“We’ve got to invest in a serious, sustained, all-of-the-above energy strategy that develops every resource available for the 21st century.”

– President Barack Obama

“Advancing hydrogen and fuel cell technology is an important part of the Energy Department’s efforts to support the President’s all-of-the-above energy strategy, helping to diversify America’s energy sector and reduce our dependence on foreign oil.”

– Energy Secretary Steven Chu

“Fuel cells are an important part of our energy portfolio...deployments in early markets are helping to drive innovations in fuel cell technologies across multiple applications.”

– Dr. David Danielson
Assistant Secretary for Energy Efficiency and Renewable Energy
**Portfolio Examples**

**Transportation: A diverse portfolio** to meet the full range of driving cycles and duty cycles in the nation’s vehicle fleet.

*H₂ and fuel cells can play a key role* — by enabling longer driving ranges and heavier duty cycles for certain vehicle types (including buses, light-duty cars & trucks, delivery vans, and short-haul trucks)

**Advantages of Batteries and Fuel Cells:**

- For shorter distances, batteries are more effective in terms of system mass
- *Fuel cells can provide the driving ranges of today’s vehicles without the weight penalty*
- *But there are challenges: H₂ production, infrastructure, fuel cell cost & durability*
Hydrogen: A Diverse Energy Carrier

- H₂ can be produced from diverse domestic resources
- ~95% of U.S. H₂ comes from natural gas reforming
- ~30% growth estimated for global production by 2016
  $118 billion in market revenues projected
Fuel Cells Overview and Benefits

The Role of Fuel Cells

Diverse Energy Sources & Fuels
- Biomass
- Natural Gas
- Propane
- Diesel
- Other Hydrocarbons
- Methane
- Methanol

Clean, Efficient Energy Conversion

Fuel Cells
- Alkaline
- Direct Methanol
- Molten Carbonate
- Polymer Electrolyte Membrane (PEM)
- Phosphoric Acid
- Solid Oxide

Diverse Applications

Stationary Power

Transportation

Portable Power

Energy Storage for Renewable Electricity

Hydrogen
from renewables or low carbon resources

Intermittent Renewables (solar, wind, ocean)

Very High Efficiency
- > 60% (electrical)
- > 70% (electrical, hybrid fuel cell / turbine)
- > 80% (with CHP)

Reduced CO₂ Emissions
- 35–50%+ reductions for CHP systems (>80% with biogas)
- 55–90% reductions for light-duty vehicles

Reduced Oil Use
- >95% reduction for FCEVs (vs. today’s gasoline ICEVs)
- >80% reduction for FCEVs (vs. advanced PHEVs)

Reduced Air Pollution
- up to 90% reduction in criteria pollutants for CHP systems

Fuel Flexibility
- Clean fuels — including biogas, methanol, H₂
- Hydrogen — can be produced cleanly using sunlight or biomass directly, or through electrolysis, using renewable electricity
- Conventional fuels — including natural gas, propane, diesel

Key Benefits

US DOE 12/5/2012 eere.energy.gov
Benefits: Well-to-Wheels CO₂ Analysis

Analysis by DOE - Argonne National Lab, DOE Vehicle Technologies Program, and Fuel Cell Technologies Program shows benefits from a portfolio of options

**Well-to-Wheels Greenhouse Gases Emissions**

- Gasoline (Today’s Vehicle): 450 grams CO₂-equivalent per mile
- Gasoline: 340
- Natural Gas: 270
- Diesel: 220
- Corn Ethanol (E85): 180
- Cellulosic Ethanol (E85): 90
- Gasoline & U.S. Grid Mix: 230
- Gasoline & Ultra-low Carbon Renewable: 195
- Cellulosic Ethanol (E85) & U.S. Grid Mix: 105
- Cellulosic Ethanol (E85) & Ultra-low Carbon Renewable: 70
- Gasoline & U.S. Grid Mix: 270
- Gasoline & Ultra-low Carbon Renewable: 155
- Cellulosic Ethanol (E85) & U.S. Grid Mix: 180
- Cellulosic Ethanol (E85) & Ultra-low Carbon Renewable: 63
- U.S. Grid Mix: 230
- Ultra-low Carbon Renewable: 0
- H₂ - Distributed Natural Gas: 95
- H₂ - Coal Gasification w/ Sequestration: 87
- H₂ - Biomass Gasification: 87
- H₂ - Nuclear High-T Electrolysis or Ultra-low Carbon Renewable: 42

**Conventional Internal Combustion Vehicles**

**Plug-in Hybrid Electric Vehicles**

- (power-split, 10-mile electric range)

**Plug-in Hybrid Electric Vehicles**

- (series, 40-mile electric range)

**Battery Electric Vehicles**

- (100-mile range)

**Fuel Cell Electric Vehicles**

**H₂ from Natural Gas**

Even FCEVs fueled by H₂ from distributed NG can result in a >50% reduction in GHG emissions from today’s vehicles.

Use of H₂ from NG decouples carbon from energy use—i.e., it allows carbon to be managed at point of production vs at the tailpipe.

Even greater emissions reductions are possible as hydrogen from renewables enter the market.

**Notes:**
For a projected state of technologies in 2035-2045. Ultra-low carbon renewable electricity includes wind, solar, etc. Does not include the lifecycle effects of vehicle manufacturing and infrastructure construction/decommissioning.

Analysis & Assumptions at: http://hydrogen.energy.gov/pdfs/10001_well_to_wheels_gge_petroleum_use.pdf
Benefits: Well-to-Wheels Petroleum Analysis

Analysis by DOE - Argonne National Lab, DOE Vehicle Technologies Program, and Fuel Cell Technologies Program shows benefits from a portfolio of options

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Analysis & Assumptions at: http://hydrogen.energy.gov/pdfs/10001_well_to_wheels_gge_petroleum_use.pdf

**H₂ from Natural Gas**
FCEVs fueled by H₂ from distributed natural gas can almost completely eliminate petroleum use.

*1 million FCEVs would require ~1 billion cubic meters/year of NG; current NG consumption is about 600 billion cubic meters/yr*
Current Status

- Over **9 million metrics tons** of hydrogen produced per year
- Over **1,200 miles** of hydrogen pipelines in use (CA, TX, LA, IL, and IN)
- Hydrogen is delivered via liquid tank truck and gas tube trailer.
- There are more than **50 fueling stations** in the U.S.

Existing Hydrogen Production Facilities

- Significant hydrogen supply infrastructure is already located near most major U.S. cities.
- Hydrogen can be delivered from central production facilities to fueling stations by liquid truck, tube trailer or new drop-tank system (Air Products).
Hydrogen Production Strategies

Goal: Develop technologies to produce hydrogen from clean, domestic resources at a delivered and dispensed cost of $2-$4/gge H₂ by 2020
## Techno-economic Pathway Analysis

### The 2012 “new & improved” H2A Model v3 with unified cost assumptions

#### General Features

**User Input**
- Process modeling
- Vendor quotes
- Literature sources

**H2A Values**
- AEO fuel prices
- Fuel properties
- GREET emissions factors
- Industry cost indexes

**H2A Calculations**
- Cost escalation
- Plant Scaling
- Financial Calculations
- Cash flow calculations and leveled cost of hydrogen

#### Improvements

- Streamlined and clarified user input
- Updated H2A “Built-In” database
- New plant scaling and CSD calculations
- Allows for across-the-board assessment of status and targets for production pathways

#### Updated Production Targets*

<table>
<thead>
<tr>
<th></th>
<th>2010 Status</th>
<th>2015 Target</th>
<th>2020 Target</th>
<th>Ultimate Production Target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distributed</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolysis from grid electricity</td>
<td>$4.10</td>
<td>$3.90</td>
<td>$2.30</td>
<td>$1-$2</td>
</tr>
<tr>
<td>Bio-derived Liquids (based on ethanol reforming case)</td>
<td>$6.65</td>
<td>$5.10</td>
<td>$2.25</td>
<td></td>
</tr>
<tr>
<td><strong>Central</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolysis From renewable electricity</td>
<td>$4.10</td>
<td>$3.00</td>
<td>$2.00</td>
<td>$1-$2</td>
</tr>
<tr>
<td>Biomass Gasification</td>
<td>$2.20</td>
<td>$2.10</td>
<td>$2.00</td>
<td></td>
</tr>
<tr>
<td>Solar Thermochemical</td>
<td>NA</td>
<td>$8.00</td>
<td>$3.00</td>
<td></td>
</tr>
<tr>
<td>Photoelectrochemical</td>
<td>NA</td>
<td>$26.00</td>
<td>$4.00</td>
<td></td>
</tr>
<tr>
<td>Biological</td>
<td>NA</td>
<td>NA</td>
<td>$10.00</td>
<td></td>
</tr>
</tbody>
</table>

*Production only. Preliminary numbers. All units are per gge.


Natural gas reforming can provide H₂ production for expanding near-term fuel cell applications and serve as a bridge to longer-term low-carbon alternative pathways.

Projected High-Volume Cost of Hydrogen Production with Feedstock Sensitivities

Notes:

[1] Based on projections from H2A analyses, excludes delivery and dispensing costs. Projections of costs assume Nth-plant construction, distributed station capacities of 1,500 kg/day, and centralized station capacities of ≥50,000 kg/day.

[2] The H₂ Production Threshold Cost of <$2/gge reflects the Production apportionment
Determined world’s first Tri-generation station (CHHP with 54% efficiency)
- Anaerobic digestion of municipal wastewater-

Fountain Valley demonstration
- ~250 kW of electricity
- ~100 kg/day hydrogen capacity (350 and 700 bar), enough to fuel 25 to 50 vehicles.
Two Main Options for Low-cost Early Infrastructure

1. Hydrogen delivered from central site
   - Low-volume stations (~200-300 kg/day) would cost <$1M and provide hydrogen for $7/gge (e.g., high-pressure tube trailers, with pathway to $5/gge at 400–500 kg/day- comparable to ~$2.10/gallon gasoline untaxed)

2. Distributed production (e.g. natural gas, electrolysis)

Other options

1. Co-produce H₂, heat and power (tri-gen) with natural gas or biogas
2. Hydrogen from waste (industrial, wastewater, landfills)
Early hydrogen cost is high, but falls with increasing scale to $3-4/gge.

Analysis is underway to determine cost reduction scenarios.

Levelized Cost of H2 ($/kWh, $2005)

Levelized Cost of H2 ($/kg, $2005)

## Challenges & Barriers

### Distributed Production
- **Bioderived Liquid Reforming**
  - Capital costs
  - Operation and Maintenance costs
  - Design for manufacturing
  - Feedstock quantity and quality
- **Electrolysis**
  - System efficiency and capital costs
  - Integration with renewable energy sources
  - Design for manufacturing

### Central Production
- **Solar Thermochemical**
  - Cost-effective reactor
  - Effective and durable construction materials
- **Photoelectrochemical**
  - Effective photocatalyst material
- **Biological**
  - Sustainable H₂ production from microorganisms
  - Optimal microorganism functionality
  - Cost effective reactor materials
- **Biomass Gasification**
  - Capital costs
  - Feedstock costs & purity
  - System efficiency

### Delivery
- **Forecourt**
  - Compressor reliability
  - Station infrastructure (compression, storage, and dispensing) costs
- **Tube Trailer Delivery**
  - Vessel capacity
- **Liquid Delivery**
  - Liquefaction efficiency & associated GHG emissions
- **Pipelines**
  - Embrittlement/cyclic fatigue effects on pipeline steel
  - Infrastructure installation and lifetime costs
- **Analysis & Standards**
  - Impact of code requirements
  - Trade study: production pressure vs. station compression.

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**Materials durability, efficiency improvements, and capital cost reductions are key challenges for all pathways**
Challenges: Delivery

Station costs dominate delivery costs—key focus area.

Fueling Station (CSD) Costs

<table>
<thead>
<tr>
<th></th>
<th>2011 Projected Cost*</th>
<th>2020 Projected Cost*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centralized Production</td>
<td>$1.90/kg</td>
<td>$1.30/kg</td>
</tr>
<tr>
<td>Distributed Production</td>
<td>$2.50/kg</td>
<td>$1.70/kg</td>
</tr>
</tbody>
</table>

Pathway Cost
Ex: CGH₂ Transport by Tube Trailer

Refueling Station (2011 Technology)

FY2012 Analysis Focus

- Identify cost drivers for H₂ delivery in early market applications
- Evaluate options to improve station compressor reliability
- Investigate the role of high-pressure tube trailers in reducing station costs

Based on preliminary HDSAM (v2.3) analysis assuming 15% market penetration in a city with a population of 1.2M

Safety, Codes and Standards

- Trained > 23,000 first-responders and code officials on hydrogen safety and permitting through on-line and in-classroom courses
- 206 Lessons Learned Events in "H2Incidents.org"
- Approximately 750 entries in the Hydrogen Safety Bibliographic Database

www.eere.energy.gov/hydrogenandfuelcells/codes/
<table>
<thead>
<tr>
<th>Recent Relevant FOAs</th>
<th>$M Planned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collect Performance Data on Fuel Cell Electric Vehicles</td>
<td>$6.0</td>
</tr>
<tr>
<td>Hydrogen Fueling Stations and Innovations in Hydrogen Infrastructure Technologies</td>
<td>$2.4</td>
</tr>
<tr>
<td>Fuel Cell Powered Baggage Vehicles at Commercial Airports</td>
<td>$2.5</td>
</tr>
<tr>
<td>Fuel Cell Hybrid for Refrigerated Truck Delivery (PNNL)</td>
<td>$0.65</td>
</tr>
<tr>
<td>Zero-Emission Cargo Transport Vehicles (VTP)</td>
<td>$10.0</td>
</tr>
<tr>
<td>Hydrogen Production Cost Analysis</td>
<td>Up to $1.0</td>
</tr>
</tbody>
</table>
| SBIR: Dispenser Hose Assemblies (active)                                           | Phase 1 $0.15  
|                                                                                   | Phase 2 $1.0  |
| Total                                                                            | $23.7M     |
Key Reports

Pathways to Commercial Success: Technologies and Products Supported by the Fuel Cell Technologies Program
By PNNL, http://www.pnl.gov/

The Business Case for Fuel Cells 2011: Energizing America’s Top Companies

State of the States 2011: Fuel Cells in America

Annual Merit Review & Peer Evaluation Proceedings
Includes downloadable versions of all presentations at the Annual Merit Review
http://www.hydrogen.energy.gov/annual_review11_proceedings.html

Annual Merit Review & Peer Evaluation Report
Summarizes the comments of the Peer Review Panel at the Annual Merit Review and Peer Evaluation Meeting
http://hydrogen.energy.gov/annual_review11_report.html

Annual Progress Report
Summarizes activities and accomplishments within the Program over the preceding year, with reports on individual projects
www.hydrogen.energy.gov/annual_progress.html

Next Annual Review: May 13–17, 2013 Arlington, VA
http://annualmeritreview.energy.gov/
Professor Thomas Jaramillo (Stanford) received a 2012 Presidential Early Career Award for Scientists & Engineers (PECASE). PECASE is the highest honor bestowed by the U.S. government on outstanding scientists and engineers who are early in their independent research careers. Jaramillo is the first ever EERE awardee.

Dr. Adam Weber (LBNL) and Professor Vijay Ramani (IIT) honored as Energy Technology Division Supramaniam Srinivasan Young Investigator Award from The Electrochemical Society in Seattle.

Professor Scott Samuelsen (UC Irvine) named a White House Champion of Change for his work as Director of the Advanced Power and Energy Program and the National Fuel Cell Research Center.

Dr. Fernando Garzon (LANL) was elected President of the National Electrochemical Society (ECS).

Dr. Radoslav Adzic (BNL) honored as 2012 Inventor of the Year by the NY Intellectual Property Law Association.

Other Presidential Awardees:

- **Professor Susan Kauzlarich** – UC Davis, a 2009 recipient of the Presidential Award for Excellence in Science, Mathematics and Engineering Mentoring—and a partner of the Chemical Hydrogen Storage Center of Excellence

- **Dr. Jason Graetz** – Brookhaven National Laboratory, a 2009 recipient of the Presidential Early Career Award for Scientists and Engineers—and a partner of the Metal Hydride Center of Excellence

- **Dr. Craig Brown** – NIST, a 2009 recipient of the Presidential Early Career Award for Scientists and Engineers—and a Partner of the Hydrogen Sorption Center of Excellence
Thank You

Sunita.Satyapal@ee.doe.gov

New energy data initiative to share the latest energy information and data. Please visit:


hydrogenandfuelcells.energy.gov