Fuel Cell Market

Market Growth
Fuel cell markets continue to grow

- >25% increase in global MWs shipped since 2012
- 35% increase in revenues from fuel cell systems shipped over last year
- Consistent ~30% annual growth in global systems shipped since 2010.

DOE Funded Reports
The Business Case for Fuel Cells 2013: Reliability, Resiliency & Savings
State of the States 2013: Fuel Cells in America
2012 Fuel Cell Technologies Office Market Report
http://energy.gov/eere/fuelcells/market-analysis-reports
Fuel Cell Cars are Here!

FCEVs on display at North American auto shows.

Honda Fuel Cell Electric Vehicle

Hyundai’s first mass-produced Tucson Fuel Cell SUVs arrive in Southern California May 20, 2014

Lease includes free $H_2$ and maintenance.

Toyota Fuel Cell Electric Vehicle
Mission: To promote the commercial introduction and widespread adoption of FCEVs across America through creation of a public-private partnership to overcome the hurdle of establishing hydrogen infrastructure.

Current partners include (additional in process):
Established H₂FIRST Project—H₂ Fueling Infrastructure Research & Station Technology

NREL and SNL Provide:

- **Technical expertise** – Hydrogen specific materials and systems
- **Facilities** - for technical collaboration and validation
- **Objectivity** – Independent and objective assessment

Leverage DOE National Lab Network

**Project Teams:**
- Station Qualification
- Dispenser Components Research
- Fuel Quality Sensor
- Station Component RD&D
- Reference Station Design
## Key Collaborations & Partnerships

### R&D
- Precompetitive R&D
  - USCAR, energy companies, EPRI, utilities

### Demonstration & Deployment
- Auto OEMs, energy companies, government, fuel cell companies

### Enabling Commercialization
- **Government partnership**
  - Coordination on policy, lessons learned, accelerating commercialization
  - 17 countries & the European Commission

### Other State Partnerships
- Government, business, academia
  - South Carolina (SCHFCA)
  - CT, MA (e.g., CCAT, H2-Fuel Cell Coalition)
  - Hawaii (Hawaii Hydrogen Initiative, H2I)

### Implementing Agreements
- **Advanced Fuel Cells**
- **Hydrogen**

### Public-private partnership
- ~30 partners including global OEMs, H₂ providers, etc.

---

**H₂ USA**

*National lab led activities with industry (SNL & NREL led project)*
### Hydrogen & Fuel Cells Budget

**EERE Funding ($ in thousands)**

<table>
<thead>
<tr>
<th>Key Activity</th>
<th>FY 2014 Enacted</th>
<th>FY 2015 Request</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell R&amp;D</td>
<td>33,383</td>
<td>33,000</td>
</tr>
<tr>
<td>Hydrogen Fuel R&amp;D¹</td>
<td>36,545</td>
<td>36,283</td>
</tr>
<tr>
<td>Manufacturing R&amp;D</td>
<td>3,000</td>
<td>3,000</td>
</tr>
<tr>
<td>Systems Analysis</td>
<td>3,000</td>
<td>3,000</td>
</tr>
<tr>
<td>Technology Validation</td>
<td>6,000</td>
<td>6,000</td>
</tr>
<tr>
<td>Safety, Codes and Standards</td>
<td>7,000</td>
<td>7,000</td>
</tr>
<tr>
<td>Market Transformation</td>
<td>3,000</td>
<td>3,000</td>
</tr>
<tr>
<td>NREL Site-wide Facilities Support</td>
<td>1,000</td>
<td>1,700</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$92,928</strong></td>
<td><strong>$92,983</strong></td>
</tr>
</tbody>
</table>

1. Hydrogen Fuel R&D includes Hydrogen Production & Delivery R&D and Hydrogen Storage R&D
2. Hydrogen and Fuel Cell related funding finalized end of FY14

**FY 2014**

<table>
<thead>
<tr>
<th></th>
<th>FY 2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Science²</td>
<td>~$25M</td>
</tr>
<tr>
<td>Fossil Energy, SECA</td>
<td>~$25M</td>
</tr>
<tr>
<td>ARPA-E (planned)</td>
<td>~$30M</td>
</tr>
</tbody>
</table>

**FY14 DOE Total: >$170M**

**FCTO Incubator FOA, $4.6M**
Concept papers due 7/7/14

### Key Targets

**Fuel Cells:**
- *Automotive:* $40/kW, 5000 hours by 2020, ultimate $30/kW
- *Stationary:* $1,000/kW (natural gas), $1,500/kW (biogas), 80,000 hrs

**Hydrogen cost:** <$4/gge by 2020
Major Technical Areas
Accomplishments

- Revised automotive fuel cell cost analysis with updated system and Pt price. **>30% cost reduction since 2008.**
- Achieved >2x increase in fuel cell catalyst specific power from 2.8 kW/g\text{PGM} (2008) to 6.0 kW/g\text{PGM}. (3M)
- Developed new nanoframe catalysts with mass activity >30X vs Pt/C in RDE testing. (ANL, LBNL)

Status

- Cost: ~$55/kW (500K/yr);
  ~$280/kW (20K/yr)
- Durability: 3,600 hours (lab data)
- Catalyst specific power: 6.0 kW/g\text{PGM}

Future Directions

- Reduce cost and enhance performance and durability of fuel cell stack components to meet 2020 targets
  - Catalysts, membranes, and MEAs
- Consortium approach to address non-PGM catalysts, interfaces, MEAs
  - Modeling & combinatorial approaches (aligned w/ Materials Genome Initiative)

FY 2015 Goal

- Improve fuel cell catalyst specific power to 6.6 kW/g\text{PGM}, on track to achieve: 8 kW/g PGM, $40/kW and 5,000 hr durability by 2020

Presolicitation Workshop
6/16 @ 6PM
Hydrogen Production & Delivery R&D

Accomplishments
- ≥10X reduction in electrolyzer PGM loading.
- Enhanced stability of III-V PEC devices (1.7X improvement in photocurrent density).
- Developed innovative refueling concept to reduce station cost 50% (compared to 2013 baseline)
- Four Workshops and a joint solicitation with NSF.

Future Directions
- RD&D on:
  - New components for 700 bar fueling
  - Low-carbon, near-term hydrogen production, and integrated solar water splitting systems
- Continued Analysis of Production & Delivery Pathways
  - Fermentative H₂ Production
  - High Temperature Electrolysis
  - Cost of Early Market P&D
  - Release new 2014 version of HDSAM
- 10 new awards in P&D! (see backup)

H₂ cost from electrolysis (at volume): ~$4.10-$5.50

Compression is 65% of the cost of H₂

FY 2015 Goals
- Reduce the cost of H₂ from renewables to $6.80/gge from $8.00/gge (2011, dispensed, untaxed)
- Demonstrate PEC with >15% efficiency vs. 2011 baseline of 12%
Hydrogen Storage R&D

Accomplishments

- 6 new awards and $7M announced for advanced storage systems, Materia, PPG Industries, SNL, LLNL, Ardica, HRL
- Developed textile PAN fibers at ~25% lower cost than conventional PAN precursor. (ORNL)
- Two sorbent system prototypes in Phase 3 with the Engineering Center to demonstrate performance against targets (see below).

### 2017 Target

<table>
<thead>
<tr>
<th>Projected H₂ Storage System</th>
<th>Performance Current Status</th>
<th>Gravimetric kWh/kg</th>
<th>Volumetric kWh/L</th>
<th>Costs* $/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 bar compressed (Type IV)</td>
<td>1.5</td>
<td>0.8</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>350 bar compressed (Type IV)</td>
<td>1.8</td>
<td>0.6</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Sorbent (MOF-5,100bar MATI, LN2)</td>
<td>1.1</td>
<td>0.7</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Hexcell, flow-through cooling</td>
<td>1.2</td>
<td>0.6</td>
<td>13</td>
<td></td>
</tr>
</tbody>
</table>

### FY 2015 Goals

- Complete sorbent system prototypes and validate Engineering system models
- Reduce the cost of 700-bar H₂ storage systems by 15% from 2013 baseline projection of $17/kWh

### Future Directions

- Develop advanced hydrogen storage materials, guided by material property requirements established by Engineering Center.
- Develop storage technologies for early markets (e.g., forklifts).
- Validate low cost carbon fiber precursors.
Manufacturing R&D

Accomplishments

• Achieved 25% 3-layer MEA cost reduction (WL Gore)

• Achieved ~30% composite mass reduction & ~20% cost savings over 2013 baseline hydrogen storage tank (Quantum)

• Held EERE/CEMI Quality Control Workshop (Co-sponsored by FCTO, AMO, SETO, VTO, & BTO); identified gaps and opportunities (CEMI: Clean Energy Manufacturing Initiative)

Future Directions

• Funding Opportunity Announcement released on 5/20/14 (up to $2M DOE)
  – Topic 1: Supply chain outreach and development
  – Topic 2: Global manufacturing competitiveness analysis

Deadline: 6/30/2014

Status

• Inline membrane defect detection using IR/DC demonstrated (Ion Power/NREL), defects detected at 60 ft/min (NREL)

• GDL cost of $1.37/kW (projected for high volume manufacturing 500K/yr (Ballard)

FY 2015 Goals

• Demonstrate 3X increase of continuous in-line measurement processes to achieve 100 ft/min for MEA/component roll-to-roll processing

• Conduct supply chain analysis
Accomplishments

- Fuel cell bus fuel economies up to 2X better than 2008 baseline. Best durability near 2016 target (18,000 hrs).
- Awarded FCEV data collection projects to 6 OEMs (~90 vehicles; up to 235,000 mi anticipated).
- 2 new projects on fuel cell hybrid electric medium-duty trucks.
- Designed and built fuel cell system for airport ground support vehicle.
- Developed prototype design for fuel cell power system for pier-side and auxiliary sea vessel power (w/ MARAD).
- Demonstrated landfill gas to H₂.

Future Directions

- Validate hydrogen refueling station/components and wind to H₂/energy storage systems.
- Accelerate H₂FIRST project.
- Test light duty battery electric fuel cell hybrid range extender and develop fleet strategies.
- RFI planned for fuel cell range extender.

Status

- FCEVs achieved 59% efficiency (target 60%); 3.5 million miles driven.
- Commercial power systems demonstrated durability between 40,000-80,000 hours.
- 1,600 DOE-supported MHE & BUP fuel cells resulted in >11,500 units with no DOE funding.

FY 2015 Goals

- Validate next generation FCEV and truck performance (e.g., parcel delivery vans with >100 mi range).
- Enable a 5X increase in the number of installed fuel cells vs. 2012 baseline.
- Complete marine power and refrigerated truck APU demos.
Accomplishments

- Global Technical Regulation adopted by UN Economic Commission for Europe Working Party 29 (US DOT NHTSA)
- Published report on SCS impact on station footprint (SNL)
- >900 downloads of Hydrogen Tools App covering 5 regions (PNNL)

Future Directions

- Quantify impact of liquid hydrogen release to reduce separation distances
- Develop hydrogen fueling station template (includes necessary safety codes & standards)
- Coordinate with State of California (e.g., CEC, CARB) to accelerate station deployment

Status

- Close to 30,000 code officials and first responders trained (NREL, PNNL)
- Assessed number of stations that can accept and deliver hydrogen (20% of 70 stations)
- \( \text{H}_2 \) Safety Panel reviewed 395 projects

FY 2015 Goals

- Initiate liquid hydrogen release studies
- Implement First Responder National Hydrogen Response Education Program
- Continued support of \( \text{H}_2 \)USA and Market Support and Acceleration Working group
Accomplishments

• Analyzed future Pt requirements for ICEVs.

• Analyzed comparative LCOE for stationary PEM fuel cells.
  – 7 to 9¢/kWh competitive with solar PV and other CHP technologies.

• 8-13% potential cost improvement from improved fuel cell efficiency through R&D.

• Analyzed sensitivity of hydrogen infrastructure cost drivers.

Future Directions

• Develop interim hydrogen cost target.

• Continue life-cycle analysis of GHG, petroleum use and water for pathways.

• Assess gaps and drivers for early market infrastructure cost.

• Evaluate the use of hydrogen for energy storage.

• Issue RFI on hGallon. hGallon equates cost of hydrogen and gasoline.

Status

• Completed JOBS H₂ model; ~1300 jobs (‘job-years’) created/retained (ARRA)

• Completed fact sheets for analysis models

FY 2015 Goals

• Continue analyses to guide R&D
• Infrastructure cost and financing scenario analysis.
Highlights
Synthesis & Evaluation of Nanoframes

New nanoframe catalysts developed with mass activity >30X higher than Pt/C catalysts in RDE testing (BES-EERE collaboration)

A PtNi$_3$ Polyhedra  B PtNi Intermediates
New nanoframe catalysts developed with mass activity >30X higher than Pt/C catalysts in RDE testing (BES-EERE collaboration)

Dispersible cathode catalyst with extended thin film catalyst properties
New nanoframe catalysts developed with mass activity >30X higher than Pt/C catalysts in RDE testing (BES-EERE collaboration)
Synthesis & Evaluation of Nanoframes

New nanoframe catalysts developed with mass activity >30X higher than Pt/C catalysts in RDE testing (BES-EERE collaboration)

“Highly Crystalline Multimetallic Nanoframes with Three-Dimensional Electro catalytic Surfaces”

Vojislav Stamenkovic (ANL) & Peidong Yang (LBNL/UCB)

Science, 343 (2014) 1339

>30-fold increase*
Infrastructure Status – California

- 10 public stations operating in CA
- 46 stations in development
- $46.6 million announced for 28 new H₂ refueling stations
- 13 in Northern CA
- 15 in Southern CA

<table>
<thead>
<tr>
<th>Station</th>
<th>Type</th>
<th>Source</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burbank</td>
<td>Gaseous</td>
<td>SMR</td>
<td>108 kg/day</td>
</tr>
<tr>
<td>Emmeryville/AC</td>
<td>Gaseous &amp; Liquid</td>
<td>Electrolyzer &amp; Liquid truck</td>
<td>60 kg/day</td>
</tr>
<tr>
<td>transit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fountain Valley</td>
<td>Gaseous</td>
<td>SOFC – biogas conversion</td>
<td>100 kg/day</td>
</tr>
<tr>
<td>Harbor City</td>
<td>Gaseous</td>
<td>Tube trailer</td>
<td>100 kg/day</td>
</tr>
<tr>
<td>UC Irvine</td>
<td>Liquid</td>
<td>Liquid truck</td>
<td>25 kg/day</td>
</tr>
<tr>
<td>New Port Beach</td>
<td>Gaseous</td>
<td>SMR</td>
<td>108 kg/day</td>
</tr>
<tr>
<td>Thousand Palms</td>
<td>Gaseous</td>
<td>SMR</td>
<td>~200 kg/day</td>
</tr>
<tr>
<td>Torrance</td>
<td>Gaseous</td>
<td>Pipeline</td>
<td>50 kg/day</td>
</tr>
<tr>
<td>West LA</td>
<td>Gaseous</td>
<td>Electrolyzer</td>
<td>32 kg/day</td>
</tr>
<tr>
<td>CSU-LA</td>
<td>Gaseous</td>
<td>Electrolyzer</td>
<td>60 kg/day</td>
</tr>
</tbody>
</table>

http://cafcp.org/stationmap
Developed infrastructure model for station rollout strategies.
Factors considered include:
• Resource availability
• Cost
• Financial analysis
• Policy and incentive analysis.

Source: M. Penev, NREL

Maps shown are draft and intended for discussion locating fleets and siting hydrogen locations.
Maps shown are draft and intended for discussion locating fleets and siting hydrogen locations.
Hydrogen Tools

- Centralized Location: organizes current H₂ resources in one robust location—including more than 20 existing tools, with plans for adding future content.
- Focused Content: tailored to the specialized needs of H₂ user groups.
- Customizable Interface: allows content to display based on the H₂ user's role or interests.
- Responsive Design: enables H₂ safety work across both desktop and mobile devices.
- Trusted Communities: fostered through social networking around H₂ subject matter expertise.
- Expandable Format: built with frequently requested future feature sets in mind.

> Credible and reliable safety information from a trustworthy source.

PNNL

24 | Fuel Cell Technologies Office eere.energy.gov
For selected projects tracked, DOE EERE funding has led to:

- **Revenues valued at >4.5 times the DOE investment**
- **Additional private investment valued at ~5.5 times the DOE investment**

---

**Example: Revenues resulting from DOE funded projects**

- **DOE Funding**
  - 2013: $50M
  - 2014: ~$95M

- **Cumulative Revenues**
  - 2013: ~$50M
  - 2014: ~>440M

**Example: Private investment resulting from DOE funded projects**

- **DOE Funding**
  - 2013: $14M
  - 2014: ~$70M

- **Additional Investment**
  - 2013: $390M
  - 2014: ~$130M
Assessing the Impact of DOE Funding

DOE FCTO funding has led to >450 patents, 42 commercial hydrogen and fuel cell technologies and 65 emerging technologies.

Leveraging DOE Funds:
Government as “catalyst” for market success of emerging technologies.

DOE cost-shared deployments led to >7X additional purchases and orders.

Over $37M saved in the last 5 years through active project management.

Source: Pacific Northwest National Laboratory
Exciting new opportunities for fuel cells in early market applications – airport ground support equipment and medium-duty trucks

**Hybrid Medium-Duty Trucks**
Delivery & refrigerated trucks and waste transport vehicles

- FedEx truck
- Garbage truck

4 new DOE projects and 2 SBIRs
Projects in CA, TN, GA

**Ground Support Equipment**
Seaports & Airports

- Airport ground support equipment
- Medium-duty trucks

Projects in CA, TN, GA
**Events & Outreach**

“**Investor Day**” events - East & West Coasts
November, 2013 at NY Times Building in NYC
April, 2014 at Stanford University

>80 news articles (blogs, etc) published in the last year

Webinars, google+hangout & workshops disseminate information

President Obama at Fuel Cell Exhibit in Sweden

Secretary Moniz at DC Autoshow
In Memorium

Peter Hoffman
Editor, Hydrogen and Fuel Cell Letters & Journalist
• Author of The Forever Fuel—The Story of Hydrogen and Tomorrow’s Energy: Hydrogen, Fuel Cells, and the Prospects for a Cleaner Planet
• Longtime supporter and hydrogen and fuel cell advocate

Dale Gardner, National Renewable Energy Laboratory
Associate Lab Director of the Renewable Fuels and Vehicle Systems Directorate
• Astronaut on space shuttle
• Longtime contributor and leader in hydrogen, biofuels and vehicle technologies

Jim McGrath, Virginia Tech University
University Distinguished and Ethyl Corporation Professor of Chemistry
• Synthesis and characterization of new directly copolymerized sulfonated aromatic copolymers for proton exchange membranes

Sheldon Shore, Ohio State University
Emeritus Professor
• Long time (~60 years) researcher of boron compounds
• First researcher to synthesize ammonia borane.
World Class Researchers & Leaders - Examples

Adam Weber (LBNL) received a 2013 Presidential Early Career Award for Scientists & Engineers (PECASE). PECASE is the most prestigious U.S. award for young scientists and engineers.

The only EERE PECASE awardees ever were from FCTO!

Maria Ghirardi (NREL)
- NREL’s Research Fellows Council

James Miller and Riccardo Scarcelli (ANL)
- SAE McFarland Award

Sanjeev Mukerjee (Northeastern University) and Piotr Zelenay (LANL)
- Electrochemical Society Fellows

Kathy Ayers (Proton OnSite)
- American Chemical Society Women Chemist Committee’s Rising Star Award

Jeff Long (LBNL, Univ. of CA – Berkeley)
- American Chemical Society Inorganic Chemistry Lectureship Award
Thank You

Sunita Satyapal
Director
Fuel Cell Technologies Office
Sunita.Satyapal@ee.doe.gov

hydrogenandfuelcells.energy.gov
New Selections for Hydrogen Production RD&D

Novel approaches to hybrid reforming, bio-derived liquids and solar water splitting

6 selections, $13.3 M in federal funds

**FuelCell Energy Inc.** ($900k), Danbury, CT
- Novel reformer-electrolyzer-purifier (REP) system

**Pacific Northwest National Laboratory** ($2.2M), Richland, WA
- Scalable, compact piston-type reactor for $H_2$ production from bio-derived liquids.

**National Renewable Energy Laboratory** ($3M), Golden, CO
- High-efficiency tandem absorbers based on novel semiconductor materials
- Economical solar hydrogen production from water.
New Selections for Hydrogen Production RD&D

Novel approaches to hybrid reforming, bio-derived liquids and solar water splitting

6 selections, $13.3 M in federal funds

University of Hawaii ($3M), Honolulu, HI
- Photoelectrodes based on novel wide-bandgap thin-films for direct solar water splitting.

Sandia National Laboratories ($2.2M), Livermore, CA
- Innovative high-efficiency solar thermochemical reactor for H₂ production.

University of Colorado, Boulder ($2M), Boulder, CO
- Novel flowing particle bed solar-thermal reactor to split water with concentrated sunlight.

RED: \( MO_x \rightarrow MO_{x-\delta} + \delta / 2O_2 \)

OX: \( MO_{x-\delta} + \delta H_2O \rightarrow \delta H_2 + MO_x \)
New Selections for Hydrogen Delivery RD&D

Innovative technologies for forecourt compression, storage and dispensing

4 selections, $7.3 M in federal funds

Southwest Research Institute ($1.8M), San Antonio, TX
- Linear motor reciprocating compressor for forecourt H₂ compression

Oak Ridge National Laboratory ($2.0M), Oak Ridge, TN
- Low cost steel concrete composite vessel for high pressure forecourt H₂ storage.

Wiretough Cylinders LLC ($2.0M), of Bristol, VA
- Low cost 875 bar H₂ storage vessel using a steel wire overwrap.

Nuvera Fuel Cells Inc. ($1.5M), Billerica, MA
- Integrated, intelligent 700 bar H₂ dispenser for fuel cell electric vehicle fueling
An example, for a constant driving distance of 300 miles:

Gasoline Vehicle
Fuel Cost = $3.8/gallon

Gasoline fillup = ~10.7 gallons
Fill up cost = ~$41 (3.8 X 10.7)

Hydrogen Fuel Cell Electric Vehicle
Fuel Cost = $8/kg → $3.8/gallon

Hydrogen fillup = ~5.1 kg = 5.1 gge
Fill up cost = ~$41 (8 X 5.1)

Concept:
Hydrogen Cost → Hydrogen gasoline gallon equivalent cost → hGallon Cost
$8/kg → $8/gge → $3.8/gallon

Filling up your tank costs the same if H₂ is $8/kg or gasoline is $3.8/gal.

1gge = gasoline gallon equivalent
Assumptions: ICE fuel economy = 28 mpg, FCEV fuel economy = 59 mpgge
Fuel cells are becoming competitive in early markets!

An Evaluation of the Total Cost of Ownership of Fuel Cell-Powered Material handling Equipment


NREL report Backup Power Cost of Ownership Analysis and Incumbent Technology Comparison FC* = fuel cell with incentives
Validated over 800 backup power units with seven industry partners
- FedEx Freight East, GENCO, Nuvera Fuel Cells, Plug Power, ReliOn Inc., Sprint Communications, Sysco of Houston –
  - 842 units in operation
  - 1.94 MW installed capacity, average site capacity of 4-6 kW
  - 99.7% successful starts (2,579 start attempts)
  - 65 continuous hours demonstrated
  - >1,600 operation hours

Validated over 450 material handling equipment units with seven industry partners
  - 490 units in operation
  - >1,800,000 operation hours, 4.4 average operation hours between fills
  - ~230,000 kg of hydrogen dispensed during more than 290,000 hydrogen fills with an average of 0.6 kg per fill

\(^1\)Not all systems have detailed data reporting to NREL. \(^2\)One project has completed.
Energy Department Launches National Fuel Cell Technology Evaluation Center

NFCTEC
a national resource for hydrogen and fuel cell stakeholders
supported through Energy Efficiency and Renewable Energy’s Fuel Cell Technologies Office

ESIF Dedication, September 2013

Photos by Dennis Schroeder, NREL