle introduction is most likely. Analysis of a "cluster" strategy for introducing hydrogen vehicles in Southern California[27] demonstrates that early vehicle deployment of 25,000 vehicles can be met with a modest number of stations (42) and at a moderate investment ($120–170 million) after which the cost of hydrogen becomes competitive on a cents-per-mile basis with gasoline. This infrastructure is obviously crucial for acceptance by the buying public.

Four 2.8 MW FuelCell Energy power plants providing clean power to the South Korean electric grid

Major foreign investments in HFC technologies continue to be impressive, especially in Germany, Japan, South Korea, and British Columbia (B.C.). For example, B.C. Premier Christy Clark recently announced $870,000 in provincial funding for the development of North Vancouver's first small-scale hydrogen liquefaction plant. And the German HFC advocacy organization, NOW, announced that its cumulative funding for HFC technologies has now reached $520 million.

Private funding of entrepreneurial companies developing HFC technologies has had some success, although several companies failed to raise needed capital. ACAL Energy in the United Kingdom (U.K.) received third-round funding of £6.1M; Clear Edge received $73.5 million in venture financing; Lilliputian Systems raised an additional $15 million; Intelligent Energy (U.K.) raised £7 million; and ReliOn raised $6 million of additional venture capital. While this funding is positive, it is not at the level needed for significant, expanded product development. Supportive government actions can play a significant role in stimulating commercialization, which leads to increased private equity investment.

Despite a difficult and uncertain financial outlook on a worldwide basis, corporations and governments continue to push forward on developing HFC technologies and investing in infrastructure and product commercialization. HTAC finds these commitments very encouraging, but is concerned that the U.S. competitive position in worldwide HFC markets is being outpaced by investments in Europe and Japan.

Conclusion

The HTAC is very impressed by the progress made in 2011 on HFC technologies. There is already significant commercial adoption of these technologies in niche areas, such as fuel cell forklifts and backup power. Commercial passenger vehicle introductions are anticipated in the 2015 timeframe, but their success will be coupled to a commitment to build up fueling infrastructure. While limited hydrogen infrastructure networks are expanding in certain regions including California, Hawaii, and New York, more will be needed for large-volume commercial sales. However, this growth will not happen without continued support of RD&D from various venues. There is growing concern that some countries are moving much faster and appear more committed than the United States. This could place the U.S. at a competitive disadvantage.

HTAC strongly supports the investments that DOE has been making in hydrogen and fuel cell technologies and urges the agency to continue to do so even in these tight financial times. This support can ensure that the early markets for HFC technologies successfully "cross the chasm" that is so often associated with early technology adoption. This will further stimulate private investment in these products and technologies, which have already been shown to be assets in niche areas. With support, these technologies will play a vital, more widespread role in meeting the United States' energy objectives.

Further Reading

There has been a continuous flow of reports addressing HFC technology development and markets again in 2011. Following is a list of the most significant of these:

- "World Fuel Cells," a study by Freedonia Group, projects that fuel cell demand will triple to $2.85 billion by 2015 and triple again to $9.3 billion by 2020.
- The "Third Annual Assessment of H2 Fueling Stations," published in Germany, reported that 212 stations were operating worldwide at the beginning of 2011 and another 127 are in the planning stage.
- Pike Research published a report titled "Hydrogen Infrastructure," which projected that 5,200 hydrogen refueling stations will be installed worldwide by 2020, with a total investment of $8.4 billion.
- In January, a report titled "Future Transport Fuels: Report of the European Export Group on Future Transport Fuels" was released. Hydrogen was recognized as the fuel having the greatest potential in the medium to larger car segment and for longer range buses.
- "Fuel Cell Today Industry Review 2011" reports fuel cell sales increasing by 25% between 2010 and 2011 to 285,000 units worldwide, of which 95% are PEM systems.

The Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) was established under Section 807 of the Energy Policy Act of 2005 to provide technical and programmatic advice to the Energy Secretary on DOE's hydrogen research, development, and demonstration efforts. For more information see http://www.hydrogen.energy.gov/advisory_htac.html

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[2] U.S. Department of Energy Record #11012.

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[5] Wipke, Keith, Cory Welch, Holly Thomas, Sam Sprik, Sigmund Gronich, and John Garbak. "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project." *World Electric Vehicle Association Journal*, 1 (2007): 1–7.

[6] U.S. Department of Energy Record #5036.

[7] Wipke, Keith. "Controlled Hydrogen Fleet and Infrastructure Analysis," U.S. Department of Energy Hydrogen Program Annual Merit Review & Peer Evaluation. Washington, D.C.: U.S. Department of Energy, 2011.

[8] National Renewable Energy Laboratory CDP Lab 01, "Operation Hours and Projected Hours to 10% Voltage Drop–Lab Data Sets." http://www.nrel.gov/hydrogen/cfm/images/cdp_lab_01_durabilityhrs.jpg.

[9] Gallon of gas equivalent (gge). 1 gallon of gasoline and 1 kg of hydrogen have the same energy content. On a 'per-mile basis' the cost in $/gge is a factor of 2.3 lower since fuel cell electric vehicles are approximately 2.3 times more efficient than conventional gasoline vehicles (http://www.hydrogen.energy.gov/pdfs/progress11/xi_8_wang_2011.pdf).

[10] Department of Energy Record #12002 (forthcoming). Costs include total cost of production and delivery (dispensed, untaxed). Forecourt compression, storage, and dispensing added an additional $1.82 for distributed technologies, while $2.61 was added as the price of delivery to central technologies. All delivery costs were based on NREL's *2009 Hydrogen Pathways Technical Report* (http://www.nrel.gov/docs/fy10osti/46612.pdf). Cost ranges for each pathway are shown in 2007$ based on n^{th} plant projections from H2A analyses, reflecting variability in major feedstock pricing and a bounded range for capital cost estimates.

[11] U.S. Department of Energy Record #12002 (forthcoming).

[12] Wipke, Keith. "Controlled Hydrogen Fleet and Infrastructure Analysis," U.S. Department of Energy Hydrogen Program Annual Merit Review & Peer Evaluation. Washington, D.C.: U.S. Department of Energy, 2011.

[13] The specific cost goal for the vehicle storage tank is under review by DOE and automakers, but the current cost at high-production volume ranges from $15-23/kWh depending upon tank specifics and is roughly a factor of 3 too high.

[14] U.S. Department of Energy Record #9017 and recent results.

[15] U.S. Department of Energy Record #9017.

[16] Ahluwalia, Rajesh K., T.Q. Hua, J-K Peng, and Romesh Kumar. "System Level Analysis of Hydrogen Storage Options," Hydrogen and Fuel Cells Program Annual Progress Report. Washington, D.C.: U.S. Department of Energy, 2011.

[17] U.S. Department of Energy. Department of Energy Hydrogen and Fuel Cell Technologies Multi-Year Research, Development and Demonstration Plan. Washington, D.C.: U.S. Department of Energy, 2011. Targets for hydrogen storage are system-level targets and are specified to achieve a 300-mile driving range on a single fill such that the "driving range must be achievable across different vehicle models and without compromising space, performance or cost." The full fleet system target is under review by the U.S. DRIVE Partnership (Driving Research and Innovation for Vehicle efficiency and Energy sustainability).

[18] Wipke, Keith, Cory Welch, Holly Thomas, Sam Sprik, Sigmund Gronich, and John Garbak. "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project." *World Electric Vehicle Association Journal*. 1 (2007): 1–7.

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[26] U.S. Department of Energy Record #11014.

[27] Ogden, Joan and Michael Nicholas. "Analysis of a "cluster" strategy for introducing hydrogen vehicles in Southern California." *Energy Policy*, 39 (2011) 1923–1938.