VII.1 Controlled Hydrogen Fleet and Infrastructure Analysis

Keith Wipke (Primary Contact), Sam Sprik, Jennifer Kurtz, Todd Ramsden, Chris Ainscough, Genevieve Saur
National Renewable Energy Laboratory (NREL)
1617 Cole Blvd.
Golden, CO 80401
Phone: (303) 275-4451
E-mail: keith.wipke@nrel.gov

DOE Manager
HQ: John Garbak
Phone: (202) 586-1723
E-mail: John.Garbak@hq.doe.gov

Start Date: October 2003
Projected End Date: Project continuation and direction determined annually by DOE

Objectives

- By 2008, validate that hydrogen vehicles have a greater than 250-mile range without impacting passenger or cargo compartments.
- By 2009, validate 2,000-hour fuel cell durability in vehicles and hydrogen infrastructure that results in a hydrogen production cost of less than $3.00/gallon gasoline equivalent (gge) (untaxed) delivered and safe and convenient fueling by drivers (with training).
- Help DOE demonstrate the use of fuel cell electric vehicles (FCEVs) and hydrogen infrastructure under real-world conditions, using multiple sites, varying climates, and a variety of hydrogen sources.
- Analyze detailed fuel cell and hydrogen data from vehicles and infrastructure to obtain maximum value for DOE and industry from this "learning demonstration."
- Identify the current status of the technology and its evolution over the project duration.
- Provide feedback and recommendations to DOE to promote hydrogen and fuel cell research and development (R&D) activities and assess technical progress.
- Publish results for key stakeholder use and investment decisions by generating composite data products (CDPs) for public dissemination.

Technical Barriers

This project addresses the following technical barriers from the Technology Validation section (3.6.4) of the Fuel Cell Technologies Program Multi-Year Research, Development, and Demonstration Plan:

(A) Lack of Fuel Cell Vehicle Performance and Durability Data
(B) Hydrogen Storage
(C) Lack of Hydrogen Refueling Infrastructure Performance and Availability Data
(D) Maintenance and Training Facilities
(E) Codes and Standards
(H) Hydrogen from Renewable Resources
(I) Hydrogen and Electricity Co-Production

Contribution to Achieving DOE Technology Validation Milestones

Throughout this project, researchers are gathering data and providing technical analysis that contributes to achieving the following DOE technology validation milestones from the Fuel Cell Technologies Program Multi-Year Research, Development, and Demonstration Plan:

- *Milestone 2: Demonstrate FCEVs that achieve 50% higher fuel economy than gasoline vehicles (Quarter [Q]3, Fiscal Year [FY] 2005).* This milestone was achieved.
- *Milestone 3: Decision for purchase of additional vehicles based on projected vehicle performance and durability and hydrogen cost criteria (Q4, FY 2006).* This milestone was achieved.
- *Milestone 4: Operate fuel cell vehicle fleets to determine if 1,000 hour fuel cell durability, using fuel cell degradation data, was achieved by industry (Q4, FY 2006).* This milestone was achieved.
- *Milestone 5: Validate vehicle refueling time of 5 minutes or less for a 5 kg tank [1kg/min] (Q4, FY 2006).* At the time of the milestone, we had analyzed more than 2,000 vehicle fueling events and had calculated an average rate of 0.69 kg/min and median rate of 0.72 kg/min, with 18% of the events exceeding the 1 kg/min target. Updates 3.5 years later, data from more than 25,000 fueling events showed improved results with an average rate of 0.77 kg/min with 23% of fueling events exceeding 1 kg/min. This milestone was achieved.
- *Milestone 7: Validate refueling time of 5 minutes or less for 5 kg of hydrogen (1 kg/min) at 5,000 psi through the use of advanced communication technology (Q4, FY 2007).* Currently, the data show that communication fills can fuel at a higher rate (up to 1.8 kg/min) and have an average fill rate 30% higher than non-communication fills (0.86 kg/min versus 0.66 kg/min). This milestone was achieved.
- *Milestone 8: Fuel cell vehicles demonstrate the ability to achieve a 250-mile range without impacting passenger cargo compartment (Q4, FY 2008).* This milestone

was achieved in 2008 using data from the Learning Demonstration results, with demonstrated range of 196–254 miles. In June 2009, an on-road driving range evaluation was performed in collaboration with Toyota and Savannah River National Laboratory. The results indicated a 431-mile on-road range was possible in southern California using Toyota's FCHV-adv fuel cell vehicle [1]. This milestone was achieved.

- *Milestone 10: Validate FCEVs 2,000-hour fuel cell durability using fuel cell degradation data (Q4, FY 2009).* On-road fuel cell voltage data from second-generation fuel cell systems were analyzed and published in the Fall 2009 CDP results. Results indicate that the highest projected team average to 10% voltage degradation for second-generation systems was 2,521 hours, with a four-team average of 1,020 hours. The Spring 2010 results only slightly increased the average (to 1,062 hours) and the highest team remained the same at 2,521 hours. This milestone was achieved.
- *Milestone 12: Validate cold start capability at -20 C (2Q, 2011).* This milestone was achieved and published in the Fall 2008 CDPs, demonstrating freeze starts from between -9 and -20 degrees C and documenting both time to drive away and time to maximum fuel cell power.
- *Milestone 23: Total of 10 stations constructed with advanced sensor systems and operating procedures (Q1, FY 2008).* This milestone was achieved.
- *Milestone 24: Validate a hydrogen cost of $3.00/gge (based on volume production) (Q4, FY 2009).* Cost estimates from the Learning Demonstration energy company partners were used as input to an H2A analysis to project the hydrogen cost for 1,500 kg/day early market fueling stations. Results indicate that on-site natural gas reformation would lead to a range of $8-$10/kg and on-site electrolysis would lead to $10-$13/kg hydrogen cost. Although these results do not meet the $3/gge cost target, two external independent panels concluded that distributed natural gas reformation could lead to $2.75-$3.50/kg [2] and distributed electrolysis could lead to $4.90-$5.70 [3]. This milestone was achieved outside the Learning Demonstration project.

Accomplishments

- Received and processed data quarterly from a total of 460,000 individual vehicle trips, amounting to more than 107 gigabyte (GB) of on-road data, since project inception.
- Created and published a total of 85 CDPs, with the Spring 2011 CDP results including five new CDPs since last year and updates to 18 previously published CDPs. The results emphasized the changes observed in the last 12 months, and included data from two Learning Demo manufacturers plus the Air Products' California Hydrogen Infrastructure Project.
- Documented and archived each quarter's analysis results in the Fleet Analysis Toolkit (FAT) graphical user interface. Executed NREL FAT to produce detailed data results and CDPs in parallel for convenient industry and internal review.
- Presented project results publicly at the Fuel Cell Seminar, EVS-25, the Fuel Cell and Hydrogen Energy Association conference, the Japanese Fuel Cell Demonstration Project conference, and the 2011 DOE Fuel Cell Technologies Program Merit Review meeting.
- Maintained NREL's Web page at http://www.nrel.gov/hydrogen/cdp_topic.html to allow direct public access to the latest CDPs organized by topic, date, and CDP number.
- Provided presentations of results to key stakeholders, including two FreedomCAR and Fuel technical teams (storage and fuel cells).
- Continued to leverage key NREL analysis tools and capabilities to enable results to be quickly generated from fuel cell forklifts and other early market fuel cell applications. This year we also began performing some new analyses on FCEVs that were developed originally for fuel cell forklifts.

✧ ✧ ✧ ✧ ✧

Introduction

The primary goal of this project is to validate vehicle/infrastructure systems using hydrogen as a transportation fuel for light-duty vehicles. This means validating the use of FCEVs and hydrogen fueling infrastructure under real-world conditions using multiple sites, varying climates, and a variety of sources for hydrogen. Specific targets for 2009 were hydrogen vehicles with a range greater than 250 miles, 2,000-hour fuel cell durability, and $3.00/gge hydrogen production cost (based on modeling for volume production). We are identifying the current status of the technology and tracking its evolution over the project duration, particularly between the first- and second-generation fuel cell vehicles, and further improvements to the second-generation vehicles demonstrated in the final two years. NREL's role in this project is to provide maximum value for DOE and industry from the data produced by this "learning demonstration." We seek to understand the progress toward the technical targets, and provide information to help move the Fuel Cell Technologies (FCT) R&D activities more quickly toward cost-effective, reliable hydrogen FCEVs and supporting hydrogen fueling infrastructure.

Approach

Our approach to accomplishing the project's objectives has been structured around a highly collaborative relationship with each industry team including Chevron/Hyundai-Kia, Daimler/BP, Ford/BP, General Motors/Shell, and Air Products (through the DOE California Hydrogen Infrastructure Project). We are receiving raw technical data from the hydrogen vehicles and from the fueling infrastructure that enable us to perform unique and valuable analyses across all teams. Our primary objectives are to feed the current technical challenges and opportunities back into the DOE FCT R&D Program and assess the current status and progress toward targets.

To protect the commercial value of these data for each company, we established the Hydrogen Secure Data Center at NREL to house the data and perform our analysis. To ensure value is fed back to the hydrogen community, we publish CDPs twice a year at technical conferences to report on the progress of the technology and the project, focusing on the most significant results. Additional CDPs are being conceived as additional trends and results of interest are identified, and as we receive requests from DOE, industry, and the codes and standards community. We also provide our detailed analytical results (not public) to each individual company's data to maximize the industry benefit of NREL's analysis work and to obtain feedback on our methodologies.

Results

The results in FY 2011 came from analyzing an additional year of data (January–December 2010), creating five new and 18 updated CDPs, and presenting these results at several technical conferences. This brings the total number of CDPs published to 85. To accomplish this, we continued to improve and revise our in-house analysis tool, FAT. In 2007 NREL launched a Web page at http://www.nrel.gov/hydrogen/cdp_topic.html to provide stakeholders and the public with direct access to the results. Some results have also been presented publicly at conferences in the last year as two distinct sets of results (labeled "Fall 2010" and "Spring 2011"). All 85 of the results are now available on the Web site, so this report will include only a few highlights from the last year.

- Status of Vehicle Deployment: Figure 1 shows the cumulative number of vehicles that have been deployed by quarter and hydrogen storage system type since project inception. A total of 155 vehicles were deployed through December 2010; 132 are retired from the project and 23 are still on the road. Before the conclusion of the project about 40 vehicles should be on the road providing data to NREL with about 170 vehicles deployed since project inception.
- Real-World Vehicle Driving Range: In FY 2008, the driving range of the project's FCEVs was evaluated based on fuel economy from dynamometer testing and on-board hydrogen storage amounts and compared to the 250-mile target. Additional on-road data were obtained from second- and first-generation vehicles in 2009, as well as improved second-generation vehicles in 2010. This enabled us to evaluate the distribution of real-world driving ranges of all the

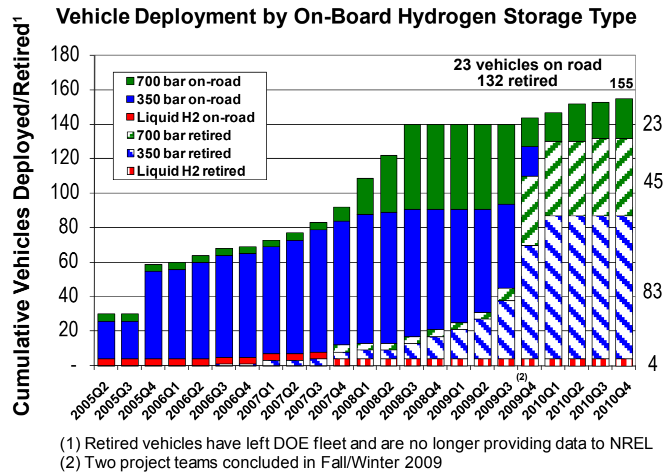
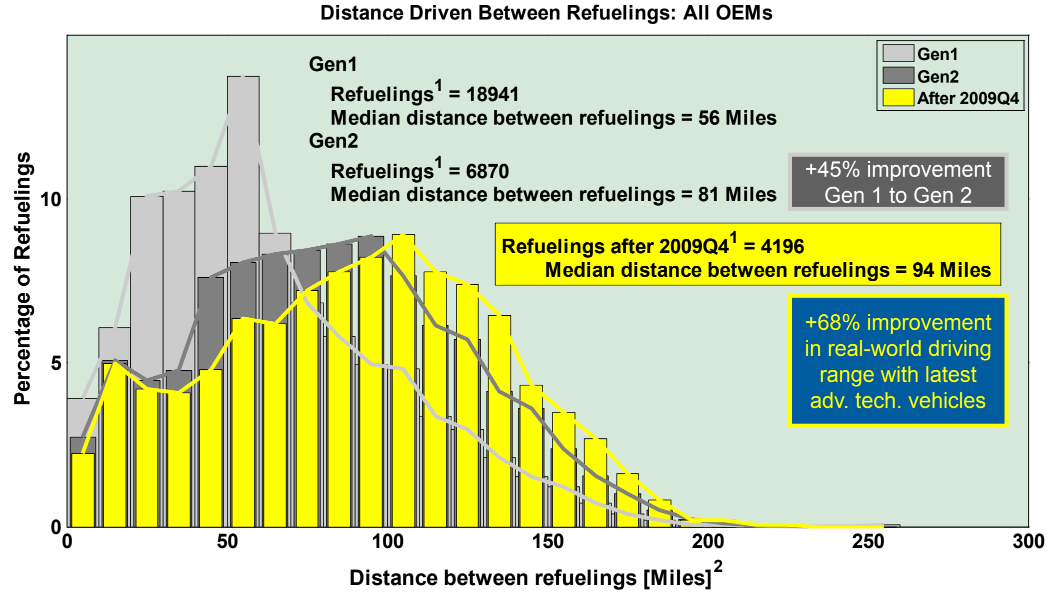


FIGURE 1. Cumulative Vehicles Deployed by Quarter and by Storage Type

vehicles in the project. The data show (Figure 2) a 45% improvement in the median real-world driving range of second-generation vehicles (81 miles) compared to first-generation (56 miles), based on distances driven between more than 25,000 fueling events. In 2010, with continued operation of some second-generation vehicles and the introduction of some improved performance second-generation vehicles, we have seen an increase in the median distance traveled between fuelings to 94 miles. This reflects a 68% improvement in real-world driving range with the latest advanced technology vehicles compared to the first-generation vehicles first introduced in 2005. As previously discussed, all the vehicles are capable of two to three times greater range than this when pushed to their full capabilities with sufficient fueling infrastructure, but the median distance traveled between fuelings is one way to measure the improvement in the vehicles' capability as well as the way in which they are actually being driven. We believe the reason for the increase in median driving distance between fuelings is due to slight improvements in the vehicle capabilities (better efficiency) and in more widespread infrastructure, which enables the vehicle storage tanks to be drawn down closer to empty because drivers are confident they can obtain fuel close by.
- Fuel Cell Durability: The Spring 2010 results indicated that the highest average projected team time to 10% voltage degradation for second-generation systems was 2,521 hours, with a multi-team average projection of 1,062 hours. Therefore, the 2,000-hour target for durability was achieved. Since that time, two automotive teams concluded their participation in the project and additional data were acquired on some second-generation vehicles. Improved second-generation vehicles were also introduced to the project. Only two companies now provide durability data, and some vehicles have limited hours on the road, so we will create new durability CDPs in Fall 2011 when



1. Some refueling events are not detected/reported due to data noise or incompleteness.
2. Distance driven between refuelings is indicative of driver behavior and does not represent the full range of the vehicle.

FIGURE 2. Real-World Improvement in Driving Range Between Gen 1, Gen 2, and Latest Advanced Technology Learning Demonstration Vehicles

additional data are available to provide robust analysis and identity protection for all the companies.

- Vehicle Fueling Rates: Because of the change in makeup of the automotive and energy teams for the final two years of the project, we separated out the fueling rates for the five years up through 2009 Q4 from the fueling rates for the year after 2009 Q4 (Figure 3). We found that in the first five years of the project, from more than 25,000 fueling events, the average fill rate was 0.77 kg/min with 23% of the events exceeding DOE's target of 1 kg/min, representing a 5 kg fill in 5 minutes. Over the last year, from a limited set of 2,766 fills,

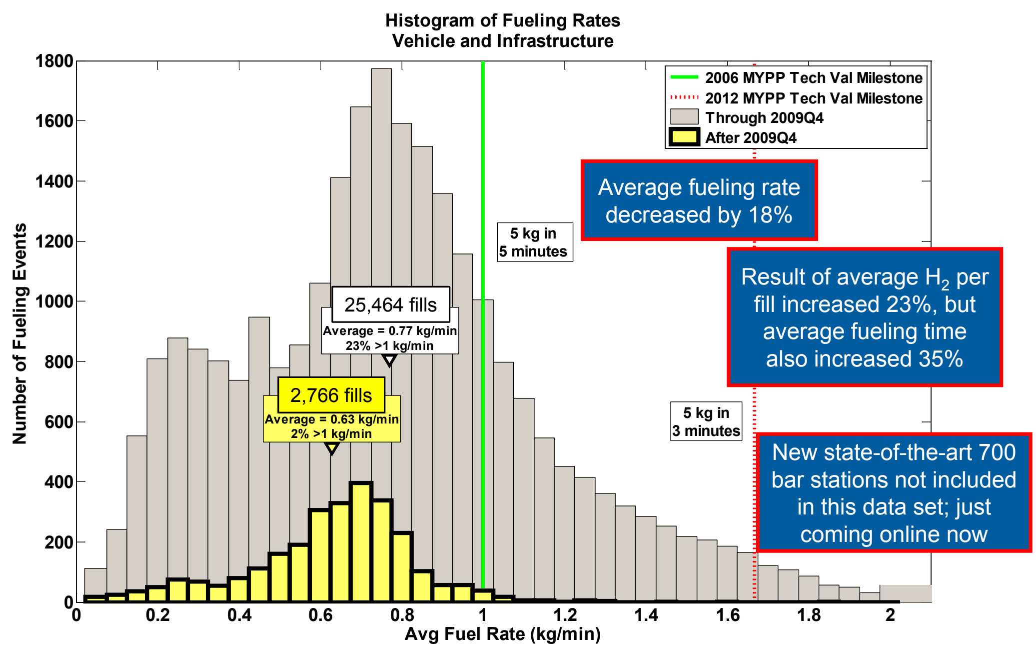


FIGURE 3. Fueling Rate Trends are Monitored as Industry Moves to 700 bar Pressure as Standard

we have observed an average fill rate of 0.63 kg/min with just 2% of the fills exceeding the 1 kg/min target. Several factors explain this 18% drop in fueling rate. The average hydrogen dispensed per fill increased by 23%, but the average fueling time increased by 35%. The root cause is that the hydrogen community is migrating toward 700 bar pressure fueling as the new standard, but the state-of-the-art stations that can achieve a fast and complete fill at this pressure with precooling are just now coming online, and data from those stations were not available through December 2010. Additionally, some 350 bar stations and vehicles that demonstrated fast-fill times have been decommissioned. So this reduction in reported fill rate should be a temporary phenomenon until the new 700 bar station data are included in the dataset later this year. With the new data and analysis results, NREL will be able to document the significant progress that has been made relative to 700 bar infrastructure.

- Hydrogen Fueling Infrastructure Usage Patterns: The final technical result to highlight is the usage patterns of the hydrogen fueling stations within the project over the last year. Figure 4 shows the percentage of hydrogen dispensed by day of the week (bars with left-axis labels) along with the average amount of hydrogen dispensed by day for each of the six stations included in this dataset (curves with right-axis labels). The data show that weekday fueling is still more common than weekend fueling, which had been shown in a previous CDP from the first five years of the project. The graph also shows that two stations have relatively high average throughput (8-14 kg/day); the other four are only lightly used, dispensing 3 kg/day or less on average. This type of result will be useful as we go forward to be able to track the throughput of each station individually and by specific geographic region to better coordinate and advise stakeholders on optimal future vehicle deployments and new station placement.

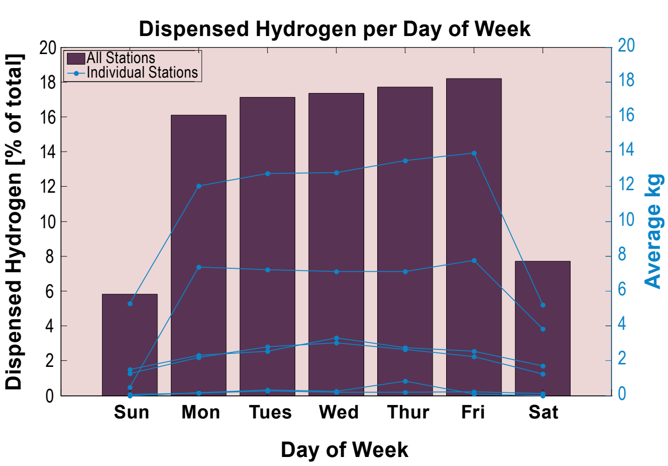


FIGURE 4. New Infrastructure CDP Provides Insight into Specific Fueling Usage Patterns

Conclusions and Future Direction

- Completed the first six years of the seven-year project with 155 vehicles deployed in fleet operation, 24 project fueling stations demonstrated, and no major safety barriers encountered.
- Analyzed data from 460,000 individual vehicle trips covering >3 million miles traveled and 140,000 kg hydrogen produced or dispensed.
- Verified that high fuel cell system efficiency was maintained from Gen 1 to Gen 2 systems, with Gen 2 efficiency at quarter-power of 53%–59%, close to the 60% DOE target.
- Published 85 CDPs to date and made them directly accessible to the public from an NREL website.
- We will create new and update CDPs based on data collected through June 2011 (Fall 2011 CDPs) and present results for publication at the 2011 Fuel Cell Seminar.
- NREL will support DOE's September 2011 milestone to document operation of advanced technology fuel cell vehicles with up to 600 hours of operation.
- We will support original equipment manufacturers, energy companies, and state organizations in California in coordinating early infrastructure plans.
- We will gather and analyze data from a relatively large (100 kg/day on-site production) hydrogen station in Burbank, California, along with many new stations that are being opened in California in 2011 (for example, the Torrance pipeline station and the Fountain Valley tri-generation station).
- NREL will continue to identify opportunities to feed findings from the project back into the Vehicle Technologies and FCT programs and industry R&D activities to maintain the project as a "learning demonstration."
- We will continue to gather data from FCEVs and hydrogen stations through the end of calendar year 2011, when the auto manufacturer Learning Demonstration projects conclude, and publish one final set of results in Spring 2012.
- As the last deliverable from this project, we will write a final comprehensive summary report for publication.
- We will continue to identify and exploit new opportunities to document fuel cell vehicle and hydrogen progress publicly beyond the end of this project.

FY 2011 Publications/Presentations

1. Wipke, K., Sprik, S., Kurtz, T., Ramsden, T., Ainscough, C., Saur, G., "Controlled Hydrogen Fleet and Infrastructure Analysis," 2011 U.S. DOE Hydrogen Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting, Washington, D.C, May 2011. (presentation)

2. Wipke, K., presentation of Learning Demonstration results to FreedomCAR and Fuels Hydrogen Storage Tech Team, April 2011. (presentation)

3. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., "National FCEV Learning Demonstration Report: Spring 2011 – All Composite Data Products with Updates through March 29, 2011," Golden, CO: National Renewable Energy Laboratory, published April 2011. (presentation)

4. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G., "Status of U.S. FCEV and Infrastructure Learning Demonstration Project," Japan Hydrogen Fuel Cell (JHFC) Demonstration Project, March 2011. (presentation)

5. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G., "Next Steps for the FCEV Learning Demonstration Project," Fuel Cell & Hydrogen Energy Conference (FCHEA), Washington, DC, February, 2011. (presentation)

6. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Garbak, J., "Entering a New Stage of Learning from the U.S. Fuel Cell Electric Vehicle Demonstration Project," prepared for the 25th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium (EVS-25), Shenzhen, China, November 2010. (paper and presentation)

7. Kurtz, J., Wipke, K., Eudy, L., Sprik, S., Ramsden, T., "Fuel Cell Technology Demonstrations and Data Analysis," draft submitted to editors of CRC book entitled Hydrogen Energy and Vehicle Systems, November, 2010. (book chapter)

8. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., 2010 Annual Progress Report for NREL's "Controlled Hydrogen Fleet and Infrastructure Analysis Project," Section VIII.1, November 2010. (paper)

9. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., "U.S. Fuel Cell Electric Vehicle Demonstration Project 2010 Status Update," presented at the 2010 Fuel Cell Seminar and Exposition, San Antonio, TX, October 2010. (presentation)

10. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., "Fall 2010 Composite Data Products for the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," Golden, CO: National Renewable Energy Laboratory, published September 2010. (presentation)

11. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., "Learning Demonstration Interim Progress Report – July 2010," NREL/TP-560-49129, September 2010. (paper)

12. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Garbak, J., "DOE's National Fuel Cell Vehicle Learning Demonstration Project – NREL's Data Analysis Results," Electric and Hybrid Vehicles, Power Sources, Models, Sustainability, Infrastructure and the Market, Chapter 12, ISBN 978-0-444-53565-8, NREL/CH-560-47111, Elsevier B.V., August 2010. (paper)

References

1. Wipke, K., Anton, D., Sprik, S., "Evaluation of Range Estimates for Toyota FCHV-adv Under Open Road Driving Conditions," prepared under SRNS CRADA number CR-04-003, August 2009.

2. Fletcher, J., Callaghan, V., "Evaluation Cost of Distributed Production of Hydrogen from Natural Gas – Independent Review," NREL/BK-150-40382, October 2006.

3. Genovese, J., Harg, K., Paster, M., Turner, J., "Current (2009) State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis – Independent Review," NREL/BK-6A1-46676, September 2009.

The Hydrogen Council is composed of 18 steering members that authored the report and 10 supporting members: Mitsui & Co, Plug Power, Faber Industries, Faurecia, First Element Fuel (True Zero), Gore, Toyota Tsusho, Hydrogenics, Ballard, Mitsubishi. McKinsey & Company provided analytical support. Contact.Â For buildings, hydrogen builds on the existing gas infrastructure and meets roughly 10% of global demand for heat. In industry, hydrogen is used for medium- and high-heat processes, for which electrification is not an efficient option.Â support to ramp up the infrastructure and deploy more vehicles. In building heat and power, we propose to replicate the approach taken in the UK, which is investigating a city-by-city.