Fuel Cell Technologies Overview

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



Flow Cell Workshop

Washington, DC

3/7/2011

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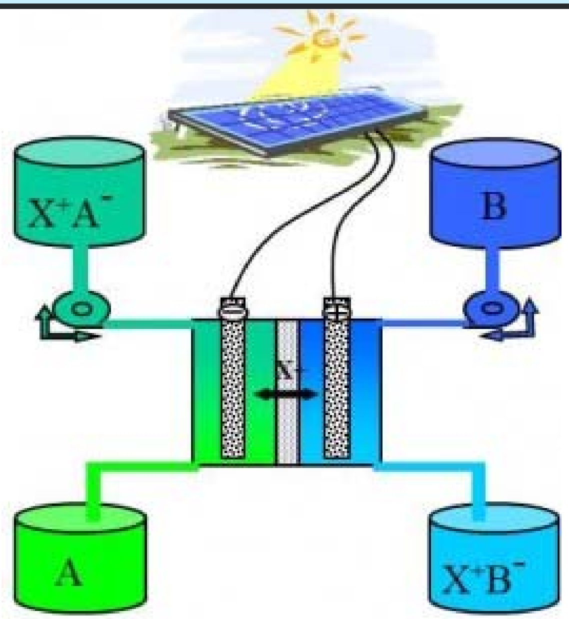
U.S. Department of Energy
Fuel Cell Technologies Program

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.

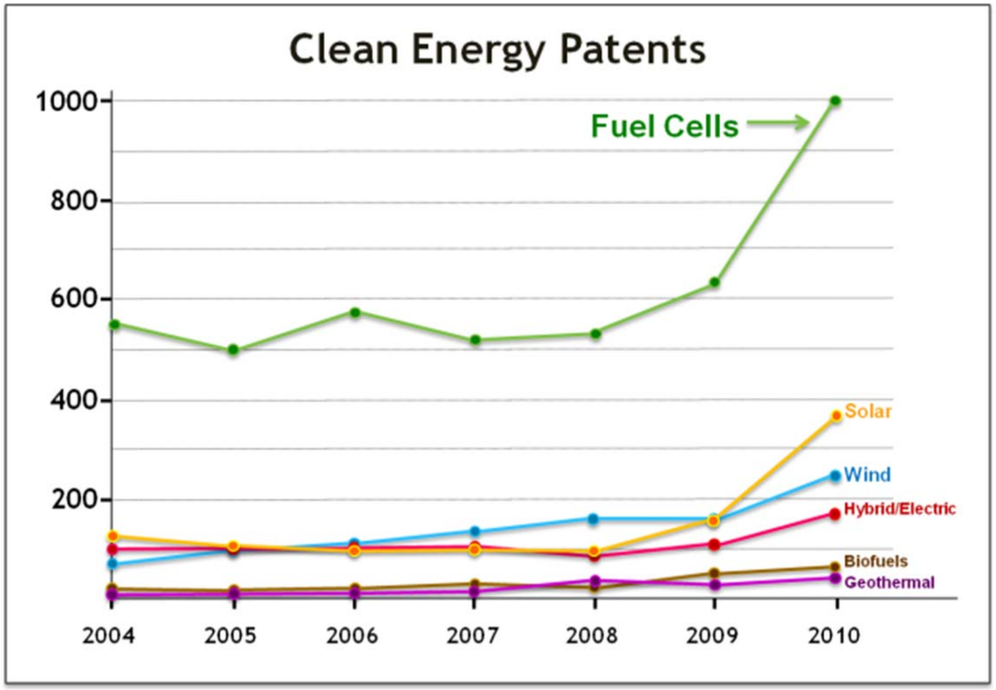


Flow cells combine the unique advantages of batteries and fuel cells and can offer benefits for multiple energy storage applications.

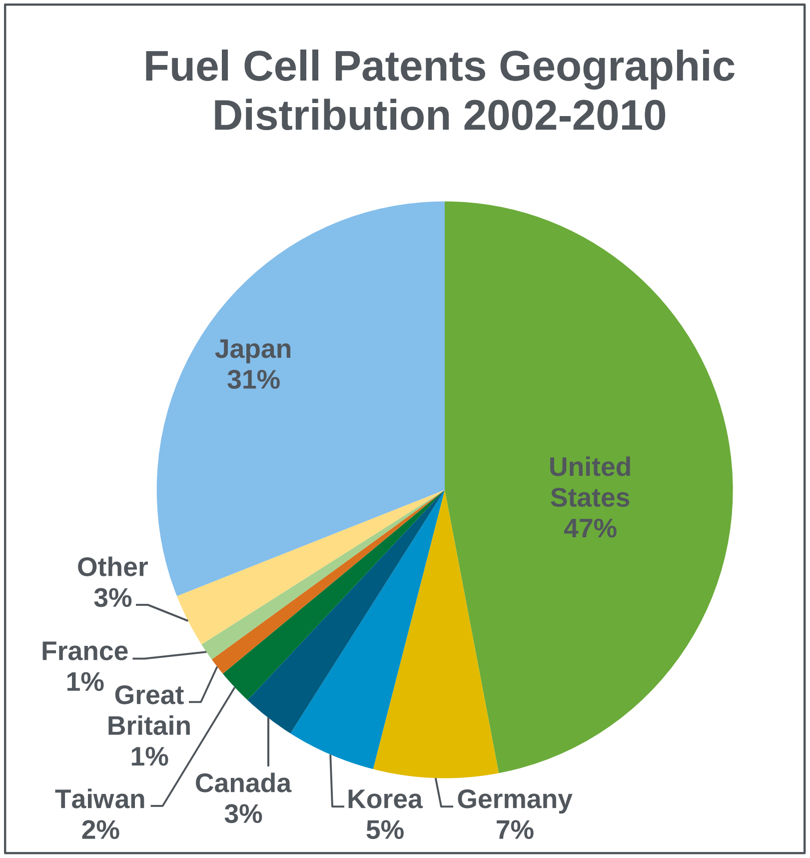
The workshop will begin with a series of speaker presentations discussing past and current R&D.

Two separate breakout sessions will then be held to discuss flow cell phenomena and components.

Fuel Cells – An Emerging Industry



Top 10 companies: Honda, GM, Toyota, UTC Power, Samsung, Ballard, Nissan, Plug Power, Delphi Technologies, Matsushita Electric Industrial



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 Overview

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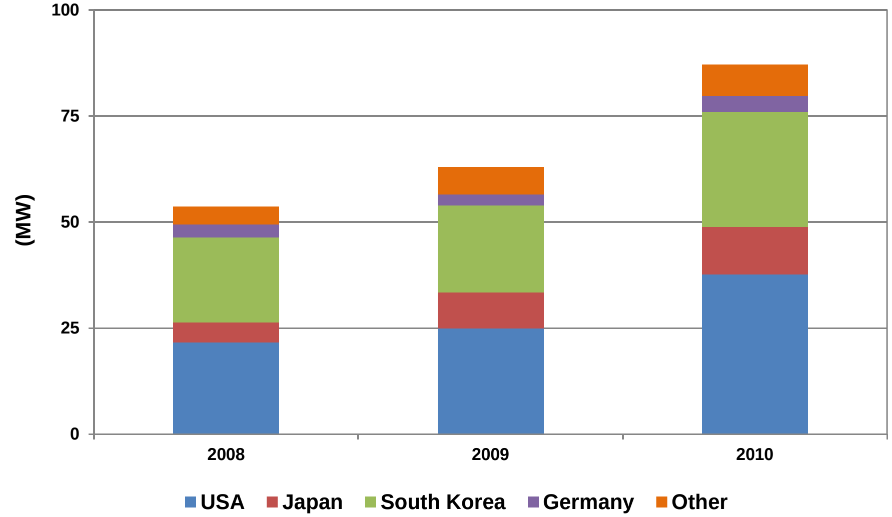
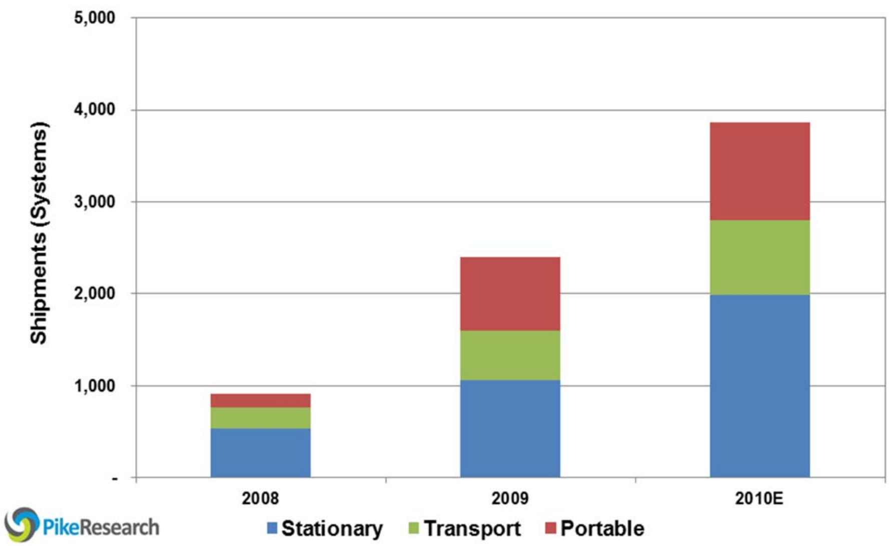
Megawatts Shipped, Key Countries: 2008-2010



North American Shipments by Application



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**

FuelCells2000, Pike Research, Fuel Cell Today, ANL

http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/program_plan2010.pdf

Fuel Cells: *Benefits & Market Potential*

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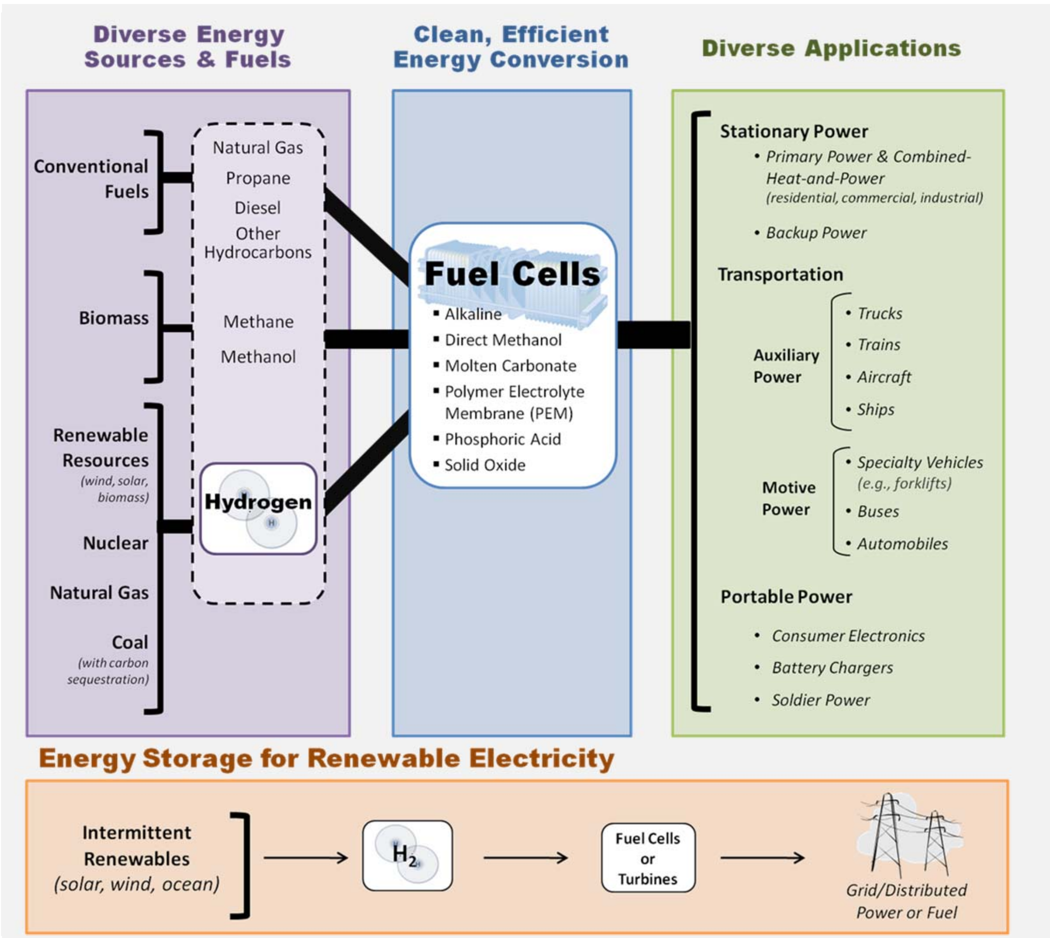
The Role of Fuel Cells



Key Benefits

Very High Efficiency

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

Reduced CO_2 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

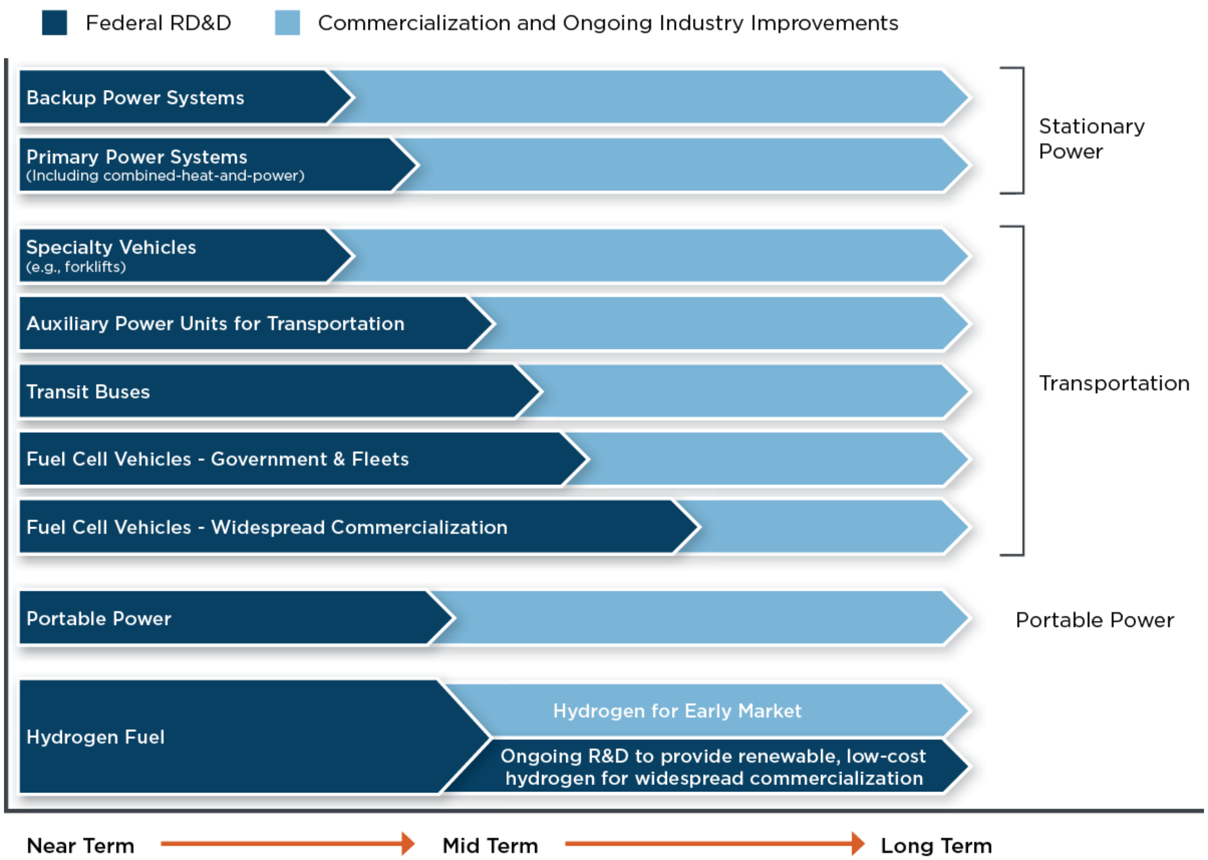
- **up to 90% reduction in criteria pollutants** *for CHP systems*

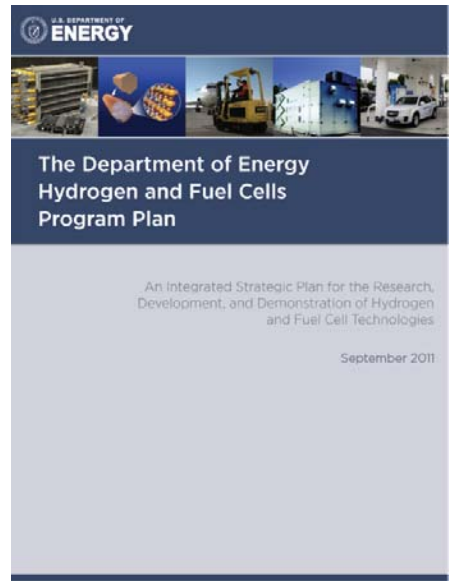
Fuel Flexibility

- **Clean fuels** — *including biogas, methanol, H_2*
- **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





Update to the Hydrogen Posture Plan (2006)

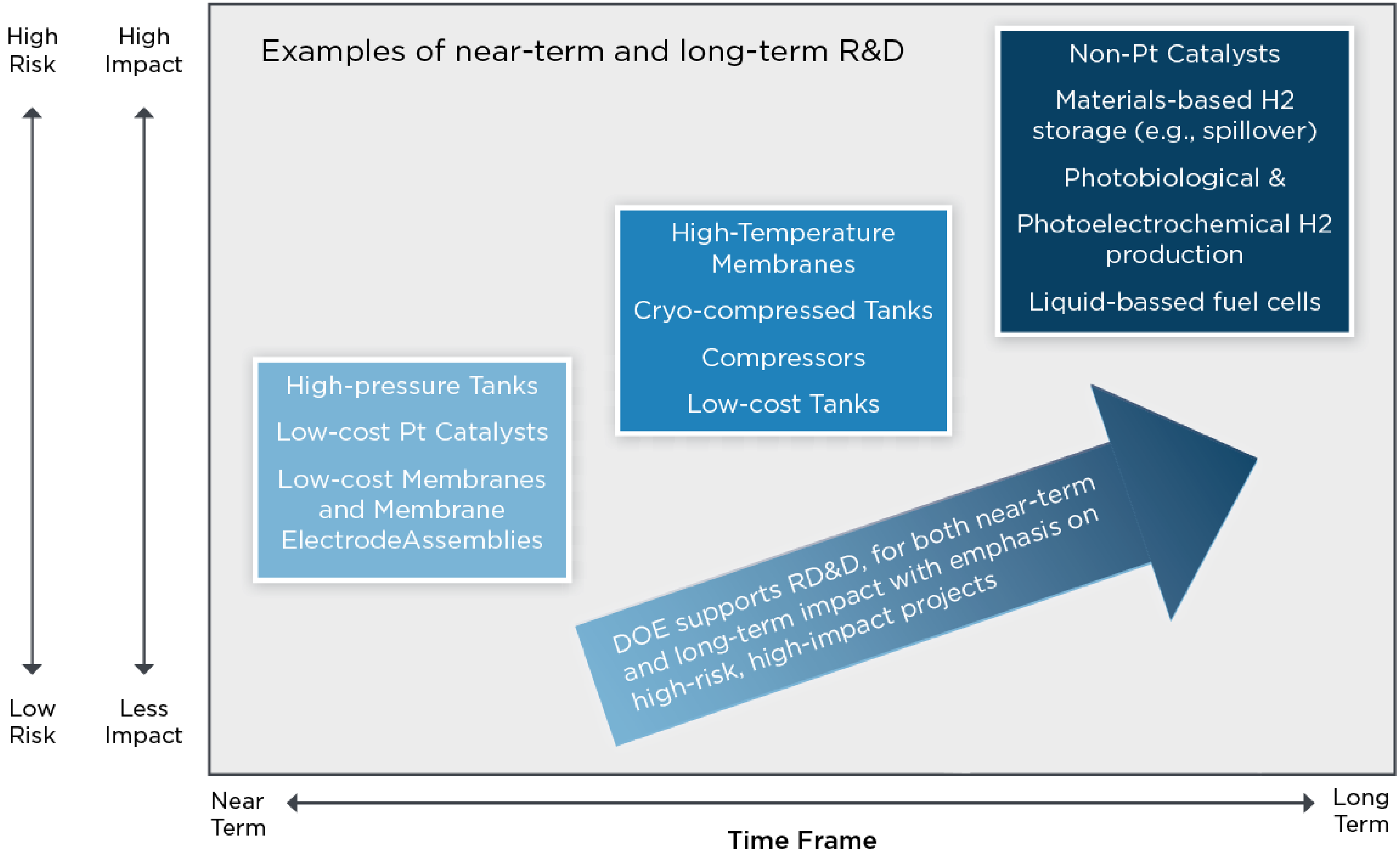
Program efforts are planned to transition to industry as technologies reach commercial-readiness.

Released September 2011

http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/program_plan2011.pdf

Program R&D – Federal Role

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



SC-EERE-ARPA-E Collaborations

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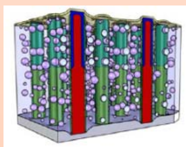
Examples of Cross-Office Collaborative Successes

Office of Science U.S. DEPARTMENT OF ENERGY

Advancing fundamental science knowledge base

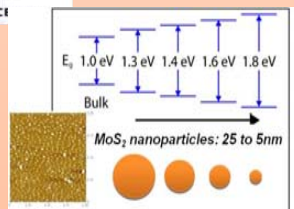
JCAP

Solar to Fuels Hub



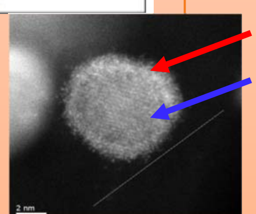
Nanowire based solar fuels generation (CalTech)

EFRC ENERGY FRONTIER RESEARCH CE



Bandgap tailoring (Stanford)

Mechanistic understanding of catalysts



Pt monolayer

Pd core

Biological H_2 production

Materials-based H_2 storage

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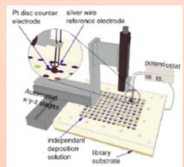
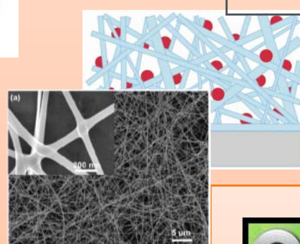
Applied RD&D of innovative technologies

High Throughput Processes (UCSB)



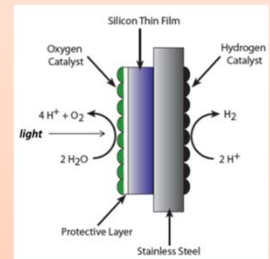
Standard protocols and benchmarking

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



Nano-catalyst support scaffold (Stanford)

Using ARPA-E developed catalyst in water splitting device



mwoe Midwest Optoelectronics

arpa·e

ARPA-E: Focus on creative, high-risk transformational energy research

Alkaline Membranes

Sun Catalytix

Developing novel catalysts (high risk/high impact)

Market Transformation: Addressing Market Barriers

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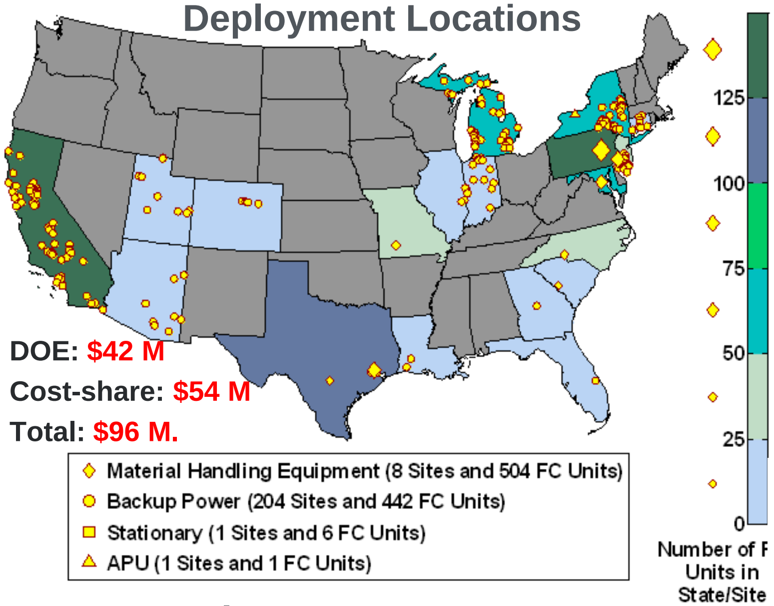
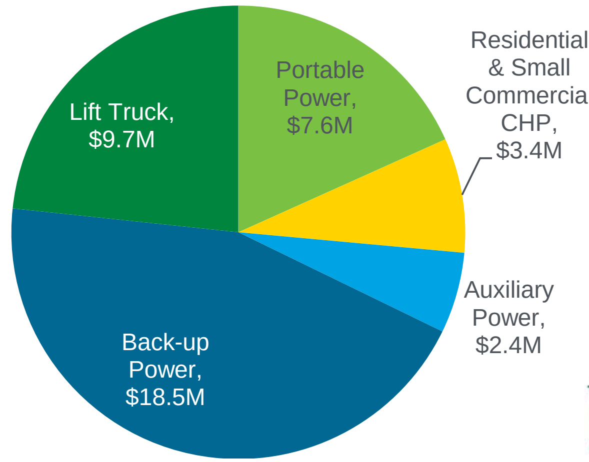
Deployments help ensure continued technology utilization growth and catalyze market penetration while providing data and lessons learned.

Deployment Locations

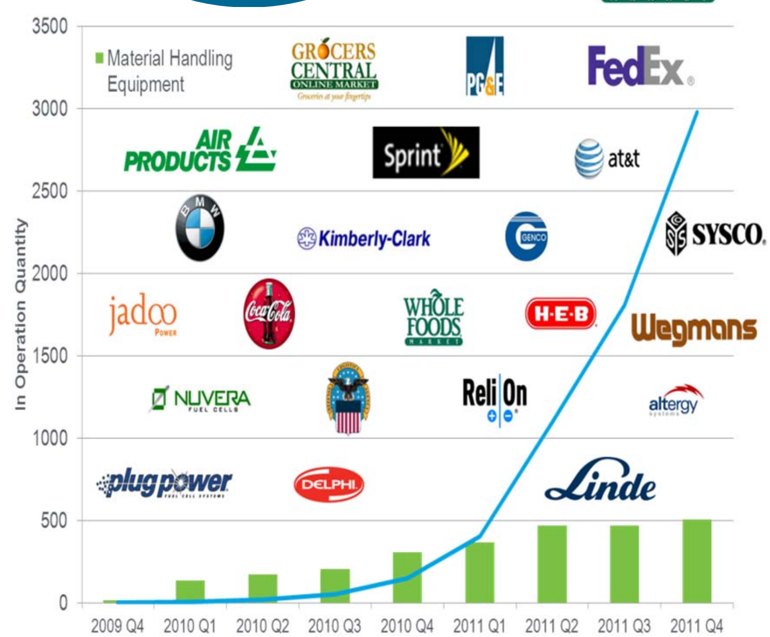


DOE: $42 M
Cost-share: $54 M
Total: $96 M.



ARRA Deployment Status – August 2011

Fuel Cell Application	Operational Fuel Cells	Total Fuel Cells Planned
Backup Power	371	539
Material Handling	467	504
Stationary	2	6
APU	0	4
Total	**840**	**> 1,000**



MORE >3,000 ADDITIONAL FUEL CELL LIFT TRUCKS PLANNED with NO DOE funding

Assessing the Impact of DOE Funding

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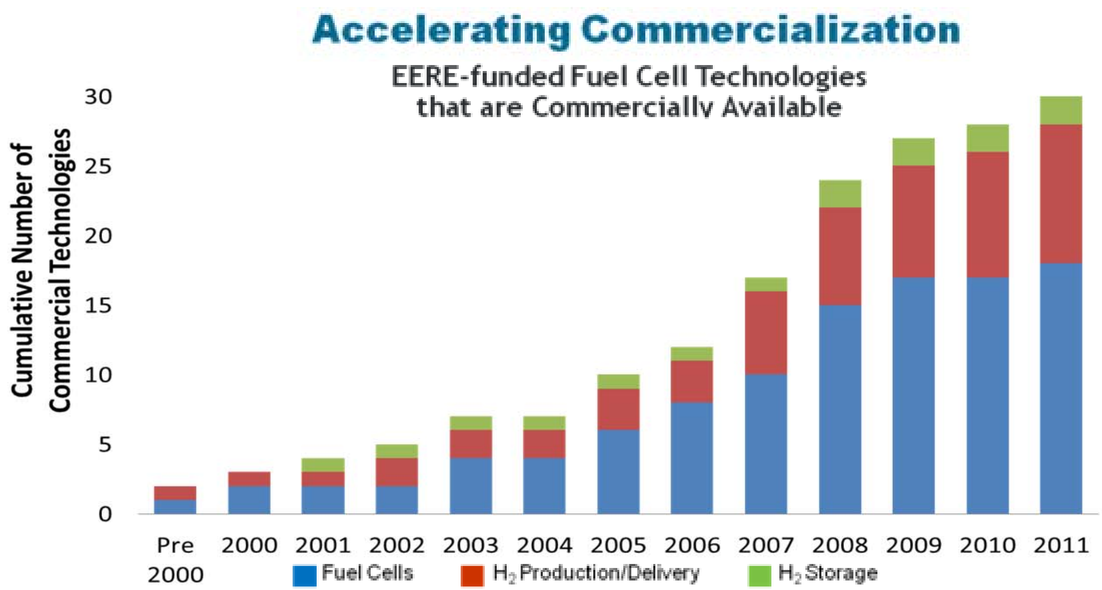
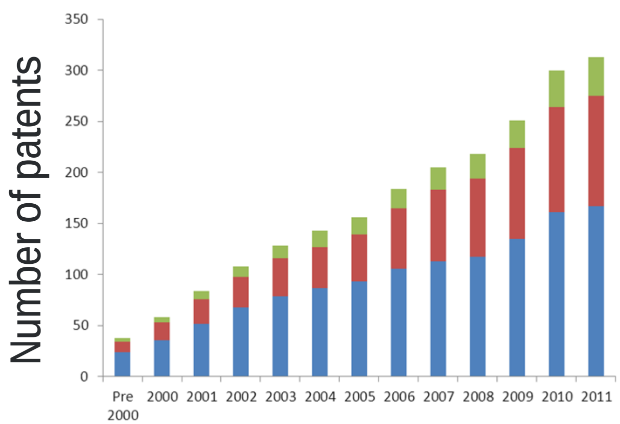
DOE funding has led led to 313 patents, ~30 commercial technologies and >60 emerging technologies.

DOE's Impact: ~$70M in funding for specific projects was tracked – and found to have led to nearly $200M in industry investment and revenues.



Source: Pacific Northwest National Laboratory
http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pathways_success_hfcit.pdf



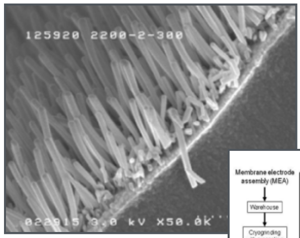
>310 PATENTS resulting from EERE-funded R&D:

- *Includes technologies for hydrogen production and delivery, hydrogen storage, and fuel cells*

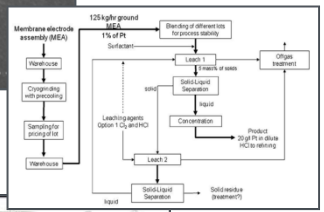
http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pathways_2011.pdf

Examples

3M



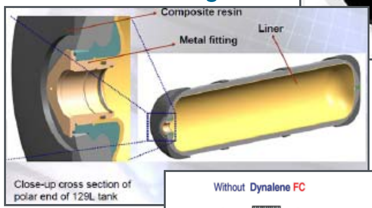
BASF Catalysts LLC



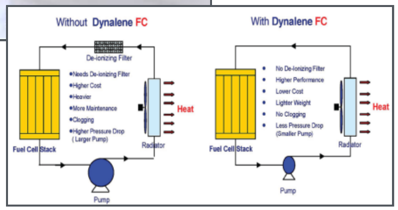
Proton Energy Systems

DuPont

Quantum Technologies



Dynalene, Inc.



Progress – Fuel Cells

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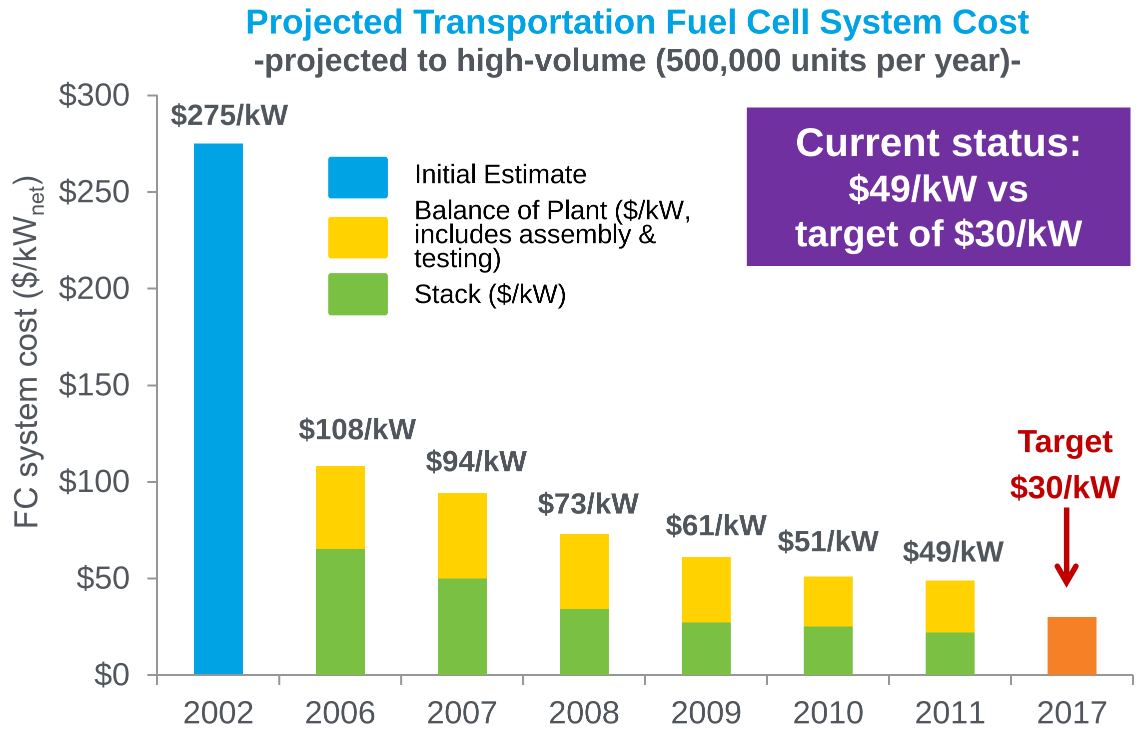
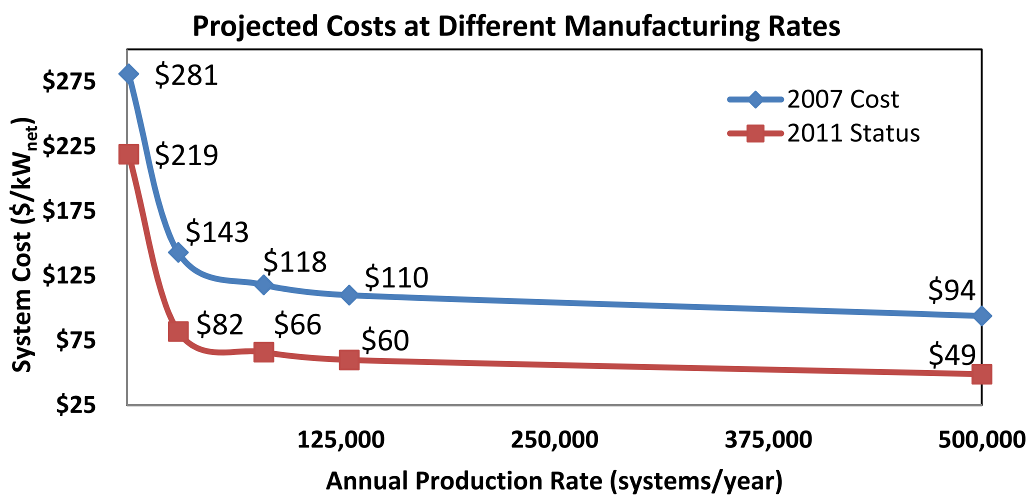
Projected high-volume cost of fuel cells has been reduced to $49/kW (2011)*

- ***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

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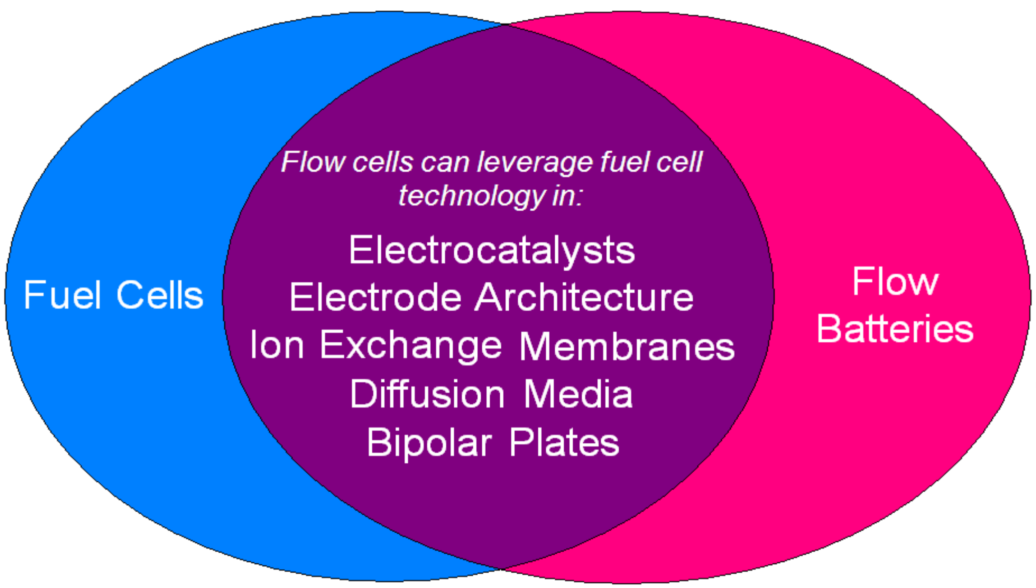
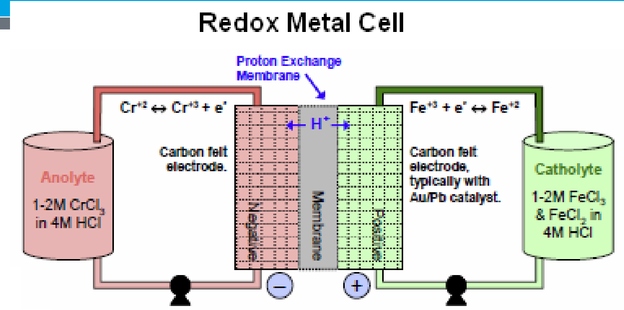
High efficiency energy storage that leverages existing fuel cell technology

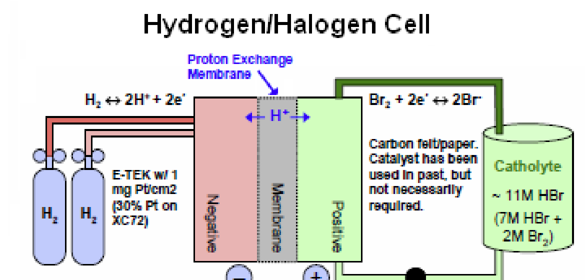
Advantages of reversible flow cells for energy storage:

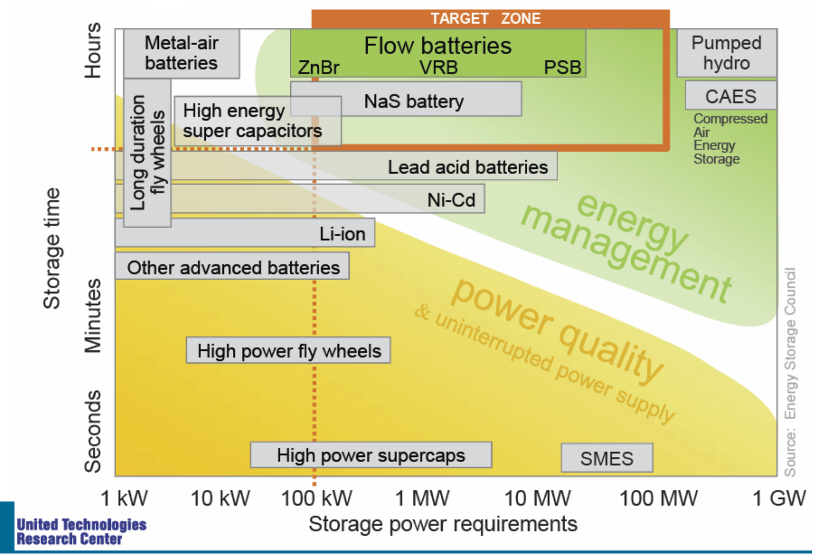
- **High round-trip efficiency (60 – 90%)**
- **Power and energy capacity are large and decoupled**
- **Long cycle life**
- **Low self-discharge**
- **Reliable and stable performance**

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







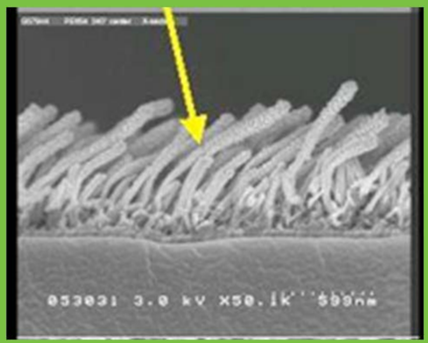


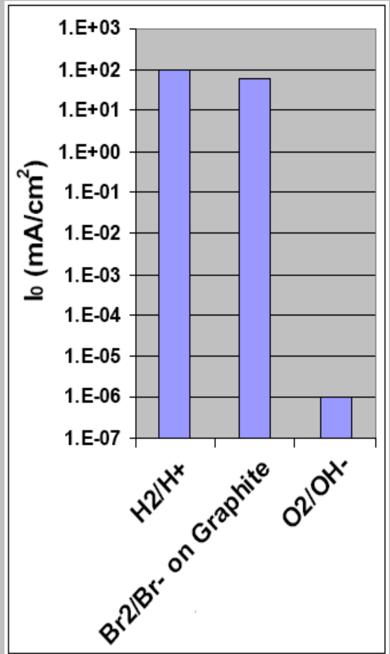
Reversible Flow Cells

Materials developed for fuel cells can be adapted for reversible flow cells (e.g. H_2/Br cell, LBNL)

Example: NSTF catalysts from 3M are being applied to H_2/Br cells in LBNL-led ARPA-E project

NSTF whiskers

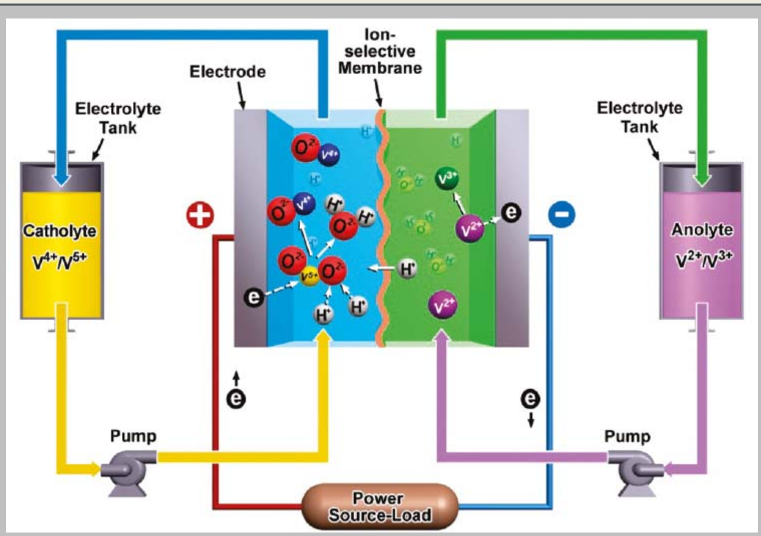


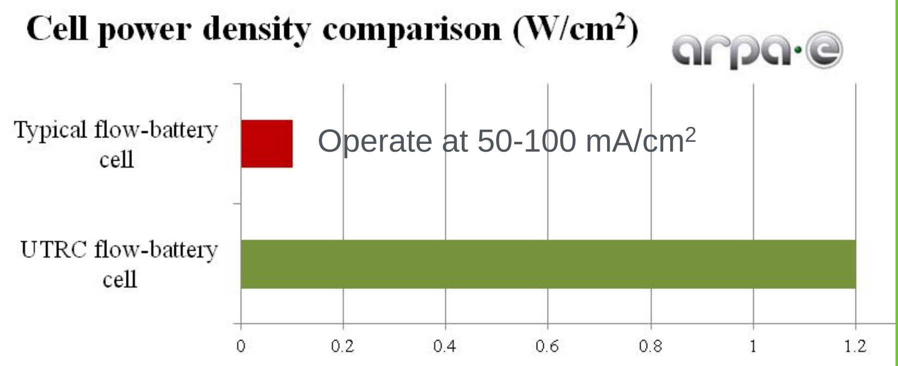


Replacement of O_2 electrodes with Br_2 electrodes in closed-loop flow cells leads to efficiency and performance improvement. Br_2 kinetics are ~8 orders of magnitude faster than O_2, with *no precious catalyst required.*

arpa·e

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.**





- Improvements obtained with *conventional materials*

Fuel Cell Catalysts: NSTF

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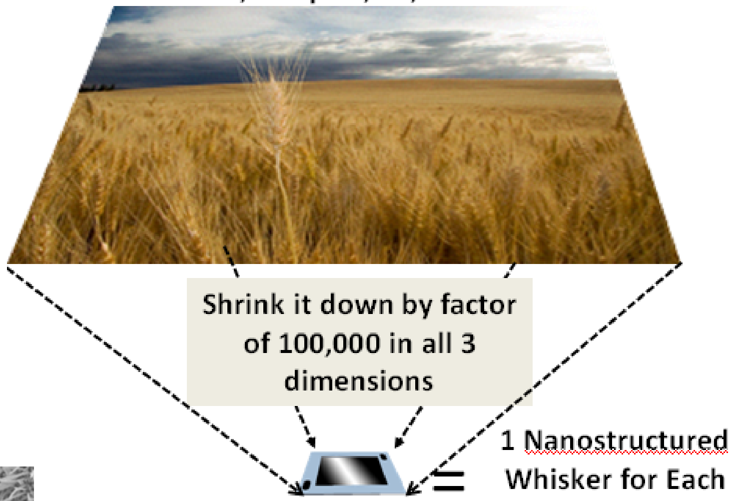
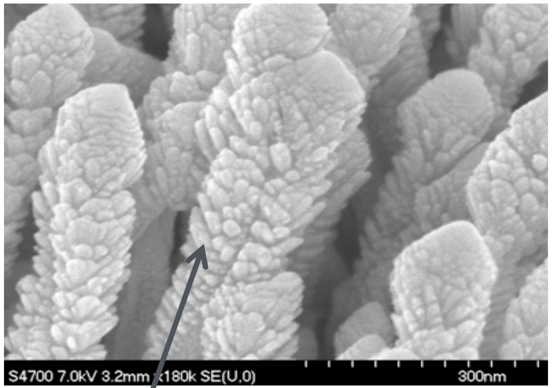
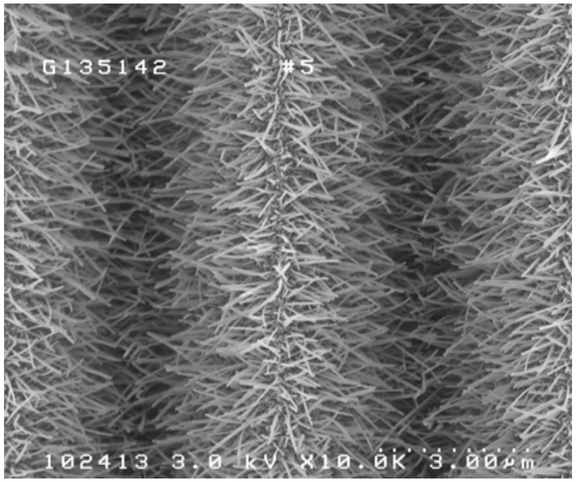
3M nanostructured thin film catalysts provide high performance, low PGM content

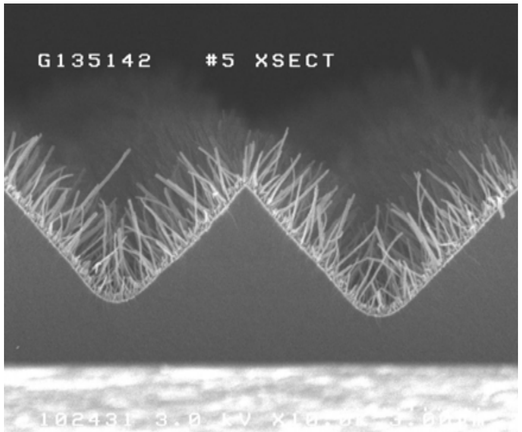
<u>3M NSTF Catalyst</u>
Oriented array of organic nanoscopic crystalline whiskers, on a microstructured substrate, sputter coated with metal catalysts

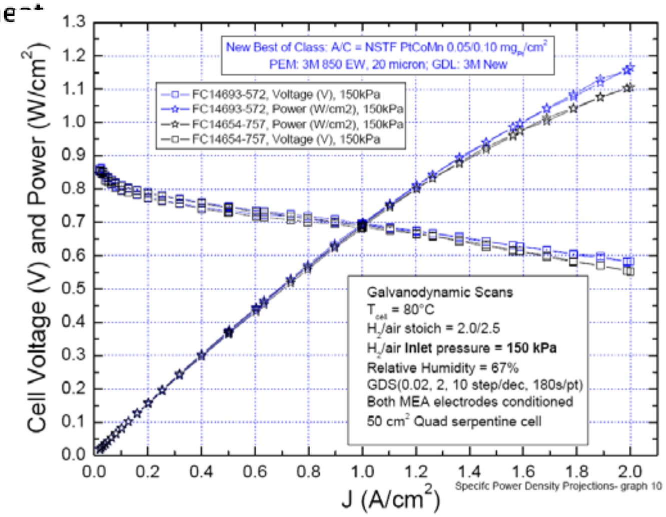




"Whiskerettes" of Pt grow off sides of crystalline whisker core at 70º



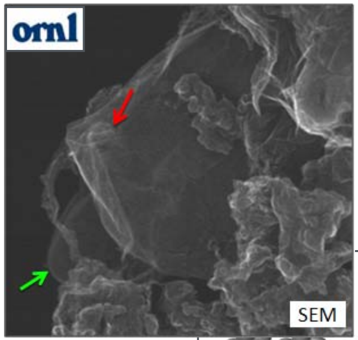




Source: 3M

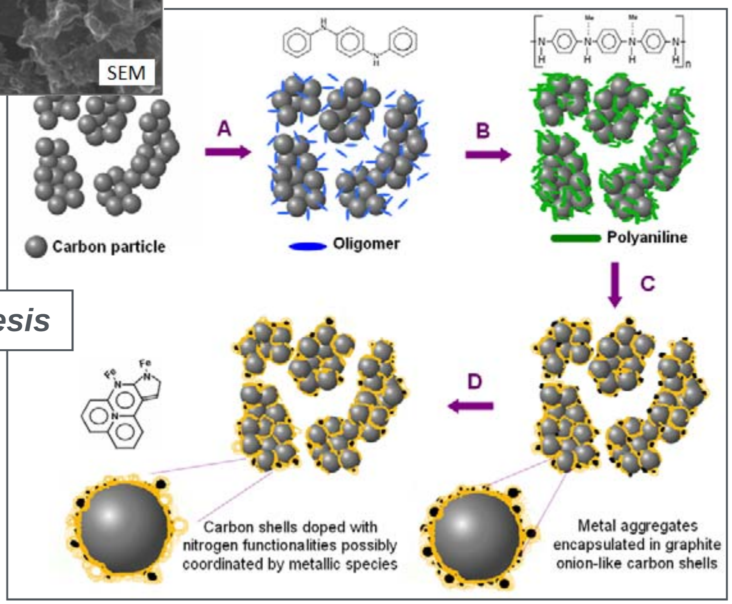
Fuel Cell Catalysts: Non-PGM

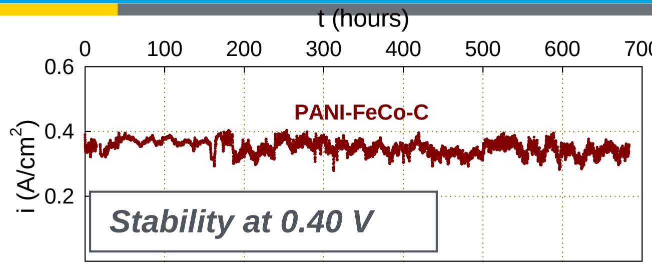
PGM-free catalysts developed at LANL for low-cost applications

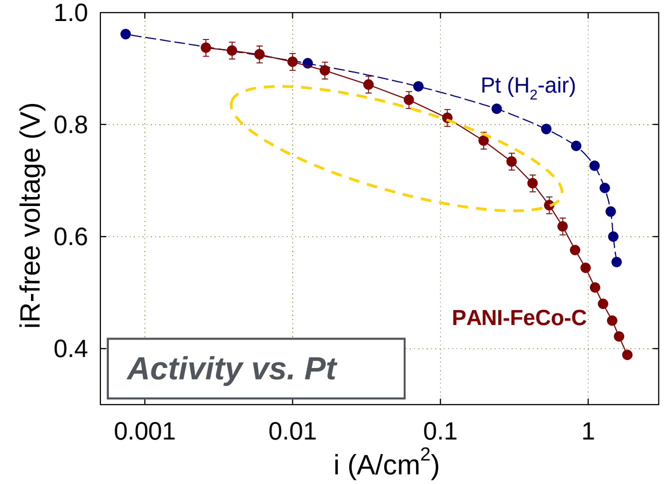


Catalyst SEM: *Layered-graphene sheet marked with green arrow; FeCo-containing nanoparticle shown with red arrow.*

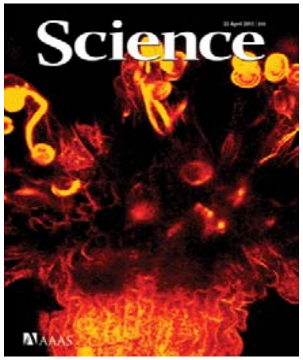
The Synthesis







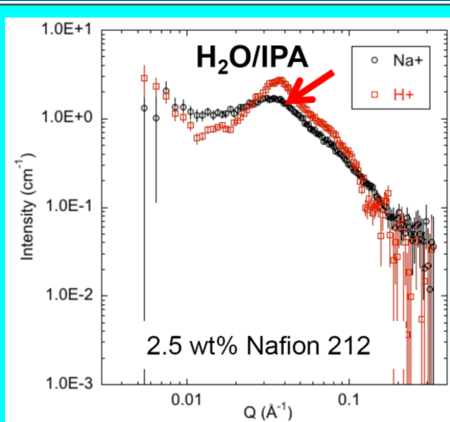
G. Wu, K. L. More, C. M. Johnston, P. Zelenay, *Science*, **332**, 443-7 (2011)

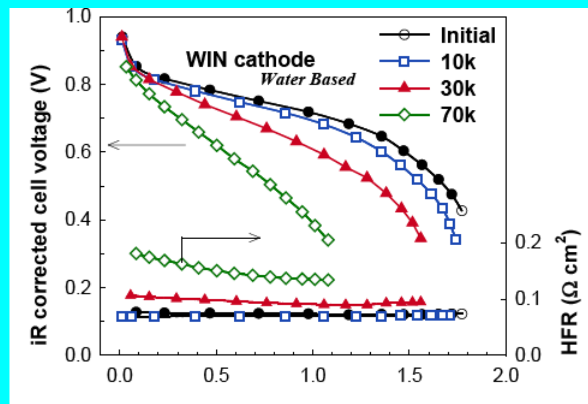


- **High ORR activity reached with polyaniline-based and cyanamide-based catalysts**
- **Intrinsic catalyst activity is projected to exceed 130 A/cm³ at 0.80 V**

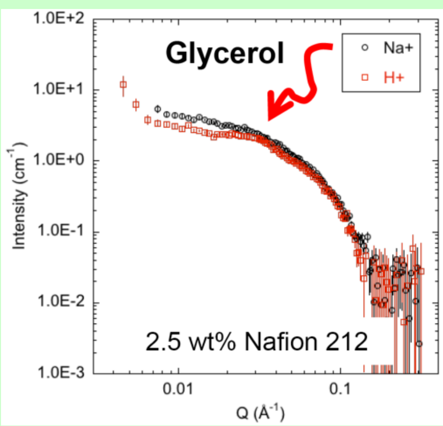
Electrode Architecture

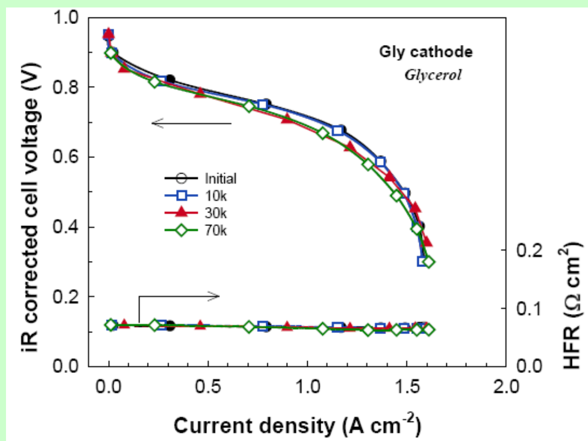
Catalyst and ionomer structure determines performance and durability



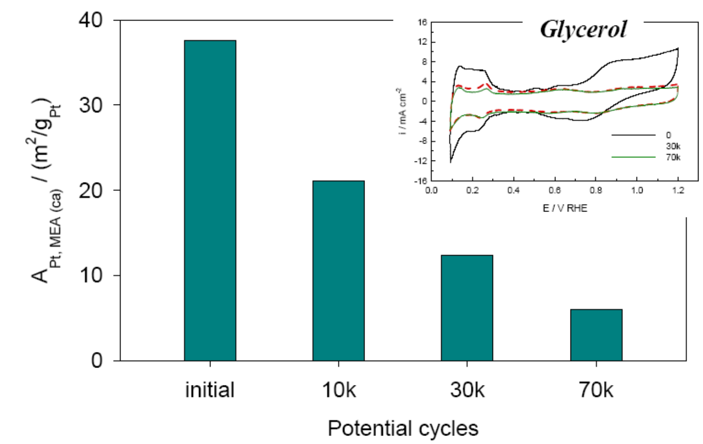


Ionomer ordering in water/alcohol → **Poor durability**

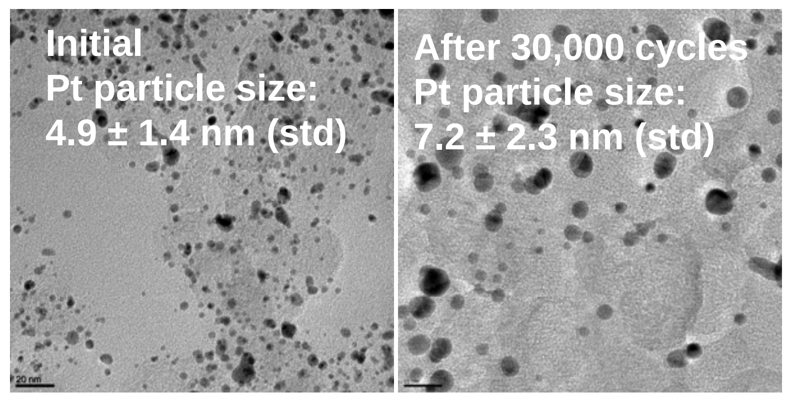




Lack of ordering in glycerol → **High durability – exceeds 30,000 cycle target**



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



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

Low-cost Bipolar Plates

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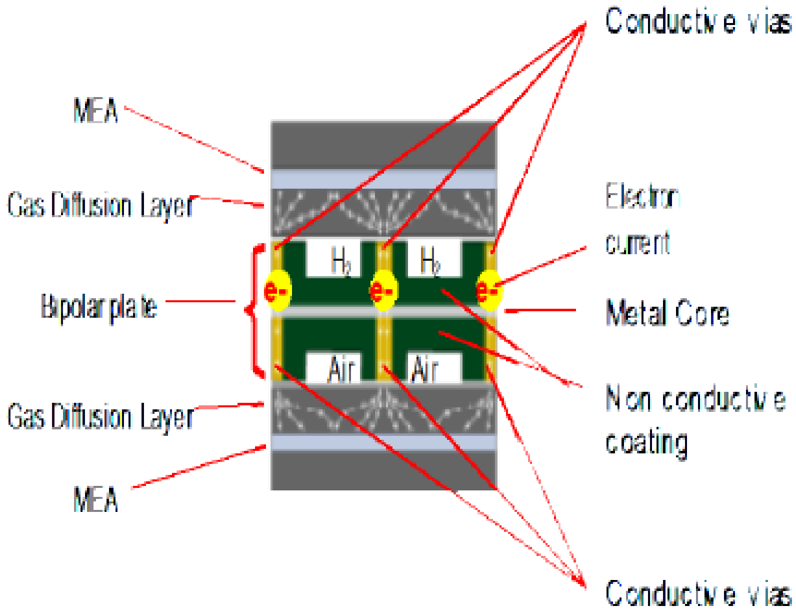
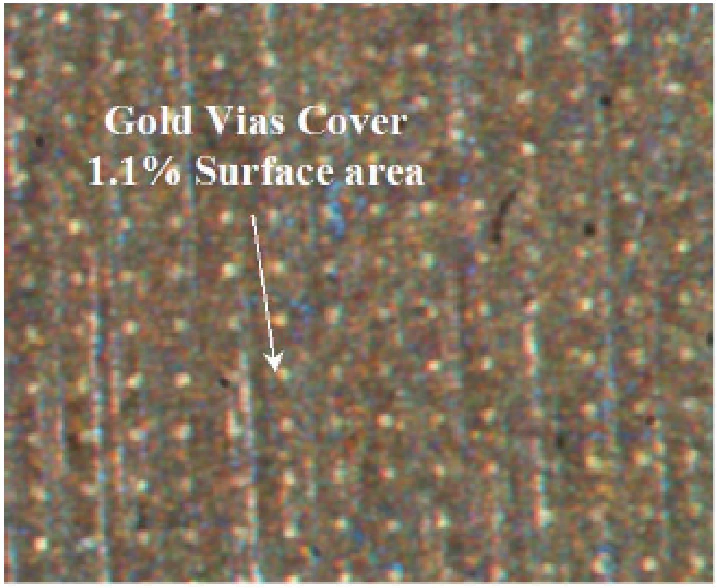
TreadStone: Surface patterning for materials cost reduction



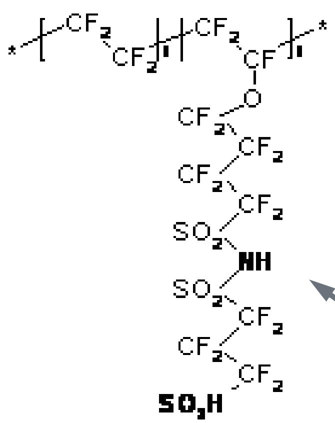


- **Small vias provide electronic conductivity, while most of the metal plate is covered by corrosion-resistant coating**
- **Plate technology successfully demonstrated with Au vias and SS substrate. Cost: ~$3.5/kW**
- **Currently developing plates with lower-cost vias (carbon nanotubes, conductive carbides)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

C. Wang, TreadStone

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**



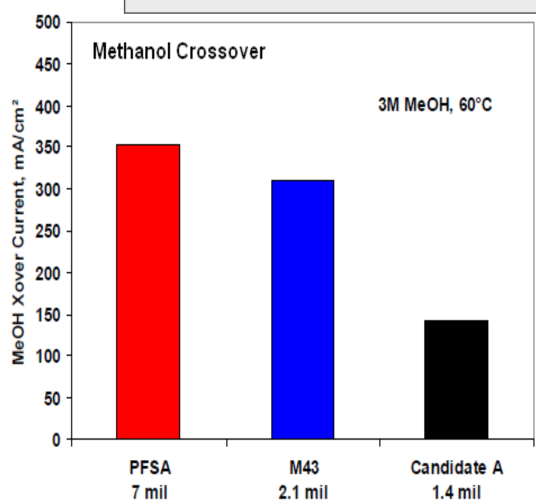
Two superacid sites per side chain

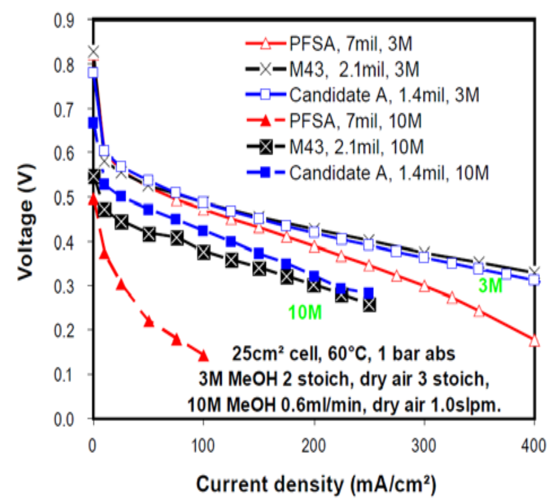
PFIA

S. Hamrock et al., 3M

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**

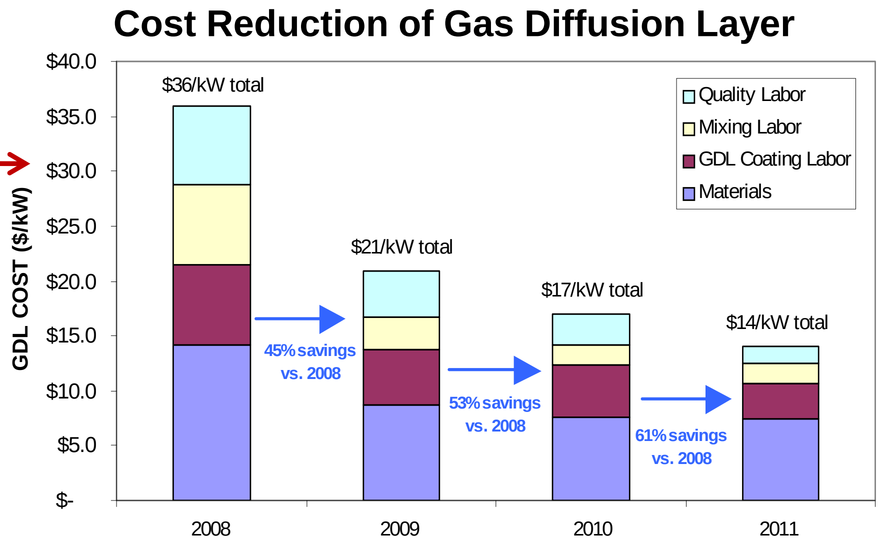




Manufacturing R&D

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

REVERSIBLE FUEL CELLS

Crystal City, Virginia, April 19, 2011

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:

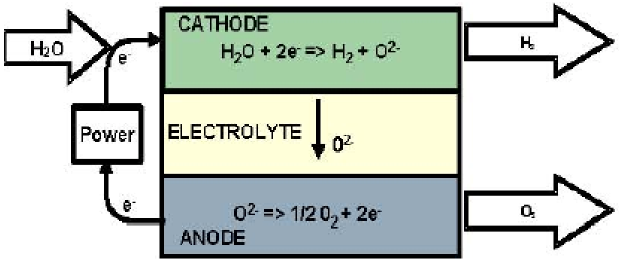
- New catalysis materials for air/oxygen electrode are needed to improve durability for both PEMFC and SOFC based systems.
- New stack designs and new approaches to heat management need to be investigated.
- Speed with which the systems can reverse directions and respond to variable inputs and loads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

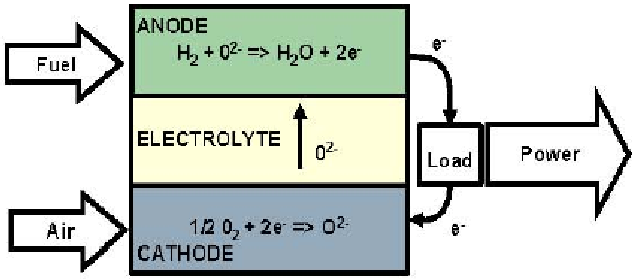
Complete workshop report available at:
http://www1.eere.energy.gov/hydrogenandfuelcells/wkshp_reversible_fc.html

Organized by: U.S. DEPARTMENT OF ENERGY, NREL NATIONAL RENEWABLE ENERGY LABORATORY

Reversible Fuel Cells

Reversible fuel cells for energy storage applications





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

Metric	Target	Status
☑ **Performance** (Area specific resistance in both SOFC and SOEC operating modes)	**< 0.3 Ω-cm²**	**0.223 Ω-cm² in SOEC** **0.224 Ω-cm² in SOFC**
☑ **Degradation** (Overall decay rate)	**< 4% per 1000 hours**	**~1.5% per 1000 hours**
☑ **Operating Duration**	**> 1000 hours**	**1005 hours** (as of Go/No-Go Decision)
☑ **Operating Current Density**	**> 300 mA/cm²**	**500 mA/cm²**

Thank you

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www.hydrogenandfuelcells.energy.gov

Additional Information

Worldwide Investment & Interest Are *Strong and Growing*

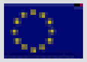
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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



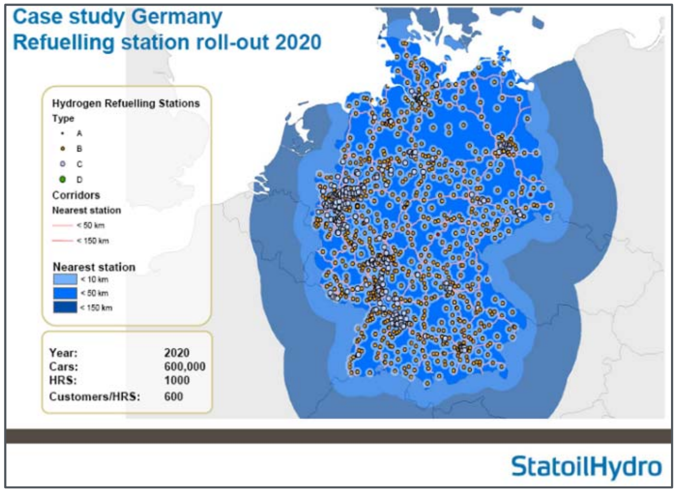
European Union: >$1.2 Billion in funding ('08–'13)

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

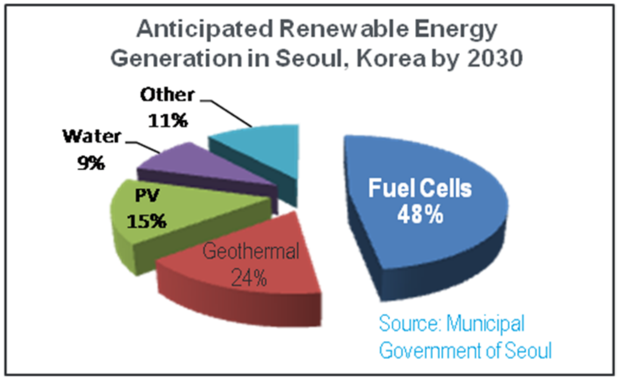
China: Thousands of small units deployed; 70 FCEVs, buses, 100 FC shuttles at World Expo and Olympics

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.

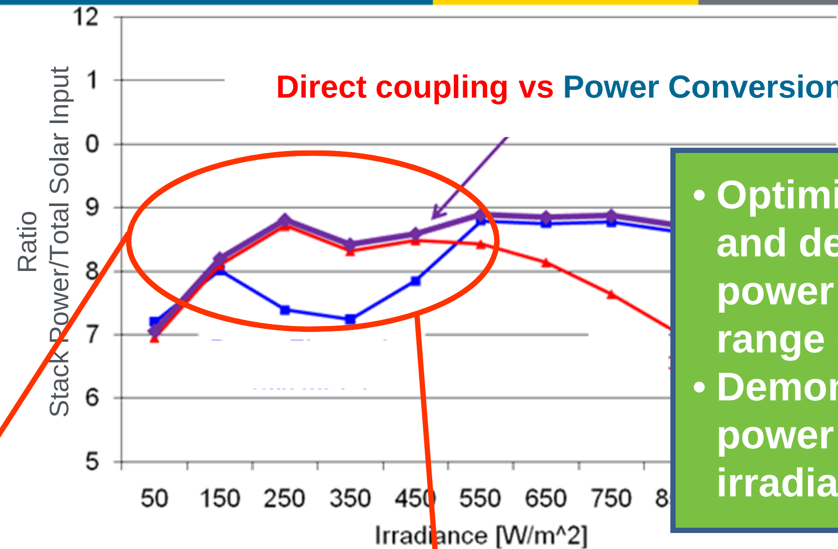


Hydrogen & Fuel Cells for Energy Storage

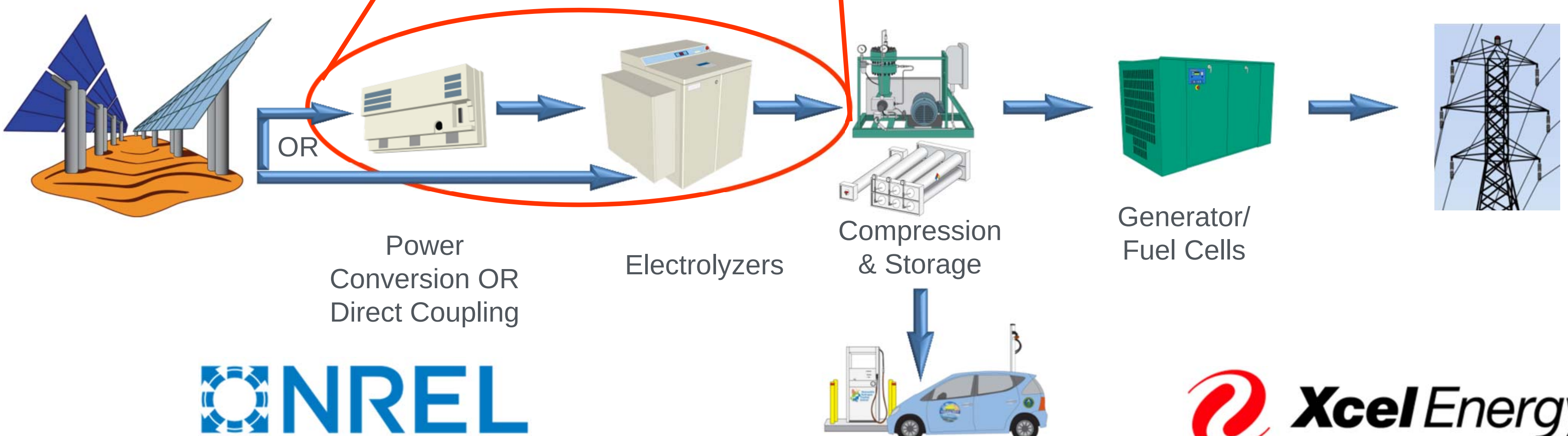
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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**



NREL NATIONAL RENEWABLE ENERGY LABORATORY

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