Overview of Hydrogen and Fuel Cell Activities

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Fuel Cell Technologies Program
United States Department of Energy

Mountain States Hydrogen Business Council
September 14, 2010
Administration’s Clean Energy Goals

- Double Renewable Energy Capacity by 2012
- Invest $150 billion over ten years in energy R&D to transition to a clean energy economy
- Reduce GHG emissions 83% by 2050
U.S. Energy Consumption

U.S. Primary Energy Consumption by Source and Sector

- Coal: 23%
- Petroleum: 37%
- Natural Gas: 24%
- Nuclear Electric Power: 9%
- Renewable Energy: 7%

Transportation: 37%
Industrial: 19%
Residential and Commercial: 31%
Electric Power: 22%

Share of Energy Consumed by Major Sectors of the Economy, 2008

Total U.S. Energy = 99.3 Quadrillion Btu
The Program has been addressing the key challenges facing the widespread commercialization of fuel cells.

### Technology Barriers*

#### Fuel Cell Cost & Durability

Targets*:  
*Stationary Systems*: $750 per kW, 40,000-hr durability  
*Vehicles*: $30 per kW, 5,000-hr durability

#### Hydrogen Cost

Target*: $2 – 3 /gge, (dispensed and untaxed)

#### Hydrogen Storage Capacity

Target: > 300-mile range for vehicles—without compromising interior space or performance

### Economic & Institutional Barriers

- Safety, Codes & Standards Development
- Domestic Manufacturing & Supplier Base
- Public Awareness & Acceptance
- Hydrogen Supply & Delivery Infrastructure

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* Targets and Metrics are being updated in 2010.

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**Market Transformation**

Assisting the growth of early markets will help to overcome many barriers, including achieving significant cost reductions through economies of scale.
Fuel Cells — Where are we today?

**Fuel Cells for Stationary Power, Auxiliary Power, and Specialty Vehicles**

The largest markets for fuel cells today are in stationary power, portable power, auxiliary power units, and forklifts.

~75,000 fuel cells have been shipped worldwide.

~24,000 fuel cells were shipped in 2009 (> 40% increase over 2008).

*Fuel cells can be a cost-competitive option for critical-load facilities, backup power, and forklifts.*

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**Fuel Cells for Transportation**

In the U.S., there are currently:

> 200 fuel cell vehicles

~20 fuel cell buses

~60 fueling stations

Several manufacturers—including Toyota, Honda, Hyundai, Daimler, GM, and Proterra (buses)—have announced plans to commercialize vehicles by 2015.

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**The Role of Fuel Cells in Transportation**

In the U.S., there are currently:

~9 million metric tons of \( \text{H}_2 \) produced annually

> 1,200 miles of \( \text{H}_2 \) pipelines
Projected high-volume cost of fuel cells has been reduced to $61/kW (2009)

- More than 15% reduction in the last two years
- More than 75% reduction since 2002
- 2008 cost projection was validated by independent panel**

As stack costs are reduced, balance-of-plant components are responsible for a larger % of costs.

*Based on projection to high-volume manufacturing (500,000 units/year).

**Panel found $60 – $80/kW to be a “valid estimate”: [http://hydrogendoedev.nrel.gov/peer_reviews.html](http://hydrogendoedev.nrel.gov/peer_reviews.html)
**Challenges for Fuel Cell Development**

### Key R&D Gaps

#### Catalysis
- Low and no-content PGM cathode, on corrosive resistant support, with containment and anion tolerance
- Improved catalyst nano-structure design and electrode/MEA optimization for novel catalysts

#### MEAs, Components & Integration
- Need to develop, test and integrate (into MEA) robust, manufacturable low-cost membranes that are tolerant to reformate impurities and operate at high-T (e.g. 95°C), low-humidity; related ionomers. High operation and maintenance costs
- Manufacturable, electrodes, MEAs, having optimized ionomer/support structures, with understanding of the interface as it relates to transport and durability for low-T and high-T operation (120-150; 150-200 °C)
- Standardized, accelerated durability tests of “real-world” degradation mechanisms for integrated systems.

#### Innovative concepts
- AFCs, high-T fuel cells for transportation applications, reversible SOFCs, novel fuel cell stack designs for early market applications

#### MCFC and PAFC high-T fuel cells  
(gap analysis report/workshop)
- Low cost stack components to address durability and performance (electrolyte support and durable cathode - MCFC; durable low-Pt catalysts, supports, bipolar plates - PAFC)

#### Low and high T fuel cell  
BOP and fuel processing
- Low cost, durable, converters, blowers, humidifier and sensors for low and high-T
- Catalysts and systems for fuel flexibility, gas clean up, and impurities studies

DOE 09/02/2010
### Hydrogen Production Pathways

**Challenge:** Reduce cost of H₂ (delivered, dispensed, and untaxed)

<table>
<thead>
<tr>
<th>NEAR-TERM</th>
<th>MID-TERM</th>
<th>LONG-TERM</th>
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<tbody>
<tr>
<td><strong>CENTRAL</strong></td>
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</table>
| Coal Gasification (No Sequestration)

Bio-Derived Liquids Reforming

Biomass Gasification (no Carbon Sequestration)

Biomass Gasification (with Carbon Sequestration)

Water Electrolysis (Solar)

High-temp Thermo-chemical

Biological

**DISTRIBUTED**

Natural Gas Reforming

Water Electrolysis (Wind)

Water Electrolysis (Wind)

High-Temp Water Electrolysis

Photo-electrochemical

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**Enabling technologies under development by**

1. The Office of Fossil Energy
2. The Biomass Program
3. The Nuclear Hydrogen Initiative
4. The Solar Energy Technologies Program
5. The Office of Basic Energy Sciences
6. The Wind Program
7. The Geothermal Technologies Program
8. The Hydrogen Utility Group
9. The International Partnership for a Hydrogen Economy

*Gray text = reduces GHG impact
Green text = significantly reduces GHG impact*

- Feedstock Source
- Energy Source
Hydrogen Costs Are Being Reduced

Progress has been made in all distributed production pathways and will continue work to reduce cost in central production pathways.

Projected High-Volume Cost of Hydrogen (Dispensed) — Status ($/gallon gasoline equivalent [gge], untaxed)

**NEAR TERM:**
- Distributed Production
  - H₂ from Natural Gas
  - H₂ from Ethanol Reforming
  - H₂ from Electrolysis

**LONGER TERM:**
- Centralized Production
  - Biomass Gasification
  - Central Wind Electrolysis
  - Coal Gasification with Sequestration
  - Solar Thermochemical Cycle
Hydrogen Production R&D
2010 Progress & Accomplishments - Examples

The key objective is to reduce cost of H₂ (delivered, dispensed & untaxed)

**Electrolysis**
> 20% reduction cost of electrolyzer cell via a 55% reduction in catalyst loading from new process techniques (Proton Energy)

![Graph showing electrolysis results]

**Algae**
Continuous fermentative / photobiological H₂ production from potato waste achieved a maximum molar yield of 5.6 H₂/glucose (NREL)

![Diagram of algae process]

**Diagram notes:**
- Cathode bipolar plate
- Cathode channel
- Cathode GDL
- Anode GDL
- Anode channel
- Anode bipolar plate
- Cathode catalyst layer
- Membrane
- Anode catalyst layer
Hydrogen Production R&D
2010 Progress & Accomplishments - Examples

Reforming & Separation Processes
Minimized the acid sites for undesired reaction pathways for aqueous phase reforming of BDL using Pt-Re/C catalysts, resulting in H2 yields well above 60%. (PNNL)

Hydrogen from Coal
Initiated tests under water-gas shift feed streams and demonstrated a H2 flux rate of 411 scfh/ft². (Eltron)

Lifetime testing reactor operated several tests to 600 hours; initial baseline membrane testing in H2/N2 feed streams show stable performance at 200 scfh/ft².

PNNL Hydrogen Lifetime Testing Skid
Hydrogen Delivery

Delivery Technologies

Stations Using Compressed Gaseous Hydrogen

Stations Using Cryo-compressed Hydrogen (from liquid hydrogen delivery)
**RECENT ACCOMPLISHMENTS**

- **Testing demonstrated Cryopump flow rates up to 2 kg / min exceeding targets (BMW, Linde, LLNL)**
  - Provides lowest cost compression option for a station and meets the challenges of sequential vehicle refueling

- **Demonstrated manufacturability and scalability of glass fiber wrapped tanks through sequential prototypes (3 to 24 to 144 inches in length) (LLNL)**

- **Completed design criteria and specifications for centrifugal compression of hydrogen which are projected to meet or exceed DOE targets. Compressor designed using off-the-shelf parts is in testing (Concepts NREC)**

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**We’ve reduced the cost of hydrogen delivery* —**

- ~30% reduction in tube trailer costs
- >20% reduction in pipeline costs
- ~15% reduction liquid hydrogen delivery costs

*Projected cost, based on analysis of state-of-the-art technology

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**Projected Cost of Delivering Hydrogen**

*Cost reductions enabled by:*

- New materials for tube trailers
- Advanced liquefaction processes
- Replacing steel with fiber reinforced polymer for pipelines

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**PROJECTED COST OF DELIVERING HYDROGEN**

- **$ / gge**

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**2005$, 20% market penetration for Sacramento at 1000 kg/ day stations**

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**RECENT ACCOMPLISHMENTS**

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Recent Progress (Lincoln Composites and Livermore National Laboratory):

- Higher capacity with carbon fiber
  - Doubled capacity to 600 kg H₂
  - Demonstrated large scale dome molding, tubular welding, and filament winding of tanks
- Trailer with glass fibers
  - Demonstrated stronger glass fibers at lower temperatures to project reduced delivery tank costs
- Identified pathway to triple capacity: 1,100 kg H₂
- Potential for up to 50% trailer cost reduction

Future Work:

- High performance glass fiber composite pressure vessels
- High pressure hydrogen tank for storage and gaseous truck delivery
- CF testing and failure analysis
- Integrated alloy/concrete vessel design and fabrication for low-cost storage at the station
Critical Challenges for H₂ Delivery

**Key R&D Gaps**

**Compression Technologies**
- Reliability
- Efficiency
- Cost
- Materials Compatibility

**Bulk Storage**
- Hydrogen Quality
- Cost (fluctuating raw materials cost)
- Materials Compatibility

**Pipeline**
- Safety
- Reliability
- Durability

**Liquefactionation**
- Cost
- Energy Efficiency
On-board Hydrogen Storage

Challenge: Providing a 300 mile driving range without sacrificing passenger and cargo space

Compressed
- 350 bar
- 700 bar
- Cryo-compressed

Low-pressure,
Materials-based:
- Adsorbents;
- Metal Hydrides;
- Chemical Hydrides

Near-term
Mid-term
Long-term
Compressed gas storage offers a near-term option for initial vehicle commercialization and early markets

- Validated driving range of up to ~ 430 mi
- Cost of composite tanks is challenging
  - carbon fiber layer estimated to be >75% of cost
- Advanced materials R&D under way for the long term

Projected Capacities for Complete 5.6-kg H\textsubscript{2} Storage Systems

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Projected Ranges of System Gravitmetric Storage Capacity
For Chemical, Metal Hydride, Sorbent and Physical Storage Technologies

350-bar Base Case Factory Cost\textsuperscript{1} = $2,500
$13/kWh based on 5.6 kg usable H\textsubscript{2} (8 kg stored H\textsubscript{2})

\textbf{Cost estimate in 2005 USD. Includes processing costs.}
## Key R&D Gaps

### System
- Cost
- Performance
  - Gravimetric
  - Volumetric
  - Lifecycle
  - Manufacturability

### Materials
- Capacity
- Thermodynamics
- Kinetics
- Cycling
RECENT ACCOMPLISHMENTS

Vehicles & Infrastructure

- Fuel cell durability
  - 2,500 hours projected (nearly 75K miles)
- Over 2.8 million miles traveled
- Over 114 thousand total vehicle hours driven
- Fuel cell efficiency 53-59%
- Vehicle Range: ~196 – 254 miles
- Over 134,000 kg- H₂ produced or dispensed
- 152 fuel cell vehicles and 24 hydrogen fueling stations have reported data to the project

Buses

- DOE is evaluating real-world bus fleet data (DOT collaboration)
  - H₂ fuel cell buses have a range of 39% to 141% better fuel economy when compared to diesel & CNG buses

Forklifts

- Forklifts at Defense Logistics Agency site have completed more than 18,000 refuelings

Recovery Act

- NREL is collecting operating data from deployments for an industry-wide report

*Not all hydrogen produced is used in vehicles
We are participating in a project to demonstrate a combined heat, hydrogen, and power (CHHP) system using biogas.

- System has been designed, fabricated and shop-tested
- Improvements in design have led to higher $\text{H}_2$-recovery (from 75% to >85%)
- On-site operation and data-collection planned for FY10 – FY11

Tri-Generation (CHHP) Concept

Combined heat, hydrogen, and power systems can:
- Produce clean power and fuel for multiple applications
- Provide a potential approach to establishing an initial fueling infrastructure

Public-Sector Partners:
- California Air Resources Board
- South Coast Air Quality Management District
- California Air Resources Board
- Fuel Cell Energy & Air Products
Hydrogen production costs for a stand-alone steam methane reforming (SMR) station and high-temperature CHHP application were compared. Costs are dependent on natural gas costs. CHHP applications may be more cost-effective at lower production capacities.

In cases where there is a low demand for hydrogen in early years of fuel cell vehicle deployment, CHHP may have cost advantages over on-site SMR production.

Source: Fuel Cell Power Model
Recovery Act Funding for Fuel Cells

DOE announced more than $40 million from the American Recovery and Reinvestment Act to fund 12 projects, which will deploy up to 1,000 fuel cells — to help achieve near term impact and create jobs in fuel cell manufacturing, installation, maintenance & support service sectors.

FROM the LABORATORY to DEPLOYMENT:

DOE funding has supported R&D by all of the fuel cell suppliers involved in these projects.

<table>
<thead>
<tr>
<th>COMPANY</th>
<th>AWARD</th>
<th>APPLICATION</th>
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</thead>
<tbody>
<tr>
<td>Delphi Automotive</td>
<td>$2.4 M</td>
<td>Auxiliary Power</td>
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<tr>
<td>FedEx Freight East</td>
<td>$1.3 M</td>
<td>Specialty Vehicle</td>
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<tr>
<td>GENCO</td>
<td>$6.1 M</td>
<td>Specialty Vehicle</td>
</tr>
<tr>
<td>Jadoo Power</td>
<td>$2.2 M</td>
<td>Backup Power</td>
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<tr>
<td>MTI MicroFuel Cells</td>
<td>$3.0 M</td>
<td>Portable</td>
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<tr>
<td>Nuvera Fuel Cells</td>
<td>$1.1 M</td>
<td>Specialty Vehicle</td>
</tr>
<tr>
<td>Plug Power, Inc. (1)</td>
<td>$3.4 M</td>
<td>CHP</td>
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<td>Plug Power, Inc. (2)</td>
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<td>Univ. of N. Florida</td>
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<tr>
<td>ReliOn Inc.</td>
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<tr>
<td>Sprint Comm.</td>
<td>$7.3 M</td>
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<tr>
<td>Sysco of Houston</td>
<td>$1.2 M</td>
<td>Specialty Vehicle</td>
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</tbody>
</table>

Approximately $54 million in cost-share funding from industry participants for a total of about $96 million.
ARRA Fuel Cell Units in Operation

DOE ARRA-funded Early Market Fuel Cell Installations
(actual and projected)

Projected Operation Quantities

<table>
<thead>
<tr>
<th>Calendar Quarter</th>
<th>APU Deployed</th>
<th>Backup Power</th>
<th>Forklift</th>
<th>Stationary</th>
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<tbody>
<tr>
<td>2009 Q4</td>
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<td>2010 Q1</td>
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<td>2011 Q3</td>
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From National Renewable Energy Laboratory

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1) American Recovery and Reinvestment Act

Some site locations TBD

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From National Renewable Energy Laboratory

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U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy

From National Renewable Energy Laboratory
U.S. Fuel Cell Deployments Using Market Transformation and Recovery Act Funding
State Activities

Example: California

- Hydrogen Fueling Stations
  - > 20 stations currently operating
  - ~ 10 additional stations planned

- Hydrogen Fuel Cell Vehicle Deployments: CA Fuel Cell Partnership is assessing the potential to deploy over
  - 4,000 vehicles by 2014
  - 50,000 vehicles by 2017

http://www.fuelcellpartnership.org/

**Requires Agencies to:**

- Set GHG reduction Targets
- Develop Strategic Sustainability Plans and provide in concert with budget submissions
- Conduct bottom up Scope 1, 2 and 3 baselines
- Track performance

**Examples:**

- **Achieve** 30% reduction in vehicle fleet petroleum use by 2020
- **Requires** 15% of buildings meet the Guiding Principles for High Performance and Sustainable Buildings by 2015
- **Design** all new Federal buildings which begin the planning process by 2020 to achieve zero-net energy by 2030

**Potential opportunities for fuel cells and other clean energy technologies....**

http://www1.eere.energy.gov/femp/regulations/EO13514.html
Potential Opportunities – Government Leadership

Examples

- **DLA**: material handling equipment and H₂ ICE shuttle buses
- **FAA**: ground support equipment and backup power
- **APTO**: ground support equipment and H₂ ICE shuttle buses
- **Army incl. CERL/TARDEC**: backup power, waste to energy, and H₂ ICE shuttle buses
- **NPS**: renewably generated backup power and H₂ ICE shuttle buses
- **ONR/USMC**: utility scale renewable hydrogen generation and H₂ ICE shuttle buses
- **NASA**: backup power and H₂ ICE shuttle buses

![Hydrogen Dispenser Fills](image1.png)

**Hydrogen Dispenser Fills**

Air Products Count by Segment

DLA, DDSP – First of several 15,000 fills/yr sites
Collaborations

Federal Agencies
- DOC
- DOD
- DOE
- DOT
- EPA
- GSA
- DOI
- DHS
- NASA
- NSF
- USDA
- USPS
- Interagency coordination through staff-level Interagency Working Group (meets monthly)
- Assistant Secretary-level Interagency Task Force mandated by EPACT 2005.

DOE Fuel Cell Technologies Program*
- Applied RD&D
- Efforts to Overcome Non-Technical Barriers
- Internal Collaboration with Fossil Energy, Nuclear Energy and Basic Energy Sciences

Industry Partnerships & Stakeholder Assn’s.
- FreedomCAR and Fuel Partnership
- National Hydrogen Association
- U. S. Fuel Cell Council
- Hydrogen Utility Group
- ~ 65 projects with 50 companies

 Universities
~ 50 projects with 40 universities

International
- IEA Implementing agreements – 25 countries
- International Partnership for the Hydrogen Economy – 16 countries, 30 projects

State & Regional Partnerships
- California Fuel Cell Partnership
- California Stationary Fuel Cell Collaborative
- SC H₂ & Fuel Cell Alliance
- Upper Midwest Hydrogen Initiative
- Ohio Fuel Coalition
- Connecticut Center for Advanced Technology

National Laboratories
- National Renewable Energy Laboratory
  P&D, S, FC, A, SC&S, TV
- Argonne
  A, FC, P&D
- Los Alamos
  S, FC, SC&S
- Sandia
  P&D, S, SC&S
- Pacific Northwest
  SC&S, P&D, S, FC, A
- Oak Ridge
  P&D, S, FC, A
- Lawrence Berkeley
  FC, A
- Lawrence Livermore
  P&D, S
- Savannah River
  S, P&D
- Brookhaven
  S, FC
- Idaho
  P
- Other Federal Labs: Jet Propulsion Lab, National Institute of Standards & Technology, National Energy Technology Lab

P&D = Production & Delivery; S = Storage; FC = Fuel Cells; A = Analysis; SC&S = Safety, Codes & Standards; TV = Technology Validation

* Office of Energy Efficiency and Renewable Energy
Key Program Documents

Fuel Cell Program Plan
Outlines a plan for fuel cell activities in the Department of Energy
→ Replacement for current Hydrogen Posture Plan
→ To be released in 2010

Annual Merit Review Proceedings
Includes downloadable versions of all presentations at the Annual Merit Review
→ Latest edition released June 2010
www.hydrogen.energy.gov/annual_review10_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
→ Latest edition released October 2009
www.hydrogen.energy.gov/annual_review08_report.html

Annual Progress Report
Summarizes activities and accomplishments within the Program over the preceding year, with reports on individual projects
→ Latest edition published November 2009
www.hydrogen.energy.gov/annual_progress.html

Next Annual Review: May 9 – 13, 2011
Washington, D.C.
http://annualmeritreview.energy.gov/
Thank you

Richard.Farmer@ee.doe.gov

hydrogenandfuelcells.energy.gov
Backup Slides
Funding for Fuel Cells and Hydrogen

DOE FY11 Budget Request

Total Requested Funding: ~$256 Million

- Fuel Cell Systems R&D: $67M
- Hydrogen Fuel R&D: $40M
- Manufacturing R&D: $5M
- Technology Validation: $11M
- Safety, Codes & Standards: $9M
- Systems Analysis: $5M
- Nuclear H₂ (NE): $5M
- Basic Science Research (SC): $52M
- H₂ from Coal: $12M
- SECA (FE): $50M

* SC funding includes BES and BER
** NE FY11 Request TBD (FY10 funding was $5M)
Models were developed to quantify the benefits of fuel cells operating on bio-methane, or hydrogen derived from bio-methane. These applications may mitigate energy and environmental issues and provide an opportunity for the commercialization of fuel cells.

Source: National Renewable Energy Laboratory

H2A Production Model
Platform for new cost analysis model aimed at calculating levelized cost of biomethane (from biogas).

Fuel Cell Power Model
Analysis of stationary fuel cell systems—in standalone and CHHP models.

SERA Model
Optimization tool, may also be used for related infrastructure analysis upon modification.

13M tons/yr of bio-methane from biogas are available in the U.S. for fuel and power production.
Chemical Hydrogen Storage

> 130 materials/combinations have been examined
~ 95% discontinued
~ 5% still being investigated-Ammonia Borane (AB)
   solid, ammonium borohydride, or mixture of AB with
   ionic liquids as liquid fuels

Metal Hydrides

More than 81 distinct material systems assessed experimentally—not including catalyst/additive studies
~ 75% discontinued
~ 25% still being investigated
Computational/theoretical screening done on more than 20 million reaction conditions for metal hydrides

Hydrogen Sorption

~ 210 materials investigated
~ 80% discontinued
~ 20% still being investigated