Status of U.S. FCEV and Infrastructure Learning Demonstration Project

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Outline

• Project Goals
• Vehicle and H₂ Station Deployment Status
• Critical Performance Compared to Targets
• Highlights of Latest Vehicle and Infrastructure Analysis Results and Progress
• Learning Demo Next Steps
• Other Relevant U.S. Activities
• Cross-Application Fuel Cell Analysis Results
• Summary
Fuel Cell Electric Vehicle Learning Demo
Project Objectives, Relevance, and Targets

• Objectives
  – Validate H\textsubscript{2} FC Vehicles and Infrastructure in Parallel
  – Identify Current Status and Evolution of the Technology

• Relevance
  – Objectively Assess Progress Toward Technology Readiness
  – Provide Feedback to H\textsubscript{2} Research and Development

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>2009</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell Stack Durability</td>
<td>2000 h</td>
<td>5000 h</td>
</tr>
<tr>
<td>Vehicle Range</td>
<td>250+ m</td>
<td>300+ m</td>
</tr>
<tr>
<td>Hydrogen Cost at Station</td>
<td>$3/gge</td>
<td>$2-3/gge</td>
</tr>
</tbody>
</table>

Note: Project extended 2 years through 2011

Burbank, CA station. Photo: NREL
Two Teams Concluded Their Projects in 2009, Three are Continuing through 2011

Ford/BP and Chevron/Hyundai-Kia Concluded in 2009

Daimler, GM, and Air Products Continue to Demonstrate Vehicles/Stations within Project through 2011
Vehicle Status: All 350 bar Vehicles Retired, Only 700 bar Vehicles Continuing

Vehicle Deployment by On-Board Hydrogen Storage Type

- 700 bar on-road
- 350 bar on-road
- Liquid H2 on-road
- 700 bar retired
- 350 bar retired
- Liquid H2 retired

(1) Retired vehicles have left DOE fleet and are no longer providing data to NREL
(2) Two project teams concluded in Fall/Winter 2009

Total of ~40 project vehicles expected on road in 2011, for total of ~170 deployed
Fueling Station Status: Stations that Continue to Operate are Mostly Delivered Compressed Hydrogen

Learning Demonstration Hydrogen Stations By Type

- Delivered Compressed H2
- Natural Gas On-Site Reforming
- On-Site Electrolysis
- Delivered Liquid H2

Station Type

- Operating Outside of Project
- Operating Within Project
- Historical 2005-2009*

*Some project teams concluded Fall/Winter 2009. Markers show the cumulative stations operated during the 2005-2009 period.
Out of 24 Project Stations, 15 Are Still Operational (2/3 are operating outside of DOE project)

SF Bay Area

Los Angeles Area

Detroit Area

DC to New York

Legend
- Current Project
- Continuing Outside
- Other

Cumulative Stations

Reporting Period

Number of Stations

Continuing Outside of Project
Retired Stations
Current Project Stations

National Renewable Energy Laboratory
Innovation for Our Energy Future
Feb-3-2011
Project Achieved Both Technical Goals; Outside Analysis Used for Cost Evaluation

<table>
<thead>
<tr>
<th>Vehicle Performance Metrics</th>
<th>Gen 1 Vehicle</th>
<th>Gen 2 Vehicle</th>
<th>2009 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel Cell Stack Durability</strong></td>
<td></td>
<td></td>
<td>2000 hours</td>
</tr>
<tr>
<td>Max Team Projected Hours to 10% Voltage Degradation</td>
<td>1807 hours</td>
<td>2521 hours</td>
<td></td>
</tr>
<tr>
<td>Average Fuel Cell Durability Projection</td>
<td>821 hours</td>
<td>1062 hours</td>
<td></td>
</tr>
<tr>
<td>Max Hours of Operation by a Single FC Stack to Date</td>
<td>2375 hours</td>
<td>1261 hours</td>
<td></td>
</tr>
<tr>
<td><strong>Driving Range</strong></td>
<td>103-190 miles</td>
<td>196-254 miles</td>
<td>250 miles</td>
</tr>
<tr>
<td><strong>Fuel Economy (Window Sticker)</strong></td>
<td>42 – 57 mi/kg</td>
<td>43 – 58 mi/kg</td>
<td>no target</td>
</tr>
<tr>
<td><strong>Fuel Cell Efficiency at ¼ Power</strong></td>
<td>51 - 58%</td>
<td>53 - 59%</td>
<td>60%</td>
</tr>
<tr>
<td><strong>Fuel Cell Efficiency at Full Power</strong></td>
<td>30 - 54%</td>
<td>42 - 53%</td>
<td>50%</td>
</tr>
</tbody>
</table>

| Infrastructure Performance Metrics              |               |               | 2009 Target |
| **H₂ Cost at Station (early market)**          |               |               | $3/gge      |
| On-site natural gas reformation                 | $7.70 - $10.30| $10.00 - $12.90|             |
| **Average H₂ Fueling Rate**                    | 0.77 kg/min   | 1.0 kg/min    |             |
What are the Most Recent Project Results?
Differences Between Spring & Fall 2010 CDPs

80 Spring 2010 Results
- Most comprehensive set we ever published
- Covers data from all 4 Learning Demo teams + CHIP project over 5 year period

16 Fall 2010 Results
- Covers data from 2 Learning Demo OEMs + CHIP project
- Emphasized changes observed in last 6 months through use of gray (old) and colors (new)
Quantified Gen 2 Fuel Cell System Durability*

Improvement from Gen 1

DOE Learning Demonstration Fuel Cell Stack Durability:
Based on Data Through 2009 Q2

Actual Operating Hours Accumulated To-Date

Projected Hours to 10% Voltage Degradation

One Gen 1 stack accumulated almost 2400 hours without maintenance

2006 Target

2009 Target

Max Projection
Avg Projection

Max Projection
Avg Projection

Gen1
Gen2
Gen1
Gen2
Gen1
Gen2

Max Hrs Accumulated\(^{1,2}\)
Avg Hrs Accumulated\(^{1,3}\)
Projection to 10% Voltage Degradation\(^{4,5,6}\)

(1) Range bars created using one data point for each OEM. Some stacks have accumulated hours beyond 10% voltage degradation.
(2) Range (highest and lowest) of the maximum operating hours accumulated to-date of any OEM’s individual stack in “real-world” operation.
(3) Range (highest and lowest) of the average operating hours accumulated to-date of all stacks in each OEM’s fleet.
(4) Projection using on-road data -- degradation calculated at high stack current. This criterion is used for assessing progress against DOE targets, may differ from OEM’s end-of-life criterion, and does not address “catastrophic” failure modes, such as membrane failure.
(5) Using one nominal projection per OEM: “Max Projection” = highest nominal projection, “Avg Projection” = average nominal projection. The shaded projection bars represents an engineering judgment of the uncertainty on the “Avg Projection” due to data and methodology limitations. Projections will change as additional data are accumulated.
(6) Projection method was modified beginning with 2009 Q2 data, includes an upper projection limit based on demonstrated op hours.

Durability is defined by DOE as projected hours to 10% voltage degradation
Fuel Cell Durability Comparison between Field and Lab Data Shows Potential Gains

Comparison of Fuel Cell Vehicle Field and Lab Durability Projections

- **Average Projection**
- **Max Projection**

Improvements in durability demonstrated

(1) Gen1 and Gen2 Data from DOE's Learning Demonstration (2005 - 2010)
(2) Lab data providers may not be the same as participants in DOE's Learning Demonstration. 56% of data are full active area short stacks.
(3) The DOE 10% voltage degradation metric is used for assessing voltage degradation; it may not be the same as end-of-life criteria and does not address catastrophic failure modes.
Completed Final Analysis of Gen 1 Fuel Cell System Power Degradation

**Max Fuel Cell Power Loss vs Op Hours: Gen1**

Note that degradation flattens out after ~200 hours

Need ~1000 hours to have higher confidence in slope of degradation

All vehicles continuing in the project will be Gen 2 vehicles

From limited Gen 2 data received so far, trend of flattening after 200 hours appears similar

Gen 2 results have larger degree of uncertainty projected against 2000 hour target

Spring 2010
Changes in Refueling Rate Trends: Average Refueling Rate Decreased 14%

Histogram of Fueling Rates
Vehicle and Infrastructure

Result of average H₂ per fill increasing 24%, but average fueling time also increasing 28%
Real-World Driving Range Between Fuelings Continues to Improve as Demonstration Progresses

Distance Driven Between Refuelings: All OEMs

<table>
<thead>
<tr>
<th>Generation</th>
<th>Refuelings</th>
<th>Median Distance between Refuelings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gen1</td>
<td>18941</td>
<td>56 Miles</td>
</tr>
<tr>
<td>Gen2</td>
<td>6870</td>
<td>81 Miles</td>
</tr>
</tbody>
</table>

Refuelings after 2009Q4 = 3185
Median distance between refuelings = 91 Miles

+45% improvement
+63% improvement

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.

“window-sticker” range from adjusted dyno tests is 196-254 miles
Rate of Mileage Accumulation Has Decreased in the Last Year, But Vehicles Still Added 550,000 Miles

Cumulative Vehicle Miles: All OEMs, Gen 1 and Gen 2
Through 2010 Q2

Vehicle Miles Traveled

<table>
<thead>
<tr>
<th>Quarter</th>
<th>Vehicle Miles Traveled</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005Q2</td>
<td>250,000</td>
</tr>
<tr>
<td>2005Q3</td>
<td>500,000</td>
</tr>
<tr>
<td>2005Q4</td>
<td>750,000</td>
</tr>
<tr>
<td>2006Q1</td>
<td>1,000,000</td>
</tr>
<tr>
<td>2006Q2</td>
<td>1,250,000</td>
</tr>
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</tr>
<tr>
<td>2009Q4</td>
<td>4,750,000</td>
</tr>
<tr>
<td>2010Q1</td>
<td>5,000,000</td>
</tr>
<tr>
<td>2010Q2</td>
<td>5,250,000</td>
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</tbody>
</table>

2,872,533
Driving Behavior (Timing) in Last 6 Months
Much More Similar to U.S. National Average

% of driving trips b/t 6 AM & 6 PM: 85.3%
% of driving trips b/t 6 AM & 6 PM: 77.1%
% of NHTS trips b/t 6 AM & 6 PM: 81.5%

1. Driving trips between 6 AM & 6 PM
2. The outer arc is set at 12 % total Driving.
3. Some events not recorded/detected due to data noise or incompleteness.

2001 NHTS Data Includes Car, Truck, Van, & SUV day trips
ASCII.csv Source: http://nhts.ornl.gov/download.shtml#2001

Fall 2010

Driving by Day of Week

% of Trips in a Day

Sun  Mon  Tues  Wed  Thur  Fri  Sat

2001 NHTS Data Includes Car, Truck, Van, & SUV day trips
ASCII.csv Source: http://nhts.ornl.gov/download.shtml#2001
Learning Demo Next Steps

- Currently analyzing July – December 2010 data
- Spring 2011 CDPs published in March, presented at DOE AMR in May
- Publish one or two more Learning Demo CDP sets after that
- Begin receiving fueling data from Burbank station and others

- Partners scheduled to provide data through September 2011
- Participating in many other demonstration and pre-commercial activities outside of this project
Other Relevant U.S. Activities

GM – LOU for Hawaii Hydrogen Initiative

The New York Times

December 8, 2010, 2:11 pm

G.M. Has Hydrogen Hopes for Hawaii

By JIM MCTAVISH

Steve Finley for General Motors The General Motors Fuel Cell vehicle on the coast of Oahu. The ideal early mark for hydrogen fuel-cell cars is small, well-contained, facing wasteful fossil fuel prices and has an abounding supply of renewable energy on tap, according to Charles Foster, executive director of General Motors’ hydrogen initiatives.

Indeed, which fits that description, had actually announced its intentions to be the world’s first hydrogen economy, but access to fuel-cell cars proved to be a crippling barrier. The Hawaiian island of Oahu, with a population of one million, may be over that hurdle.

On Wednesday, G.M. announced the Hawaii Hydrogen Initiative (or H2I in marketing speak) in Honolulu. It’s a new partnership with, among others, Aloha Petroleum (which operates filling stations that sell hydrogen).

The State of Hawaii

At an event with Governor David Ige, General Motors, the State of Hawaii, and others, announced the Hawaii Hydrogen Initiative. GM will donate its hydrogen fuel cell, and the State of Hawaii will contribute its renewable energy resources.
Other Relevant U.S. Activities

State of California Supporting 11 H₂ stations

- 11 H₂ station awards announced by CEC in Oct.
  - 8 new stations, 3 upgrades
  - Air Products planning 8 stations: 7 new, 1 upgrade – all in Southern CA
  - Linde planning 3 stations: 1 new, 2 upgrades
NREL Also Publishes Results from Analyzing Multiple Applications
Number of Fuel Cell Units Being Evaluated and Providing Data to NREL

Much has been learned about FC FC bus and car performance

Understanding of MHE & Back-up less mature, but rapidly emerging
Each Fuel Cell Application Has Different Requirements and Operation

- **Hours**
  - MHE, 251,177
  - FCEV, 106,413
  - FCB, 43,006

- **Miles**
  - FCEV, 2,872,533
  - FCB, 438,903

- **Hydrogen Amount**
  - MHE, 19,831
  - FCEV, 90,865
  - FCB, 87,597

- **Hydrogen Fills**
  - MHE, 36,468
  - FCEV, 27,194
  - FCB, 1,626

National Renewable Energy Laboratory

Innovation for Our Energy Future
Forklifts Acquire Data Very Rapidly – Data from 5 Years of Cars, 2 Years of Forklifts

Stack Op Hours By Application

- FCEV
- FCMHE

Created: Oct 16, 10:11 PM
Fueling Rates Vary By Application, Primarily Driven by Constraints on Pressure, Volume, Time
Summary

- Project has completed ~6 years of validation
- **Vehicle operation**: 114,000 hours, 2.87 million miles, 436,000 trips
- **H₂ station operation**: 134,000 kg produced or dispensed, 27,000 fuelings
- DOE Key Technical Targets Met: FC Durability and Range
- Data reporting and analysis continues through remainder of this year
- New CA fueling stations planned for inclusion in future NREL infrastructure analysis as they come online and provide data
Contact Info. and Web Resources

Project Contact: Keith Wipke, National Renewable Energy Lab
303.275.4451 keith.wipke@nrel.gov

NREL's Renewable H₂ Station Now Stores Over 250 kg H₂ and can dispense at 350 bar

All public Learning Demo and FC Bus Evaluation papers and presentations are available online at http://www.nrel.gov/hydrogen/proj Tech_validation.html