Entering a New Stage of Learning from the U.S. Fuel Cell Electric Vehicle Demonstration Project

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This presentation does not contain any proprietary, confidential, or otherwise restricted information
Outline

- Project Goals
- Vehicle and H2 Station Deployment Status
- Performance Compared to Targets
- Highlights of Latest Results and Progress
- Summary and Future work
Fuel Cell Electric Vehicle Learning Demo
Project Objectives, Relevance, and Targets

• Objectives
  – Validate H₂ FC Vehicles and Infrastructure in Parallel
  – Identify Current Status and Evolution of the Technology

• Relevance
  – Objectively Assess Progress Toward Technology Readiness
  – Provide Feedback to H₂ 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 hours</td>
<td>5000 hours</td>
</tr>
<tr>
<td>Vehicle Range</td>
<td>250+ miles</td>
<td>300+ miles</td>
</tr>
<tr>
<td>Hydrogen Cost at Station</td>
<td>$3/gge</td>
<td>$2-3/gge</td>
</tr>
</tbody>
</table>

Key Targets

Note: Project extended 2 years to 2011
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

Cumulative Vehicles Deployed/Retired

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

22 vehicles on road
130 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 Reforming
- On-Site Electrolysis
- Delivered Liquid H2

Markers show the cumulative stations operated during the 2005-2009 period.

*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 outside of DOE project)
Evaluation Against 3 Primary Metrics: Project Met All Major Technical Goals

<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></td>
</tr>
<tr>
<td>Max Team Projected Hours to 10% Voltage Degradation</td>
<td>1807 hours</td>
<td>2521 hours</td>
<td>2000 hours</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                                |               |               |             |
| **H₂ Cost at Station (early market)**                            |               |               |             |
| On-site natural gas reformation                                  | $7.70 - $10.30| $10.00 - $12.90| $3/gge     |
| Average H₂ Fueling Rate                                         | 0.77 kg/min   | 1.0 kg/min    |             |

Outside of this project, DOE independent panels concluded at 500 replicate stations/year:
- Distributed natural gas reformation at 1500 kg/day: $2.75-$3.50/kg (2006)
- Distributed electrolysis at 1500kg/day: $4.90-$5.70 (2009)
With Fewer Industry Partners Providing Data, Analysis Takes on a New Dimension

80 Spring 2010 Results

- Most comprehensive set we ever published
- Includes durability, range, fuel economy, etc.
- Covers data from all 4 Learning Demo teams + CHIP project over 5 year period
- Majority of these will now stay static, serving as a historical record of Gen 1 & Gen 2 comparisons.

16 Fall 2010 Results

- No “new” CDPs, but we updated 16 previously published CDPs with data from the last 6 months
- Results on most recent durability, range, fuel economy, not yet possible to publish until more data accumulated (in 2011)
- 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

*Durability is defined by DOE as projected hours to 10% voltage degradation*

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(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.
Completed Final Analysis of Gen 1 Fuel Cell System Power Degradation

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
Based on Limited Data from Last 6 Months, Average Fueling Rate Decreased 14%
Real-World Driving Range Between Refuelings Continues to Improve as Demonstration Progresses

**Distance Driven Between Refuelings: All OEMs**

- **Gen1**
  - Refuelings \(^1\) = 18,941
  - Median distance between refuelings = 56 Miles

- **Gen2**
  - Refuelings \(^1\) = 6,870
  - Median distance between refuelings = 81 Miles
  - +45% improvement

- Refuelings after 2009Q4 \(^1\) = 3,185
  - Median distance between refuelings = 91 Miles
  - +63% improvement

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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
Driving Behavior in Last 6 Months
Much More Similar to U.S. National Average

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.
Range: NREL/SRNL Verified Toyota FCHV-adv Driving Range
>400-Mile (Without Refueling) on June 30, 2009

![Test Route Map]

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Average trip distance (miles)</th>
<th>H₂ consumed (kg)</th>
<th>Remaining usable H₂ (kg)</th>
<th>Calculated remaining range (miles)</th>
<th>(miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>331.50</td>
<td>4.8255</td>
<td>1.4854</td>
<td>102.04</td>
<td>433.55</td>
</tr>
<tr>
<td>#2</td>
<td>331.45</td>
<td>4.8751</td>
<td>1.4328</td>
<td>97.41</td>
<td>428.87</td>
</tr>
</tbody>
</table>

**Average:**
- **Distance:** 331 miles
- **H₂ Consumption:** 4.8255 kg
- **Usable H₂:** 1.4854 kg
- **Calculated Range:** 431 miles

**Evaluation of Range Estimates for Toyota FCHV-adv Under Open Road Driving Conditions**

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August 10, 2009

National Renewable Energy Laboratory

Innovation for Our Energy Future
Summary and Future Work

- Project has completed >5 full years of operation
- Vehicle operation: 114,000 hours, 2.87 million miles, 436,000 trips
- H2 station operation: 134,000 kg produced or dispensed, 27,000 refuelings
- DOE Key Technical Targets Met: FC Durability and Range
- Future Work:
  - Progress to be tracked over final 2 years of project
  - Additional collaboration with remaining auto OEM teams
  - New CA fueling stations planned for inclusion in future results as data becomes available
Questions and Discussion

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All public Learning Demo papers and presentations are available online at http://www.nrel.gov/hydrogen/proj_tech_validation.html