DOE HYDROGEN PROGRAM

Overview

The Biomass – Hydrogen Connection

Biomass R&D Technical Advisory Committee

November 12, 2007

Mark Paster
Technology Development Manager
U.S. Department of Energy Hydrogen Program
Why Hydrogen?

Domestic CO₂ Emissions by Sector (2005)

- **Residential**: 6%
- **Electric Power**: 39%
- **Industrial**: 18%
- **Transportation**: 33%
- **Commercial**: 4%

Domestic Oil Consumption (2005)

- **Electric Power**: 3%
- **Industrial**: 25%
- **Transportation**: 67%
- **Light Duty Vehicles**: 67%
- **Heavy Duty Vehicles**: 19%
- **Marine**: 4%
- **Rail**: 2%
- **Air**: 8%

- **Transportation**: Use of Hydrogen in fuel cell vehicles can reduce oil use and carbon emissions in the transportation sector.

- **Power Generation**: Hydrogen can enable clean, reliable energy for stationary and portable power generation.
HYDROGEN FUEL INITIATIVE (Jan. 2003):
- Launched the Department of Energy Hydrogen Program
- Committed $1.2 billion over five years (2004 – 2008)
- Provides funds to develop H₂, fuel cell and infrastructure technologies
- Goal: to make fuel cell vehicles practical and cost-effective by 2015

ADVANCED ENERGY INITIATIVE (Feb. 2006):
- Accelerates research on technologies for reducing dependence on oil for transportation and natural gas for power generation
- 22% increase in funding for clean energy research
- Reinforces Hydrogen Fuel Initiative
- Accelerates R&D for near-term vehicle options: biofuels & plug-in hybrids

“20-in-10” INITIATIVE (Jan. 2007):
- Sets target of 35 billion gallons of alternative fuels by 2017, to displace 15% of annual gasoline use in 2017 (plus 5% reduction in gasoline use through increased vehicle efficiency)
- Expands Renewable Fuel Standard (RFS) to “Alternative Fuel Standard” (includes corn ethanol, cellulosic ethanol, biodiesel, methanol, butanol, hydrogen, and other alternative fuels)
Hydrogen Economy Timeline

I. Technology Development
Research to meet technology performance and cost targets and establish technology readiness.

II. Initial Market Penetration
Portable power and stationary/transport systems are validated, infrastructure investment begins with governmental policies.

III. Expansion of Markets and Infrastructure
Hydrogen power and transportation systems commercially available, infrastructure business case realized.

IV. Fully Developed Markets and Infrastructure
Hydrogen power and transportation systems commercially available in all regions, national infrastructure developed.

EPACT Title VIII authorizes $3 billion in funding (FY 2006 – FY 2010) for hydrogen and fuel cell research, development, demonstration, education, and codes and standards development. Additional funding is authorized for FY 2011 – FY 2020.
Benefits — Reducing Greenhouse Gas Emissions

Well-to-wheels analysis* shows that use of H$_2$—from a variety of sources—would reduce greenhouse gas emissions.

*Analysis based on technology expected to be available in 2015, except for central hydrogen production pathways, which are based on delivery infrastructure expected in 2030.
Benefits — Reducing Petroleum Use

Well-to-wheels analysis* shows that use of hydrogen—from a variety of sources—would reduce oil consumption.

*Analysis based on technology expected to be available in 2015, except for central hydrogen production pathways, which are based on delivery infrastructure expected in 2030.
Challenges & Barriers

Technology Barriers

• Hydrogen Cost
  (target: $2 – $3/gge)

• Hydrogen Storage Capacity & Cost
  (targets: 2.7kWh/L, 3kWh/kg, and $2/kWh)

• Fuel Cell Cost and Durability
  (targets: $30 per kW, 5000-hour durability)

Technologies must be validated under real world conditions.

Economic & Institutional Barriers

• Delivery Infrastructure
  (target: <$1/gge)

• Domestic Manufacturing and Supplier Base

• Safety, Codes & Standards Development

• Public Awareness & Acceptance
The DOE Hydrogen Program is structured to tackle the wide range of barriers facing hydrogen and fuel cell commercialization.

Hydrogen Program Activities

- Basic Research & Applied R&D
- Manufacturing R&D
- Safety, Codes & Standards
- Education

Chart showing the integration of basic research, manufacturing, safety, and education to support hydrogen technology validation and commercialization.

H₂ Commercialization
DOE – Office of Energy Efficiency & Renewable Energy
Research, develop, and validate fuel cell and H2 production, delivery, and storage technologies for transportation and stationary applications.

DOE – Office of Nuclear Energy
Operate sulfur-iodine thermochemical and high-temperature electrolysis experiments to gather data on operability and reaction rates.

DOE – Office of Science
Expand basic research on nano-materials for storage, catalysis for fuel cells, and bio-inspired and solar H2 production. Increase emphasis on nano-structured design, novel synthesis, and theory and modeling of the physical and chemical interactions of hydrogen with materials.

DOE – Office of Fossil Energy
Continue studies for scaling up hydrogen membrane reactors and CO2/H2 separation technologies for coal-based hydrogen systems.
## Hydrogen Fuel Initiative Funding — By Participant Organization

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td><strong>HYDROGEN FUEL INITIATIVE</strong></td>
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<tr>
<td>EERE Hydrogen (HFCIT)</td>
<td>144,881</td>
<td>166,772</td>
<td>153,451</td>
<td>189,511</td>
<td>213,000</td>
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<tr>
<td>Fossil Energy (FE)</td>
<td>4,879</td>
<td>16,518</td>
<td>21,036</td>
<td>22,997</td>
<td>12,450</td>
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<tr>
<td>Nuclear Energy (NE)</td>
<td>6,201</td>
<td>8,682</td>
<td>24,057</td>
<td>18,855</td>
<td>22,600</td>
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<tr>
<td>Science (SC)</td>
<td>0</td>
<td>29,183</td>
<td>32,500</td>
<td>36,388</td>
<td>59,500</td>
</tr>
<tr>
<td><strong>DOE Hydrogen TOTAL</strong></td>
<td><strong>155,961</strong></td>
<td><strong>221,155</strong></td>
<td><strong>231,044</strong></td>
<td><strong>267,751</strong></td>
<td><strong>307,550</strong></td>
</tr>
<tr>
<td>Department of Transportation</td>
<td>555</td>
<td>549</td>
<td>1,411</td>
<td>1,420</td>
<td>1,425</td>
</tr>
<tr>
<td>Hydrogen Fuel Initiative TOTAL</td>
<td><strong>156,516</strong></td>
<td><strong>221,704</strong></td>
<td><strong>232,455</strong></td>
<td><strong>269,171</strong></td>
<td><strong>308,975</strong></td>
</tr>
</tbody>
</table>
The Program maintains strong partnerships with industry and government, and coordinates extensively with other stakeholder groups.

INTERNATIONAL PARTNERSHIPS

International Partnership for the Hydrogen Economy
- Represents 16 member countries and the European Commission
- Coordinates inter-governmental research, development and deployment programs
- Provides a forum for advancing policies and common codes and standards

International Energy Agency – Implementing Agreements
- **Hydrogen Implementing Agreement**: 22 member countries, plus the European Commission. Currently implementing Tasks 18 – 25.

U.S. PARTNERSHIPS
- FreedomCAR and Fuel Partnership
- Hydrogen Utility Group (e.g., Xcel Energy, Sempra)
- Other Federal Agencies (e.g., Interagency Hydrogen and Fuel Task Force (with OSTP), Interagency Working Group on Manufacturing R&D)
- State/Local Governments (e.g., California Fuel Cell Partnership, Upper Midwest Hydrogen Initiative)
Hydrogen Production & Delivery

**GOAL:** Diverse, domestic pathways to hydrogen production

**KEY OBJECTIVE:**
Reduce the cost to $2.00 – $3.00/gge (gallon gasoline equivalent) at the pump.

**Diagram:**
- **Near-Term:** Natural Gas Reforming, Bio-Derived Liquid Reforming, Water Electrolysis, Photoelectrochemical / Biological
- **Mid-Term:** Distributed (Natural Gas Reforming), Bio-Derived Liquid Reforming, Water Electrolysis, Photoelectrochemical / Biological
- **Long-Term:** Central (Coal with CO2 Sequestration, Biomass Gasification, Renewable Water Electrolysis, Solar or Nuclear High Temp Thermochem, Biological, Photoelectrochemical)
Hydrogen Production — Costs

The Program has reduced the cost of producing hydrogen from multiple pathways.

Near-term: Distributed Hydrogen → Produced at station to enable low-cost delivery

Longer-term: Centralized Production → Large investment in delivery infrastructure needed

**COST TARGET**

$\text{($2 – 3/gge)}$

**DISTRIBUTED PRODUCTION**

- Distributed Bio-Derived Renewable Liquids
- Distributed Electrolysis
- Distributed Natural Gas

**CENTRALIZED PRODUCTION**

- Biomass Gasification
- Central Wind Electrolysis
- Coal Gasification with Sequestration
- Nuclear
- Solar High-Temperature Thermochemical Cycle
Xcel-NREL Wind2H2 Project
installation complete, initial testing begun

Wind Turbine 100kW

Alkaline and PEM Electrolyzers

Compressor (150 psi – 3,500 psi)

AC-DC Converter

H₂ Storage (85kg)

H₂ Fuel Cell

Utility Grid

H₂ Fueling Station
Hydrogen Production — Solar Water Splitting

**Demonstrated small-scale solar-driven high-temperature thermochemical water splitting**

On-sun reduction at 1550 °C;
- H₂ production at 1100 °C
- YSZ-stabilized ferrite shows stability, repeatability

High-temperature water splitting (a "thermochemical" process) uses high temperatures produced from concentrated solar energy to drive chemical reactions that produce hydrogen. This is a long-term technology in the early stages of development.
Hydrogen from Biomass

Biomass Supply

• 6 – 10 Quads/year currently possible (300 – 600 million metric tons)
• >20 Quads/year projected potential by 2050 (> 1.2 billion metric tons)
• (Current LDV fleet consumes ~16 Quads)

Key Issues: Feedstock Cost, Technology Improvements, and Infrastructure.
Centralized Hydrogen Production Options

- Gasification/Pyrolysis $\rightarrow$ Hydrogen
- Biomass Hydrolysis $\rightarrow$ Aqueous Phase Reforming $\rightarrow$ Hydrogen
- Anaerobic Fermentation (e.g. landfill gas) $\rightarrow$ Methane $\rightarrow$ Hydrogen
  - Agriculture, MSW or industrial sites
- Biomass Hydrolysis to Sugars $\rightarrow$ Fermentation $\rightarrow$ Hydrogen

Central Biomass to Hydrogen R&D

- NREL: Pilot/Bench Scale integrated “standard biomass gasification
- GTI: Integrated gasification, reforming, membrane separation
- UTRC: Central biomass hydrolysis and aqueous phase reforming
Distributed Reforming of Bio-Derived Liquids

- Hydrolysis to Sugars → Fermentation → Ethanol → Hydrogen
- Gasification/Pyrolysis → Syngas → Ethanol, Mixed Alcohols, FTs → Hydrogen
- Pyrolysis → Bio-Oil → Hydrogen
- Hydrolysis to Sugars, etc. → Hydrogen  (Aqueous Phase Reforming)
Biomass Gasification/Pyrolysis Options

- **Gasification** (500 – 1000°C)
- **Reforming** (400 – 800°C)
- **Water Gas Shift** (~400°C)
- **Separation and Purification**

**Products:**
- Ethanol, mixed alcohols, FT-Liquids Synthesis
- Bio-oil

**End Products:**
- Hydrogen ($\text{H}_2$)
Sugar-Based Liquids for Distributed Reforming

- **Starch from Corn**
  - Enzyme Hydrolysis
  - Sugar
  - Ethanol

- **Cellulosic Biomass**
  - Hydrolysis
  - Sugars

- **Ethanol**

- **Distributed Reforming, Shift, and Separation/Purification**
  - \( H_2 \)
## Hydrogen Production Options — Summary

<table>
<thead>
<tr>
<th>Process Option</th>
<th>$/kg (Current)</th>
<th>$/kg (Projected)</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coal: Central Gasification</strong></td>
<td>$0.90 – $1.80</td>
<td>$0.50 – 1.40</td>
<td>$1/kg delivery, O₂ Separations, H₂ Separations, CO₂ sequestration</td>
</tr>
<tr>
<td><strong>Natural Gas: Distributed Reforming</strong></td>
<td>$3.00 ($2.75 – $3.50)</td>
<td>$2.00 – 3.00</td>
<td>Capital cost, NG Cost</td>
</tr>
<tr>
<td><strong>Biomass: Central Gasification/Pyrolysis</strong></td>
<td>$2.00 ($1.60-$2.20)</td>
<td>$1.00 – $2.00</td>
<td>Capital Cost, Process Intensification, Biomass Cost</td>
</tr>
<tr>
<td><strong>Biomass: Central Hydrolysis and APR</strong></td>
<td>--</td>
<td>--</td>
<td>Process Research/Feasibility, Biomass Cost</td>
</tr>
<tr>
<td><strong>Biomass: Central Anaerobic Fermentation/Methane/H₂</strong></td>
<td>--</td>
<td>--</td>
<td>?</td>
</tr>
<tr>
<td><strong>Biomass: Central sugar fermentation</strong></td>
<td>Very high</td>
<td>??</td>
<td>Breakthrough in Yield on Sugars</td>
</tr>
<tr>
<td><strong>Biomass: Distr. Ethanol Reforming</strong></td>
<td>$4.40 ($4.20 – $5.00)</td>
<td>&lt;$3</td>
<td>Capital Cost, Catalyst Life, Coking, Ethanol Cost</td>
</tr>
<tr>
<td><strong>Biomass: Distr. Liquids Reforming</strong></td>
<td>--</td>
<td>&lt;$3</td>
<td>Capital Cost, Catalyst Life, Coking, Feedstock Cost</td>
</tr>
<tr>
<td><strong>Biomass: Distr. APR</strong></td>
<td>--</td>
<td>&lt;$3</td>
<td>Capital Cost, Yield, Feedstock Cost</td>
</tr>
</tbody>
</table>
## Biomass Potential

### Biofuel yields per biomass dry ton

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Biomass (H₂/ton)</th>
<th>Corn Stover (ETOH/ton)</th>
<th>Wood Chips (ETOH/ton)</th>
<th>Stover/Lignin (ETOH/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Year</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005: State of Technology</td>
<td>54 Kg</td>
<td>65 gal</td>
<td>56 gal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>623 L</td>
<td>246 L</td>
<td>212 L</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.14 MBTU</td>
<td>4.94 MBTU</td>
<td>4.26 MBTU</td>
<td></td>
</tr>
<tr>
<td>2012: Target</td>
<td>90 gal</td>
<td>341 L</td>
<td>76 gal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>341 L</td>
<td>288 L</td>
<td>5.78 MBTU</td>
<td></td>
</tr>
<tr>
<td>2030: Estimate</td>
<td>&gt; 85 Kg</td>
<td>&gt; 980 L</td>
<td>&gt; 100 gal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt; 9.6 MBTU</td>
<td>&gt; 379 L</td>
<td>&gt; 7.60 MBTU</td>
<td></td>
</tr>
</tbody>
</table>

### Maximum #s for each vehicle-type powered by Biomass

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Fuel Volume³</th>
<th>#s 15K mile vehicles⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Fuel Cell</td>
<td>85x10¹⁰ Kg</td>
<td>400,000,000</td>
</tr>
<tr>
<td>E85 conventional</td>
<td>1.18x10¹¹ gal</td>
<td>240,720,000</td>
</tr>
<tr>
<td>E85 hybrid</td>
<td>1.18x10¹¹ gal</td>
<td>328,040,000</td>
</tr>
</tbody>
</table>

¹Assumes large scale, advanced, integrated technology
²10.4 MJ/L - George, T. 2000. DOE Hydrogen Program Review. San Ramon, CA.
³Estimate based on 2030 conversion technology and 1B ton of Biomass.
⁴Estimate based on PSAT model (Argonne) and 2020 vehicle technology.
Hydrogen/Biomass Programs Collaboration

- Joint participation in Annual Program Reviews
- Solicitation planning and selections
- Common research participants
- USDA/DOE MOU Ad-Hoc Hydrogen and Fuel Cell Committee
  - Thermochemical Biomass Process Teleseminars
  - Other
- Cost analysis collaboration
Hydrogen Delivery

**CURRENT:**
$2.50/kg (e.g., pipeline) –
$12.00/kg (e.g., liquid)

**TARGET:**
<$1.00/kg

Pathways
- Gaseous Hydrogen Delivery
- Liquid Hydrogen Delivery
- Carriers

Including mixed pathways

Components
- Pipelines
- Compression
- Liquefaction
- Carriers & Transformations
- Gaseous Storage Tanks
- Geologic Storage
- GH2 Tube Trailers
- Purification
- Terminals
- Dispensers
- Liquid Storage Tanks
- Mobile Fuelers
- Liquid Trucks, Rail, Ships
# Hydrogen Delivery — Challenges

<table>
<thead>
<tr>
<th>Pathway/Technology/Issue</th>
<th>Major Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipelines</td>
<td>Hydrogen embrittlement, capital cost, urban distribution</td>
</tr>
<tr>
<td>Compression—Transmission and Refueling Stations</td>
<td>Reliability, capital cost, energy efficiency, new technologies</td>
</tr>
<tr>
<td>Liquefaction</td>
<td>Capital cost, energy efficiency</td>
</tr>
<tr>
<td>Off-Board Storage Vessels</td>
<td>Capital cost</td>
</tr>
<tr>
<td>Geologic Storage</td>
<td>Sufficient suitable sites and capacity?</td>
</tr>
<tr>
<td></td>
<td>Contamination?</td>
</tr>
<tr>
<td>Gaseous Tube Trailers</td>
<td>Is 1000-kg capacity possible?</td>
</tr>
<tr>
<td>Hydrogen Quality</td>
<td>Must meet stringent quality requirements for PEM FC</td>
</tr>
<tr>
<td><strong>Carriers (leverages the onboard-storage program)</strong></td>
<td>Liquid two-way carriers: low cost and efficient hydrogenation and dehydrogenation, high (~100%) yields and selectivity</td>
</tr>
</tbody>
</table>
**KEY OBJECTIVE:** On-board H₂ storage to enable > 300 mile driving range while meeting all requirements for safety, cost, & performance (weight, volume, kinetics, etc.)

**NEAR TERM:** Allows for early market use of H₂ vehicles, but won’t provide full range on all platforms
- Pressurized tanks: currently in use in most H₂ vehicles
- Cryo-compressed storage: combines low-temperature H₂ storage with pressurization

**LONGER TERM:** Needed to enable >300-mile range
- Diverse portfolio with materials focus, for low-pressure storage
- Focus materials research on temperature, pressure, kinetics (as well as capacity)

New Engineering Center of Excellence Planned for FY08
Hydrogen Storage R&D — Application-driven goals and targets

**Capacity**
- > 300 mile range
- No loss of passenger/cargo space

**Operating temperature range**
- -40 to +85°C

**System cost & Fuel cost**

**Hydrogen supply rate/refueling rate**
- 0.02 g H₂ per sec. per kW of power
- Refueling time < 3 min. for 5 kg H₂

**Operability**
- On-board refueling with gas or liquid
- Off-board regeneration of hydrogen carrier
- Closed loop, no byproducts, energy efficient

**Safety, codes & standards, reliability, cycle life, efficiency . . .**

- Weight
- Volume (& conformability)
- System cost (& fuel cost)
- Durability/Operability
- Charging/Discharging Rates
- Efficiency
- Fuel Purity
- Environmental Health & Safety

There are many more DOE targets— not just wt%!
Hydrogen Storage — Systems Status

No technology meets targets—Results include data from vehicle validation

Hydrogen Storage: Status vs. Targets

Current focus: DOE system targets

Volumetric Capacity (g/L)

Gravimetric Capacity (wt%)

~ 103-190 miles verified, DOE Tech Val Program—77 vehicles

Estimates from developers & analysis results; periodically updated by DOE.
Examples of H₂ Storage Progress —
Material Capacity vs. Temperature

- Material Capacity vs. Temperature
  - DOE system targets
  - metal hydrides
  - chemical hydrides
  - adsorbents

<table>
<thead>
<tr>
<th>M-B-N-H</th>
<th>Mg(BH₄)₂(NH₃)₂</th>
<th>Mg(BH₄)₂</th>
<th>Ca(BH₄)₂</th>
<th>LiBH₄/CA</th>
<th>MgH₂</th>
<th>Li₃AlH₆/LiNH₂</th>
<th>1,6 naphthyridine</th>
<th>Mg(BH₄)₂(AlH₄)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgH₂</td>
<td>Li₃AlH₆/Mg(NH₂)₂</td>
<td>LiNH₂/MgH₂</td>
<td>Mg(BH₄)₂(AlH₄)</td>
<td>MgH₂</td>
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<td>Mg(BH₄)₂(AlH₄)</td>
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G. Thomas, et al., DOE (April 2007)
Fuel Cell R&D

MAJOR RESEARCH AREAS:
- Membranes
- Catalysts & Supports
- Water Transport
- Characterization & Analysis

PRIMARY FOCUS
- Primary focus is on fuel cells for transportation applications
- R&D is focused on components rather than systems

SECONDARY FOCUS
- Stationary and other early-market fuel cells to establish the manufacturing base

KEY TARGETS:
- $45/kW by 2010; $30/kW by 2015
- 5,000-hour durability by 2015

KEY TARGETS:
- Distributed Power: $750/kW and 40,000-hour durability (with 40% efficiency) by 2011
- APUs: Specific power of 100 W/kg and power density of 100 W/L by 2010
- Portable Power: Energy density of 1,000 Wh/L by 2010
Fuel Cells — Progress

**Fuel Cell Cost**
(80kW Direct H₂ automotive fuel cell)

- $275/kW*
- $110/kW*
- $84/kW* — preliminary
- $45/kW
- $30/kW

*Projected to high-volume manufacturing of 500,000 units/year*

**Fuel Cell Stack Durability**
(automotive)

- 2003 Status: 1000 hours
- 2006 Status: 2000 hours
- 2015 Target: 5000* hours

*5000 hours corresponds to roughly 150,000 miles of driving*
Fuel Cell Progress —
Improved Membrane Durability

Developed membrane with nearly 5,000-hour durability — with humidity and voltage cycling

• improved durability with no performance loss
• more resistant to mechanical and chemical stresses

![Graph showing time to failure of different membranes](graph.png)

- Reinforced Membrane + Advanced Stabilization
- Reinforced CS Membrane
- Reinforced Membrane (non-CS)
- Baseline 1 mil cast Nafion®

3M Membrane Development

- New 3M Membrane (Mix of 800 and 1,000 EW samples): 4,289 hours
- Standard PFSA Membrane: 235 hours
Technology Validation — Vehicles & Infrastructure

Technologies are validated and progress evaluated through learning demonstrations.

DOE Vehicle/Infrastructure Demonstration

Four teams, in 50/50 cost-shared projects, operating 77 fuel cell vehicles and 14 hydrogen stations.

Verified fuel cell vehicle performance:
- EFFICIENCY: 53 – 58% (>2x higher than internal combustion gasoline engines)
- RANGE: 103 – 190 miles
- FUEL CELL SYSTEM DURABILITY: 1600 hours (~48,000 miles)

Demonstrated Fuel Cost: $3/gge, from natural gas.

DOT is demonstrating fuel cell buses and providing data to DOE for analysis.

Eight buses in California, Massachusetts, New York, South Carolina, and Washington, DC.
DOE is actively promoting commercialization of PEM fuel cell technologies by supporting early adoption, and by building partnerships with the public and private sectors.

**EARLY MARKET OPPORTUNITIES**

**Fuel Cells for Backup Power:**
- Longer continuous run-time, greater durability than batteries
- Require less maintenance than batteries or generators
- Potential cost savings over batteries and generators

**Fuel Cells for Material Handling Equipment:**
- Allow for rapid refueling — much faster than changing-out or recharging batteries
- Provide constant power — without voltage drop
- Eliminate need for space for battery storage and chargers
Looking Ahead —
Scenario analysis examines infrastructure development

Los Angeles and New York City metro areas represent the most attractive initial marketplaces for the introduction of hydrogen FCVs. This is due to these areas’ high population density.

“Lighthouse” concept: targets top urban areas

2012-2015: INITIAL INTRODUCTION
- New York/Northern NJ/Long Island
- Los Angeles/Riverside/Orange County/San Diego

2016-2019: TARGETED REGIONAL GROWTH
- San Francisco/Oakland/San Jose/ Sacramento/Yolo
- Boston/Worcester/Lawrence
- Washington/Baltimore
- Chicago/Gary/Kenosha
- Detroit/Ann Arbor/Flint
- Dallas/Fort Worth
- Atlanta

2020-2025: INTER-REGIONAL EXPANSION
- Houston/Galveston/Brazoria
- St. Louis
- Minneapolis/St. Paul
- Philadelphia/Wilmington/
- Atlantic City
- Phoenix/Mesa
- Denver/Boulder/Greeley
Looking Ahead – Analysis of potential vehicle market penetration scenarios* helps to assess infrastructure needs

**Initial Stages** | **Interim Growth** | **Market Penetration by 2025**
---|---|---
**Scenario 1** | By 2012: *hundreds to thousands* of vehicles per year | By 2018: *tens of thousands* of vehicles per year | 2.0 million vehicles
**Scenario 2** | By 2012: *thousands of vehicles* per year | By 2015: *tens of thousands* per year; by 2018: *hundreds of thousands* per year. | 5.0 million vehicles
**Scenario 3** | By 2012: *thousands of vehicles* per year | By 2021: *millions* of vehicles per year | 10.0 million vehicles

*These are scenarios for analysis purposes only. They do not represent a strategy or a proposal.*
Questions?

For more information visit: [www.hydrogen.energy.gov](http://www.hydrogen.energy.gov)

**Hydrogen Posture Plan**
*For more information on the Hydrogen Program*
[www.hydrogen.energy.gov/roadmaps_vision.html](http://www.hydrogen.energy.gov/roadmaps_vision.html)

**Learning Demonstration Interim Progress Report**
*For more information on the vehicle/infrastructure demonstration*

**Hydrogen Overview Book**
*For more information on hydrogen and fuel cell technologies*
[www1.eere.energy.gov/hydrogenandfuelcells/education/h2iq.html](http://www1.eere.energy.gov/hydrogenandfuelcells/education/h2iq.html)
Back-up Slides
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