Expanding the Use of Biogas – DOE Fuel Cell Technologies Program

Innovative Energy and Environmental Technology Workshop
Power Generation and Sustainable Biomass in New Jersey
Bordentown, New Jersey 5/7/2012
Fuel Cells: Benefits & Market Potential

The Role of Fuel Cells

Diverse Energy Sources & Fuels
- Conventional Fuels
  - Natural Gas
  - Propane
  - Diesel
  - Other Hydrocarbons
- Biomass / Biogas
  - Methane
  - Methanol
- Renewable Resources (wind, solar, biomass)
- Nuclear
- Natural Gas
- Coal (with carbon sequestration)

Clean, Efficient Energy Conversion
- Fuels Cells
  - Alkaline
  - Direct Methanol
  - Molten Carbonate
  - Polymer Electrolyte Membrane (PEM)
  - Phosphoric Acid
  - Solid Oxide

Diverse Applications
- Stationary Power
  - Primary Power & Combined Heat-and-Power (residential, commercial, industrial)
  - Backup Power
- Transportation
  - Trucks
  - Trains
  - Aircraft
  - Ships
  - Specialty Vehicles (e.g., forklifts)
  - Buses
  - Automobiles
- Auxiliary Power
  - Consumer Electronics
  - Battery Chargers
  - Soldier Power
- Portable Power

Energy Storage for Renewable Electricity
- Intermittent Renewables (solar, wind, ocean) → H₂ → Fuel Cells or Turbines → Grid/Distributed Power or Fuel

Key Benefits

Very High Efficiency
- up to 60% (electrical)
- up to 70% (electrical, hybrid fuel cell / turbine)
- up to 85% (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
Clean Energy Patent Growth Index\(^1\) shows that fuel cell patents lead in the clean energy field with nearly 1,000 fuel cell patents issued worldwide in 2010.

- 3x more than the second place holder, solar, which has just ~360 patents.
- Number of fuel cell patents grew > 57% in 2010.

\(^1\) 2010 Year in Review from http://cepgi.typepad.com/heslin_rothenberg_farley_/

Top 10 companies: Honda, GM, Toyota, UTC Power, Samsung, Ballard, Nissan, Plug Power, Delphi Technologies, Matsushita Electric Industrial
Fuel cell market continues to grow
• ~36% increase in global MWs shipped
• ~50% increase in US MWs shipped

Global fuel cell/hydrogen market could reach maturity over the next 10 to 20 years, producing revenues of:
• $14 – $31 billion/year for stationary power
• $11 billion/year for portable power
• $18 – $97 billion/year for transportation

Widespread market penetration of fuel cells could lead to:
• 180,000 new jobs in the US by 2020
• 675,000 jobs by 2035

Fuel Cells 2000, Pike Research, Fuel Cell Today, ANL

U.S. Greenhouse Gas and Methane Emissions

Landfills and Wastewater Treatment contribute ~30% of Methane Emissions in the U.S.

U.S. Methane Emissions by Source, 2009

Energy, 303 (41%)
Landfills, 180 (25%)
Agriculture, 216 (30%)
Domestic Wastewater Treatment, 18 (2%)
Industrial Wastewater Treatment, 10 (1%)
Industrial Processes, 4 (1%)
Other Carbon Dioxide, 87 (1%)
Nitrous Oxide, 220 (3%)
High-GWP Gases, 178, (3%)


Energy Related Carbon Dioxide, 5359 (82%)
Methane, 731 (11%)

2009 total = 6575

Fuel cells operating on bio-methane or hydrogen derived from bio-methane can mitigate energy and environmental issues and provide an opportunity for their commercialization. Other drivers are: need for fuel diversity/flexibility, evolving policies for renewables, and related incentives.

Source: National Renewable Energy Laboratory
Biogas as an Early Source of Renewable Hydrogen and Power

- The majority of biogas resources are situated near large urban centers—ideally located near the major demand centers for hydrogen generation for hydrogen fuel cell vehicles (FCEVs) and power generation from stationary fuel cells.
- Hydrogen can be produced from this renewable resource using existing steam-methane-reforming technology.

**U.S. biogas resource has capacity to produce ~5 GW of power at 50% electrical efficiency.**

**SOURCE: Wastewater Treatment, could provide enough H₂ to refuel ~600,000 vehicles/day.**

- 500,000 MT per year of methane is available from wastewater treatment plants in the U.S.
- ~50% of this resource could provide ~340,000 kg/day of hydrogen.

**SOURCE: Landfills, could provide enough H₂ to refuel ~13 million vehicles/day.**

- 12.4 million MT per year of methane is available from landfills in the U.S.
- ~50% of this resource could provide ~8 million kg/day of hydrogen.
Overview of Combined Heat-Power

- **Electricity**
- **Power**
- **Heat / Cooling**

**Natural Gas** or Biogas

**Fuel Cell**

Excess power generated by the fuel cell is fed to the grid

Coproduction of $H_2$

Combined heat, hydrogen and power (CHHP) or Trigeneration

Adapted from NREL
Demonstrated 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.
- 47% LHV electrical efficiency (>80% LHV overall efficiency)
Stationary Fuel Cells – Cost Analysis

Cost of Electricity from Commercial-Scale Stationary Fuel Cell

Performance Parameters
- System Electric Efficiency = 45% (LHV Basis)
- System Total Efficiency = 77% (LHV Basis)
- System Size = 1,400 kW
- System Life = 20 years
- Capital cost = $3.5 million
- Installed cost = $5.3 million

Financial Assumptions
- Startup year = 2010
- Financing = 54% equity
- Interest rate = 7%
- Financing period = 20 years
- After-tax Real IRR = 5%
- Inflation rate = 1.9%
- Total tax rates = 38.9%
- Depreciation schedule = 7 years (MACRS)
- Payback period = 11 years
- Stack replacement cost distributed annually

Source: NREL Fuel Cell Power Model

Operation Assumptions
- System utilization factor = 95%
- Restacking cost = 30% of installed cap. cost
- Heat value = cost of displaced natural gas from 80% efficient device

Stationary Fuel Cells – Cost Analysis

MCFC 1.4 MW

Source: NREL Fuel Cell Power Model
Fuel Cell Technical Analysis Tool – Fuel Cell Power Model

Publically available model for analysis of fuel cells

Model inputs
- Model database
- User inputs

Energy analysis done for 8,760 h of one year

Source: National Renewable Energy Laboratory
Biogas Benefits

Preliminary Well to Wheels Analysis Results

Fuel cell vehicles utilizing hydrogen produced from landfill gas is a renewable pathway with low carbon emissions.

Notes:
- Information for gasoline ICE, HEV and H2FCV is based on the Program Record #9002, www.hydrogen.energy.gov/program_records.html.
- Information for H2FCV with hydrogen from landfill gas is based on ANL GREET model and analysis.
- The landfill gas is assumed to be flared in this scenario.

Well to Wheels Analysis – Greenhouse Gas Emissions, gm/mile

Vehicle Fuel Economy Assumptions

<table>
<thead>
<tr>
<th></th>
<th>Gasoline ICE</th>
<th>Gasoline HEV</th>
<th>Fuel Cell Vehicle</th>
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<tr>
<td>MPGGE</td>
<td>21</td>
<td>47</td>
<td>60</td>
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</table>
The fuel cell vehicles fueled with hydrogen produced from landfill gas will reduce light duty vehicle petroleum use.

Well to Wheels Analysis – Petroleum Use, Btu/mile

Notes:
- Information for gasoline ICE, HEV and H2FCV is based on the Program Record #9002, www.hydrogen.energy.gov/program_records.html.
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Vehicle Fuel Economy Assumptions

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<td>21</td>
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Source: ANL GREET Model
GHG Emissions of CHHP, CHP, and Competing Technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Generator</th>
<th>Feedstock</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAFC, Electric</td>
<td>28%</td>
<td>34%</td>
</tr>
<tr>
<td>CHHP, MCFC</td>
<td>10%</td>
<td>29%</td>
</tr>
<tr>
<td>NG ICE, NG MT</td>
<td>43%</td>
<td>48%</td>
</tr>
<tr>
<td>CAMix, Grid</td>
<td>43%</td>
<td>48%</td>
</tr>
</tbody>
</table>

GHG Emissions (grams/mmBtu Eh4)

Legend:
- Generator
- Feedstock
Landfill Gas for CHP and Combined Heat Hydrogen and Power (CHHP) Fuel Cells achieve Large GHG Emissions Reduction Relative to NG-Powered Fuel Cells
NOx Emissions of CHHP, CHP, and Competing Technologies
PM Emissions of CHHP, CHP, and Competing Technologies
Use of biogas for hydrogen production as transportation fuel and stationary fuel cells for power and heat generation will be impacted by contaminant content and cleanup costs.

**Barriers**

- High level of contaminants
- High variability of contaminant concentrations
- High capital cost for contaminant removal
- Low experience level with biogas cleanup
- Location of resources relative to demand centers and understanding cost impacts of transportation

**Activities**

- Held workshops to understand gaps for utilizing biogas for hydrogen and power production
- Working with Argonne National Laboratory to understand impact of biogas impurities on stationary fuel cell performance
- Working with National Renewable Energy Laboratory on location of biogas resources and development of biogas H2A model for biogas cost analysis
What are the tolerance limits for the Fuel Cells?

### Sulfur
- Corrosive, affects catalyst and electrolyte
- Rapid initial followed by slower voltage decay. Effect may be recoverable
- Tolerance limits 0.5-5 ppm
- More severe effect with CH₄/CO rich fuels to Fuel Cell and anode recirculation

### Siloxanes
- Thermally decompose forming glassy layers
- Fouls surfaces (HEx, sensors, catalysts)
- Few studies on the effects on FC’s, but tolerance limits may be practically zero

### Halogens
- Corrosive, affects electrolyte
- Long term degradation effect
- Tolerance limits, 0.1-1 ppm

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<table>
<thead>
<tr>
<th>Impurity</th>
<th>Tolerance</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molten Carbonate Fuel Cells</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂S</td>
<td>0.1</td>
<td>ppm</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>ppm</td>
</tr>
<tr>
<td></td>
<td>0.1-5</td>
<td>ppm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COS, CS₂, mercaptan</td>
<td>1</td>
<td>ppm</td>
</tr>
<tr>
<td>Organic Sulfur</td>
<td>&lt;6</td>
<td>ppm</td>
</tr>
<tr>
<td>H₂S, COS, CS₂</td>
<td>0.5-1</td>
<td>ppm</td>
</tr>
<tr>
<td></td>
<td>&lt;10</td>
<td>ppm</td>
</tr>
<tr>
<td>Halogens (HCl)</td>
<td>0.1-1</td>
<td>ppm</td>
</tr>
<tr>
<td>Halides: HCl, HF</td>
<td>0.1-1</td>
<td>ppm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alkali Metals</td>
<td>1-10</td>
<td>ppm</td>
</tr>
<tr>
<td>NH₃</td>
<td>1</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>1-3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Siloxanes: HDMS, D5</td>
<td>10-100 ppm</td>
<td>(Cigolotti, 2009)</td>
</tr>
<tr>
<td></td>
<td>&lt;1</td>
<td>ppm</td>
</tr>
<tr>
<td>Tars</td>
<td>2000</td>
<td>ppm</td>
</tr>
<tr>
<td>Heavy Metals: As, Pb, Zn, Cd, Hg</td>
<td>1-20</td>
<td>ppm</td>
</tr>
</tbody>
</table>

Source: Argonne National Laboratory
Digester gas contains predominately cyclic (D4,D5) organosilicon (siloxanes) species

- Cyclic compounds (D4 & D5) are dominant in WWTP gas
- Concentration of linear compounds and TMS are usually low
- ADG temperature affects speciation and concentration of siloxane compounds
- Solid silica deposits on surfaces. Tolerance level often require “below detection limit”

Legend:
ADG – Anaerobic Digestion Gas
LFG – Land Fill Gas

Source: Argonne National Laboratory
### Policies and Incentives Promoting Fuel Cells and Biogas

<table>
<thead>
<tr>
<th>Incentive Program</th>
<th>Description</th>
<th>Limit/Expiration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advanced Power System Technology Incentive Program</strong></td>
<td>1.8¢/kWh for qualifying advanced power system technology and an additional 0.7¢/kWh for a qualifying security and assured power facility for electricity generated.</td>
<td>10,000,000kWh limit per fiscal year. Expires 9/30/2013.</td>
</tr>
<tr>
<td><strong>Renewable Electricity Production Tax Credit</strong></td>
<td>2.2¢/kWh for wind, geothermal, closed-loop biomass; 1.1¢/kWh for other eligible technologies (landfill gas, municipal solid waste)</td>
<td>Expires 12/31/2013.</td>
</tr>
<tr>
<td><strong>Renewable Energy Production Incentive</strong></td>
<td>1.5¢/kWh in 1993 dollars (indexed for inflation) for biogas, biomass, hydrogen, LFG for combustion turbines, Boilers, condensing turbines, fuel cells, microturbine, reciprocating engine, heat recovery generator, Stirling engine.</td>
<td>Expires 12/31/2026</td>
</tr>
</tbody>
</table>

*Applies to fuel cell and CHP technologies*
### Federal Policies Promoting Fuel Cells

<table>
<thead>
<tr>
<th>Policy</th>
<th>Description</th>
<th>Deadline/Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Investment Tax Credit</strong></td>
<td>30% tax credit for qualified fuel cell property or $3,000/kW of the fuel cell nameplate capacity. 10% credit for CHP-system property.</td>
<td>Equipment must be installed by Dec. 31, 2016.</td>
</tr>
<tr>
<td><strong>Alternative Fuel Infrastructure Tax Credit</strong></td>
<td>30% of expenditures. $30,000 maximum.</td>
<td>Expires 2/31/2014.</td>
</tr>
<tr>
<td><strong>Residential Renewable Energy Tax Credit</strong></td>
<td>30% of expenditures. Fuel cell maximum: $500 per 0.5 kW.</td>
<td>Expires December 31, 2016. Fuel cell must have at least 0.5 kW of electricity using an electrochemical process.</td>
</tr>
<tr>
<td><strong>Residential Energy Efficiency Credit</strong></td>
<td>Raises ITC dollar cap for residential fuel cells in joint occupancy dwellings to $3,334/kW.</td>
<td>Fuel cells must have electricity-only generation efficiency greater than 30% and 0.5 kW minimum. Expires Dec. 31, 2016.</td>
</tr>
<tr>
<td><strong>Modified Accelerated Cost-Recovery System (MACRS)</strong></td>
<td>Fuel cell property placed in service between 9/8/2010 1/1/2012 qualifies for 100% first-year bonus depreciation. For 2012, bonus depreciation is still available, but at 50% of the eligible basis.</td>
<td>The property must have a recovery period of 20 years or less under normal federal tax depreciation rules and been acquired and placed in service between 2008 – 2012.</td>
</tr>
</tbody>
</table>

*Applies to fuel cell and CHP technologies*
Peer-reviewed employment model for job creation potential for states and regions released for public use

- ANL-RCF developed an employment and economic impact tool to estimate stationary FC industry impacts:
  - Production (PEMFC, PAFC and MCFC) in target applications
  - Installation of FCs and required infrastructure
  - O&M including fuel
  - Construction/expansion of manufacturing capacity
- Model was peer reviewed and beta tested prior to model launch.
- State, regional and national level analyses including supply chain impacts
- Applications included forklifts, back-up power, specialty vehicles, etc.
- Jobs model will enable analysis of gross and net jobs, and revenues generated from fuel cell installation and investment.

Model available 5/14/12 from ANL website: JOBSFC.es.anl.gov
Freedom Tower to tap green fuel cell power: 
*Low emission fuel cells to provide onsite heat and power for landmark project*

“New York’s Freedom Tower, the skyscraper being constructed on the site of the World Trade Center, is to use fuel cells to power its heating and cooling systems.

UTC Power, the fuel cell division of engineering conglomerate United Technologies, announced that it has received orders from the **New York Power Authority (NYPA)** for 12 fuel cells totaling 4.8MW of power to serve the Freedom Tower and three other new towers under construction at the site in Manhattan.”
Potential Future Work

- Investigate options to reduce the purification costs and technologies for removing contaminants of biogas streams.
- Explore the possibility of formulating a correlation between the cost of the biogas upgrading system and the purification requirements.
- Investigate the effect of combining biogas products from multiple sites/sources on temporal variation of the feed chemical composition for the cleanup process.
- Investigate options to remove limits for transporting purified biogas in natural gas pipelines.
Thank You

Fred Joseck
fred.joseck@ee.doe.gov

DOE Annual Merit Review: May 14 – 18, 2012
Arlington, VA
http://annualmeritreview.energy.gov/
Examples of Fuel Cell CHP Industry Deployments

Waste Treatment Deployments:

Nine Sites Include:

- **Orange County Sanitation District (CA, 300 kW)**
  - 1-300 kW fuel cell
  - Operates on biogas from wastewater treatment plant
  - Produces >100 kg/day of fuel cell grade hydrogen (99.9999% purity)

- **Tulare (CA, 1 MW)**
  - 4-300 kW fuel cells
  - Generates ~50% of waste water treatment plant’s electrical demand
  - Waste heat used for generating steam and boiling beer

Completed Food Producer Deployments:

- **Gills Onions (CA, 600 kW)**
  - 2-300kW fuel cells
  - Generates power for facility @ 47% electrical efficiency
  - Processes ~32 scfm of biogas per fuel cell

- **Sierra Nevada Brewery (CA, 1 MW)**
  - Generates ~100% of brewery’s electrical demand
  - Waste heat used for generating steam and boiling beer

The Food Industry and Waste Treatment are emerging markets for stationary fuel cells

Source: Gills Onions
The bulk of total sulfur species in the digester gas is mainly $H_2S$.

- $H_2S$ show variability in the order of 10 to 1000 ppm
- DMS, Mercaptans can vary from ppb to few ppm
- Iron salts used in the water treatment process sequesters sulfide
- Impacts Reformer/Fuel cell catalyst/Electrolyte. Sulfur impurities need to be reduced to levels of ~0.1-1 ppm

Average $H_2S$ ~400 ppm

Source: Argonne National Laboratory

Low $H_2S$ content due to iron salt used in the waste water treatment process, i.e. for sludge thickening, phosphate precipitation
Landfill gas contains a variety of halocarbons and at much higher concentrations than Digester Gas

- Concentration of halogens are generally much lower in WWTP than LFG gas
- Chlorine is the dominant halogen species
- Forms corrosive gases, combustion or reforming
- Affects long-term performance of fuel cell

**Legend:**
- ADG – Anaerobic Digestion Gas
- LFG – Land Fill Gas

Source: Argonne National Laboratory
Sulfur Species Content of Land Fill Gas

Land Fill Gas contains a wide spectrum of sulfur compounds creating a challenge for impurity cleanup

Concentration of organic sulfur is higher in landfill gas in particular Dimethyl Sulfide (DMS)

Source: Argonne National Laboratory
Northeast Hydrogen Fuel Cell Industry Status and Direction

Report by Joel M. Rinebold, Alexander C. Barton, and Adam J. Brzozwski
Connecticut Center for Advanced Technology, Inc.

Highlights potential for fuel cell industry in northeast US detailing relevant information on products and markets, employment, and system efficiency and cost.

See report:

State by state plans identifying fuel cell opportunities and potential implementation strategies (drafts in process)

Available for:
Connecticut
Massachusetts
Maine
New Hampshire
New Jersey
New York
Rhode Island
Vermont
# Northeast Hydrogen Fuel Cell Cluster

## Preliminary Analysis - Economic Impact Summary

<table>
<thead>
<tr>
<th></th>
<th>CT</th>
<th>NY</th>
<th>MA</th>
<th>ME</th>
<th>NH</th>
<th>RI</th>
<th>VT</th>
<th>NJ</th>
<th>Regional</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Employment</strong></td>
<td>2,529</td>
<td>1,728</td>
<td>964</td>
<td>18</td>
<td>45</td>
<td>32</td>
<td>16</td>
<td>111</td>
<td>5,443</td>
</tr>
<tr>
<td><strong>Total Revenue / Investment in 2010 ($ million)</strong></td>
<td>$496</td>
<td>$292</td>
<td>$171</td>
<td>$2.9</td>
<td>$8.7</td>
<td>$6.9</td>
<td>$3.3</td>
<td>$26.5</td>
<td>$1,009</td>
</tr>
<tr>
<td><strong>Total Supply Chain Companies</strong></td>
<td>599</td>
<td>183</td>
<td>322</td>
<td>28</td>
<td>25</td>
<td>19</td>
<td>5</td>
<td>8</td>
<td>1189</td>
</tr>
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Northeast Hydrogen Fuel Cell Cluster

Targets: Geographic Information System (GIS) Mapping

Education

Food Sales

Food Services

Inpatient Healthcare

Airports (Military)

Lodging

Energy Intensive Industry

Alternative Fueling Stations

The Connecticut Center for Advance Technology, Inc.

www.ccat.us

eere.energy.gov
Partnerships & Collaboration

Federal Agencies
- DOC
- DOD
- DOE
- DOT
  - Interagency coordination through staff-level Interagency Working Group (meets monthly)
  - Assistant Secretary-level Interagency Task Force mandated by EPACT 2005.

External Input
- Annual Merit Review & Peer Evaluation
- H2 & Fuel Cell Technical Advisory Committee
- National Academies, GAO, etc.

Industry Partnerships & Stakeholder Assn’s.
- Tech Teams (USCAR, energy companies- U.S. DRIVE)
- Fuel Cell and Hydrogen Energy Association (FCHEA)
- Hydrogen Utility Group
- ~ 65 projects with 50 companies

Universities
- ~ 50 projects with 40 universities

International
- IEA Implementing agreements – 25 countries
- International Partnership for Hydrogen & Fuel Cells in the Economy – 17 countries & EC, 30 projects

DOE Hydrogen & Fuel Cells Program

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, MN
- Argonne
  A, FC, P&D, SC&S
- Los Alamos
  S, FC, SC&S
- Sandia
  P&D, S, SC&S
- Pacific Northwest
  P&D, S, FC, SC&S, A
- Oak Ridge
  P&D, S, FC, A, SC&S
- Lawrence Berkeley
  FC, A
- Lawrence Livermore
  P&D, S, SC&S
- Savannah River
  S, P&D
- Brookhaven
  S, FC
- Idaho National Lab
  P&D

Other Federal Labs: Jet Propulsion Lab, National Institute of Standards & Technology, National Energy Technology Lab (NETL)

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