Fuel Cell Technologies Overview

Flow Cell Workshop
Washington, DC
3/7/2011

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Fuel Cell Technologies Program
Purpose
To understand the applied research and development needs and the grand challenges for the use of flow cells as energy-storage devices.

Objectives
1. Understand the needs for applied research from stakeholders.
2. Gather input for future development of roadmaps and technical targets for flow cells for various applications.
3. Identify grand challenges and prioritize R&D needs.

Flow cells combine the unique advantages of batteries and fuel cells and can offer benefits for multiple energy storage applications.

The workshop will begin with a series of speaker presentations discussing past and current R&D.

Two separate breakout sessions will then be held to discuss flow cell phenomena and components.
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/
Fuel cell market continues to grow
• ~36% increase in global MWs shipped
• ~50% increase in US MWs shipped

Various analyses project that the 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
The Role of Fuel Cells

Key Benefits

**Very High Efficiency**
- 40 - 60% (electrical)
- > 70% (electrical, hybrid fuel cell / turbine)
- > 80% (with CHP)

**Reduced CO₂ Emissions**
- 35–50%+ reductions for CHP systems
- > 70% 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
DOE Program Plan Released

An integrated strategic plan for the research, development, and demonstration activities of DOE’s Hydrogen and Fuel Cells Program: Includes Stationary, Portable and Transportation Fuel Cells

Program efforts are planned to transition to industry as technologies reach commercial-readiness.

Update to the Hydrogen Posture Plan (2006)

Released September 2011

R&D efforts are focused on pre-competitive, high-risk technologies.

Examples of near-term and long-term R&D:
- High-pressure Tanks
- Low-cost Pt Catalysts
- Low-cost Membranes and Membrane Electrode Assemblies
- High-Temperature Membranes
- Cryo-compressed Tanks
- Compressors
- Low-cost Tanks
- Non-Pt Catalysts
- Materials-based H2 storage (e.g., spillover)
- Photobiological & Photoelectrochemical H2 production
- Liquid-basined fuel cells

DOE supports RD&D, for both near-term and long-term impact with emphasis on high-risk, high-impact projects.
**Examples of Cross-Office Collaborative Successes**

**SC-EERE-ARPA-E Collaborations**

**Advancing fundamental science knowledge base**
- Solar to Fuels Hub
  - Nanowire based solar fuels generation (CalTech)
- Bandgap tailoring (Stanford)
  - Mechanistic understanding of catalysts
- Biological H₂ production
  - Materials-based H₂ storage

**Applied RD&D of innovative technologies**
- High Throughput Processes (UCSB)
  - Standard protocols and benchmarking
- Nano-catalyst support scaffold (Stanford)
  - Pt monolayer
  - Pd core
- ARPA-E: Focus on creative, high-risk transformational energy research
  - Developing novel catalysts (high risk/high impact)

**Working Groups**
- PEC, Biological, High T Membranes, Storage Systems

**Using ARPA-E developed catalyst in water splitting device**
- Alkaline Membranes
- Sun Catalytix
- Midwest Photovoltaics
Deployments help ensure continued technology utilization growth and catalyze market penetration while providing data and lessons learned.

**Market Barriers**

**Market Transformation: Addressing Market Barriers**

**Fuel Cell Technology Program**

**ARRA Deployment Status – August 2011**

<table>
<thead>
<tr>
<th>Fuel Cell Application</th>
<th>Operational Fuel Cells</th>
<th>Total Fuel Cells Planned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backup Power</td>
<td>371</td>
<td>539</td>
</tr>
<tr>
<td>Material Handling</td>
<td>467</td>
<td>504</td>
</tr>
<tr>
<td>Stationary</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>APU</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>840</td>
<td>&gt; 1,000</td>
</tr>
</tbody>
</table>

DOE: $42 M
Cost-share: $54 M
Total: $96 M.

MORE >3,000 ADDITIONAL FUEL CELL LIFT TRUCKS PLANNED WITH NO DOE FUNDING

**Diagram**

- **Deployment Locations**
  - DOE: $42 M
  - Cost-share: $54 M
  - Total: $96 M.

- **Fuel Cell Application**
  - Backup Power
  - Material Handling
  - Stationary
  - APU

- **ARRA Deployment Status**
  - Backup Power: 371 (539 total)
  - Material Handling: 467 (504 total)
  - Stationary: 2 (6 total)
  - APU: 0 (4 total)

- **Total**
  - 840 (>1,000 total)

**Website**: eere.energy.gov
Assessing the Impact of DOE Funding

DOE funding has led to 313 patents, ~30 commercial technologies and >60 emerging technologies. DOE’s Impact: ~$70M in funding for specific projects was tracked – and found to have led to nearly $200M in industry investment and revenues.

>310 PATENTS resulting from EERE-funded R&D:
- Includes technologies for hydrogen production and delivery, hydrogen storage, and fuel cells

Source: Pacific Northwest National Laboratory

Examples:
- 3M
- BASF
- Proton Energy Systems
- DuPont
- Quantum Technologies
- Dynalene, Inc.

Projected high-volume cost of fuel cells has been reduced to $49/kW (2011)*

- More than 30% reduction since 2008
- More than 80% reduction since 2002

*Based on projection to high-volume manufacturing (500,000 units/year). The projected cost status is based on an analysis of state-of-the-art components that have been developed and demonstrated through the DOE Program at the laboratory scale. Additional efforts would be needed for integration of components into a complete automotive system that meets durability requirements in real-world conditions.
**Reversible Flow Cells**

High efficiency energy storage that leverages existing fuel cell technology

**Advantages of reversible flow cells for energy storage:**

- High round-trip efficiency (60 – 90%)
- Power and energy capacity are large and decoupled
- Long cycle life
- Low self-discharge
- Reliable and stable performance

Applying breakthroughs from core fuel cell technologies would improve efficiency, performance, durability, and cost
Reversible Flow Cells

Materials developed for fuel cells can be adapted for reversible flow cells (e.g. H₂/Br cell, LBNL)

Example: NSTF catalysts from 3M are being applied to H₂/Br cells in LBNL-led ARPA-E project

NSTF whiskers

Knowledge from fuel cell technology can lead to great improvements in reversible flow cells. UTRC ARPA-E flow cell project has produced Vanadium Redox Batteries with 10X power density of conventional VRBs.

Replacement of O₂ electrodes with Br₂ electrodes in closed-loop flow cells leads to efficiency and performance improvement. Br₂ kinetics are ~8 orders of magnitude faster than O₂, with no precious catalyst required.

Cell power density comparison (W/cm²)

Typical flow-battery cell

UTRC flow-battery cell

Operate at 50-100 mA/cm²

• Improvements obtained with conventional materials
**3M nanostructured thin film catalysts provide high performance, low PGM content**

**3M NSTF Catalyst**
Oriented array of organic nanoscopic crystalline whiskers, on a microstructured substrate, sputter coated with metal catalysts

50 square km field of new wheat, 4" tall, 2" apart, 12,355 Acres

50 cm² MEA

Shrink it down by factor of 100,000 in all 3 dimensions

1 Nanostructured Whisker for Each Blade of Wheat

“Whiskerettes” of Pt grow off sides of crystalline whisker core at 70°

**Source:** 3M
PGM-free catalysts developed at LANL for low-cost applications

Catalyst SEM: Layered-graphene sheet marked with green arrow; FeCo-containing nanoparticle shown with red arrow.

The Synthesis

- High ORR activity reached with polyaniline-based and cyanamide-based catalysts
- Intrinsic catalyst activity is projected to exceed 130 A/cm³ at 0.80 V

Catalyst and ionomer structure determines performance and durability

**Electrode Architecture**

Catalyst degradation is complex – major loss in ECSA with negligible loss in performance.

After 30,000 cycles
- Pt particle size: $7.2 \pm 2.3$ nm (std)

Initial
- Pt particle size: $4.9 \pm 1.4$ nm (std)

Ionomer ordering in water/alcohol → Poor durability

Lack of ordering in glycerol → High durability – exceeds 30,000 cycle target

Y. Kim, C. Johnston et al., LANL

Source: US DOE 4/3/2012 eere.energy.gov
- Small vias provide electronic conductivity, while most of the metal plate is covered by corrosion-resistant coating
- Plate technology successfully demonstrated with Au vias and SS substrate. Cost: ~$3.5/kW
- Currently developing plates with lower-cost vias (carbon nanotubes, conductive carbides) and substrates (carbon steel) to achieve $3/kW cost target

C. Wang, TreadStone
Ion Exchange Membranes

Innovative membranes for PEMFCs and DMFCs

- 3M PFIA membranes meet most DOE targets for performance and durability
- PFIA maintains high crystallinity at lower equivalent weight than PFSAs → better mechanical properties

Arkema PVDF/polyelectrolyte blended membranes have low methanol permeability
- Kynar®PVDF
  - Chemical stability, mechanical strength
  - Excellent barrier against methanol
- Polyelectrolyte
  - H⁺ conduction
- PVDF can be compatibilized with a range of polyelectrolytes

S. Hamrock et al., 3M

Two superacid sites per side chain

Methanol Crossover
RECENT ACCOMPLISHMENTS

• Developed process model for controlling GDL coating conditions (Ballard)
  – Significant improvement in quality yields and GDL cost reduction estimated at 53% to-date

• Manufacturing of Low-Cost, Durable MEAs Engineered for Rapid Conditioning (Gore)
  – Cost model results indicate that a new three layer MEA process has potential to reduce MEA cost by 25%

• Adaptive process controls and ultrasonics for high temp PEM MEA manufacturing allows for more than 95% energy savings during the sealing process (RPI)

• Developed an innovative online X-ray fluorescence for high-speed, low-cost fabrication of gas diffusion electrodes (BASF)

This is the first time a scanning XRF has been used on GDEs – BASF
This workshop addressed reversible SOFC and reversible PEMFC in renewable electricity storage applications.

Workshop participants generally agreed that reversible technology is feasible for cost effective storage of renewable electricity, with further development required.

Issues requiring further study:
- New catalysis materials for air/oxygen electrode are needed to improve durability for both PEMFC and SOFC based systems.
- New stack designs and new approaches to heat management need to be investigated.
- Speed with which the systems can reverse directions and respond to variable inputs and loads is important for grid support.

Complete workshop report available at:
http://www1.eere.energy.gov/hydrogenandfuelcells/wkshp_reversible_fc.html
Reversible fuel cells for energy storage applications

Reversible SOFCs under development at Versa Power Systems provide hydrogen generation and energy storage capability

<table>
<thead>
<tr>
<th>Metric</th>
<th>Target</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>&lt; 0.3 Ω-cm²</td>
<td>0.223 Ω-cm² in SOEC</td>
</tr>
<tr>
<td>(Area specific resistance in both SOFC and SOEC operating modes)</td>
<td>0.224 Ω-cm² in SOFC</td>
<td></td>
</tr>
<tr>
<td>Degradation</td>
<td>&lt; 4% per 1000 hours</td>
<td>~1.5% per 1000 hours</td>
</tr>
<tr>
<td>(Overall decay rate)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating Duration</td>
<td>&gt; 1000 hours</td>
<td>1005 hours</td>
</tr>
<tr>
<td>(as of Go/No-Go Decision)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating Current Density</td>
<td>&gt; 300 mA/cm²</td>
<td>500 mA/cm²</td>
</tr>
</tbody>
</table>
Thank you

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www.hydrogenandfuelcells.energy.gov
Additional Information
Worldwide Investment & Interest
Are Strong and Growing

Interest in fuel cells and hydrogen is global, with more than $1 billion in public investment in RD&D annually, and 17 members of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE).

Activity by Key Global Players

**Germany:** >$1.2 Billion in funding ’07 – ’16; plans for 1000 hydrogen stations; >22,000 small fuel cells shipped.

**Japan:** ~$1.0 Billion in funding (’08 – ’12); plans for 2 million FCEVs and 1000 H2 stations by 2025; 100 stations by 2015; 15,000 residential fuel cells deployed

**European Union:** >$1.2 Billion in funding (’08–’13)

**South Korea:** ~$590 M (’04–’11); plans to produce 20% of world shipments and create 560,000 jobs in Korea

**China:** Thousands of small units deployed; 70 FCEVs, buses, 100 FC shuttles at World Expo and Olympics

International Highlights

**Germany** plans for 1,000 hydrogen stations by 2017—in partnership with an industry consortium.

**South Korea** has purchased >100 MW of fuel cells from two U.S. companies, and fuel cells are major part of Seoul’s renewable energy plan.
Improved efficiency of renewable $H_2$ production by matching the polarization curves of PV & electrolyzers to enable direct coupling.

Expanded Facility to test multiple technologies (wind, solar, electrolyzers, fuel cells/generators, plus $H_2$ refueling)

- Optimized power conversion and demonstrated consistent power output across larger range of solar input
- Demonstrated up to nearly 20% power improvement at low irradiance