

Overview of DOE Hydrogen and Fuel Cell Activities

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United States Department of Energy

Fuel Cell Technologies Program

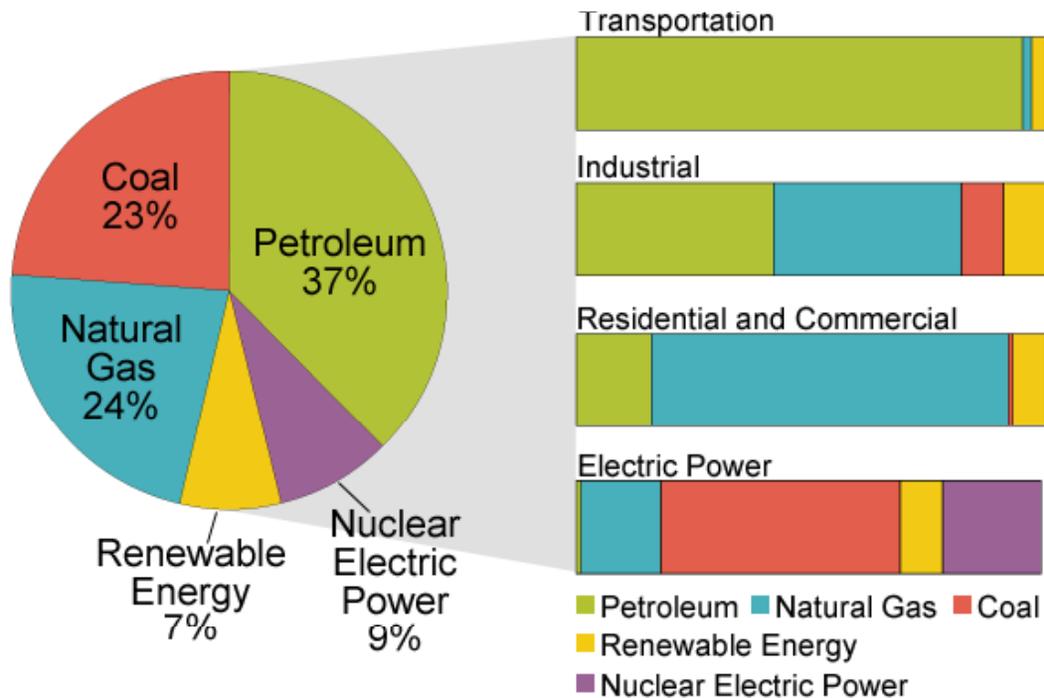
Gordon Research Conference: Fuel Cells, Rhode Island

August 1, 2010

- ✓ 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



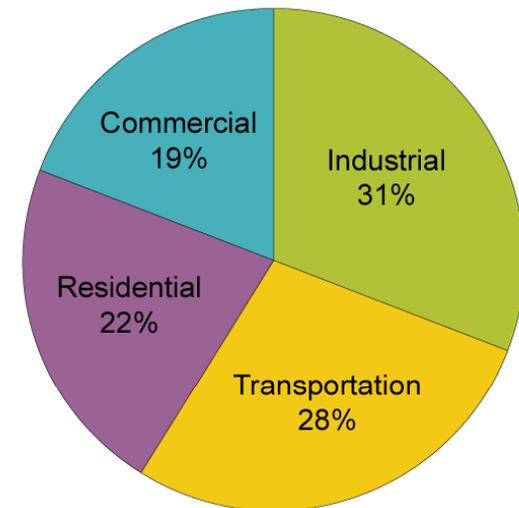
U.S. Primary Energy Consumption by Source and Sector



Total U.S. Energy = 99.3 Quadrillion Btu

Source: Energy Information Administration, *Annual Energy Review 2008*, Tables 1.3, 2.1b-2.1f.

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



Source: Energy Information Administration, *Annual Energy Review 2008*.

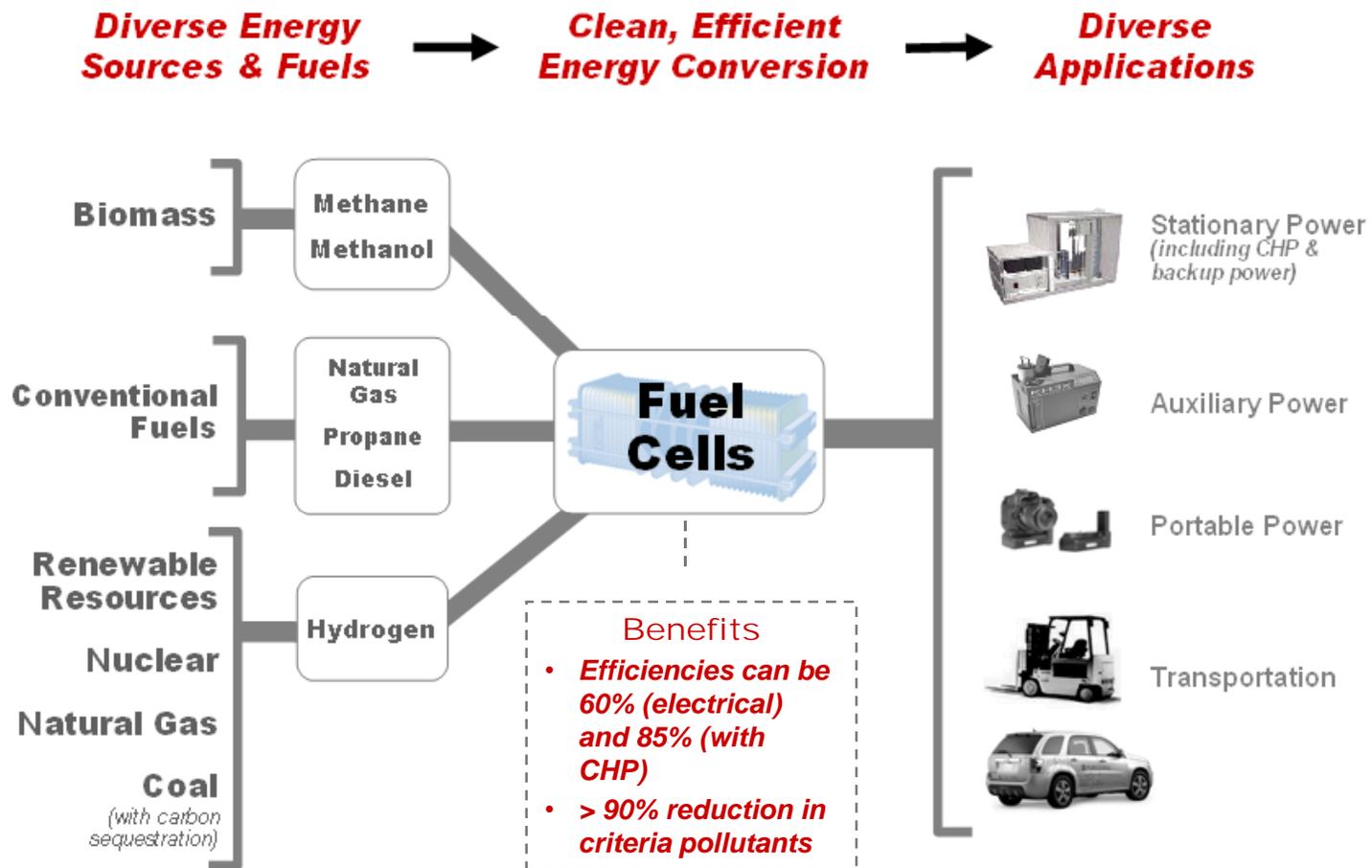
Fuel Cells: Addressing Energy Challenges

Energy Efficiency and Resource Diversity

→ *Fuel cells offer a highly efficient way to use diverse fuels and energy sources.*

Greenhouse Gas Emissions and Air Pollution:

→ *Fuel cells can be powered by emissions-free fuels that are produced from clean, domestic resources.*



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.



Fuel Cells for Transportation

In the United States:

> 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.



Production & Delivery of Hydrogen

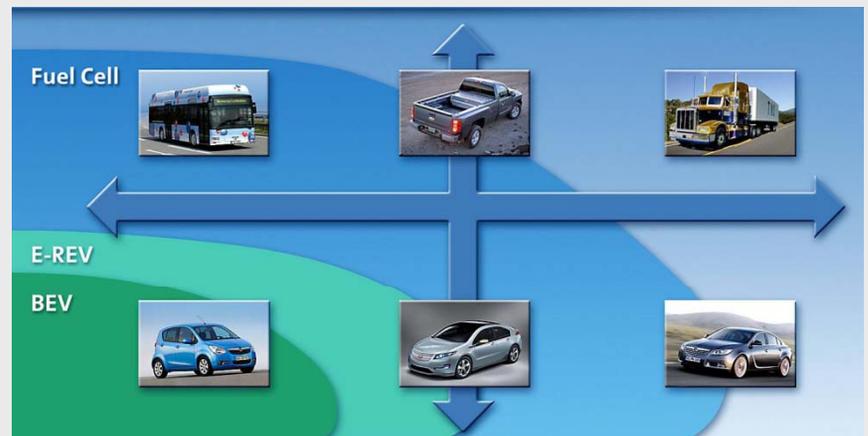
In the U.S., there are currently:

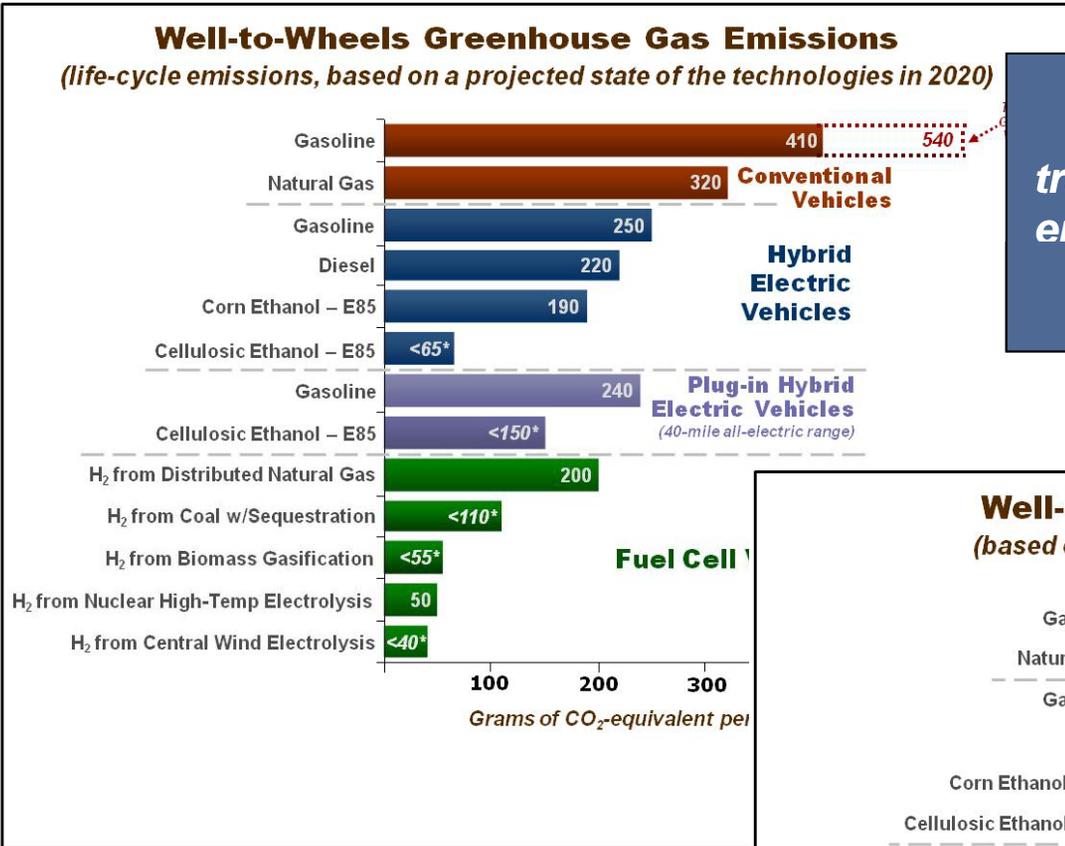
~9 million metric tons of H₂ produced annually

> 1200 miles of H₂ pipelines

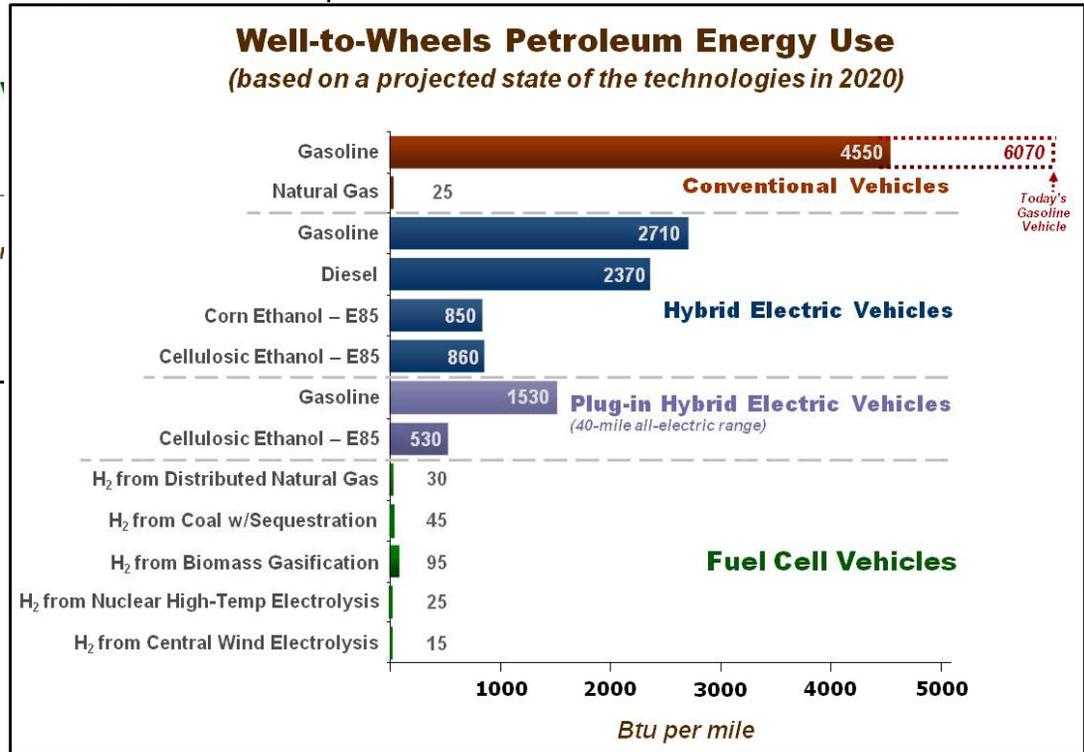


The Role of Fuel Cells in Transportation



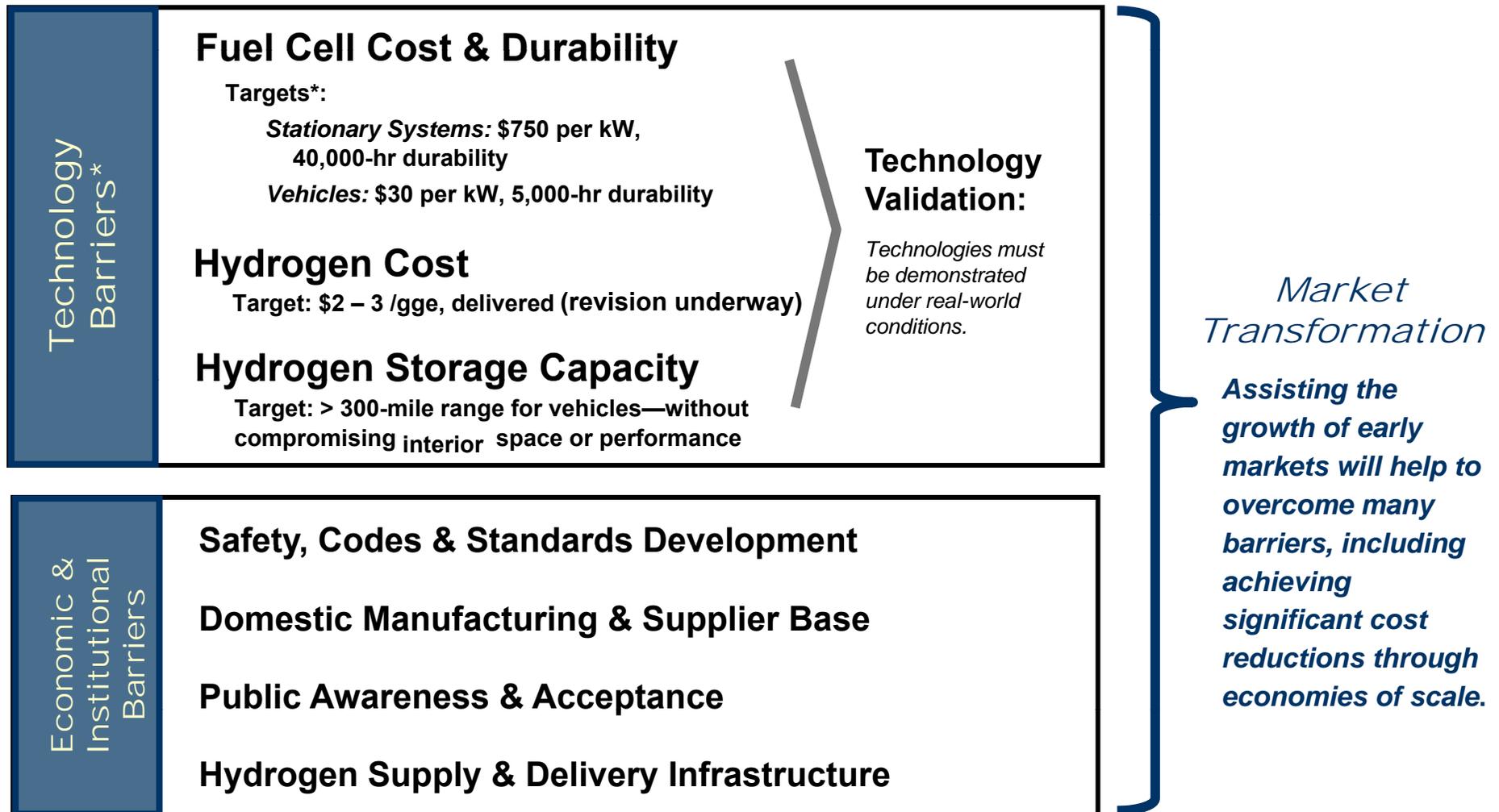


Analysis shows DOE's portfolio of transportation technologies will reduce emissions of greenhouse gases and oil consumption.



Key Challenges

The Program has been addressing the key challenges facing the widespread commercialization of fuel cells.



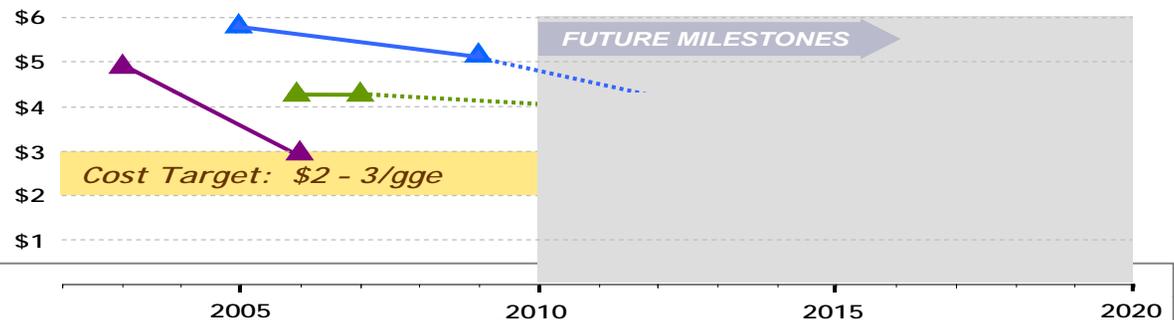
*Metrics available/under development for various applications

Projected* High-Volume Cost of Hydrogen (Delivered) — Status & Targets (\$/gallon gasoline equivalent [gge], untaxed)

NEAR TERM:

Distributed Production

- ▲ Natural Gas Reforming
- ▲ Bio-Derived Renewable Liquids
- ▲ Electrolysis



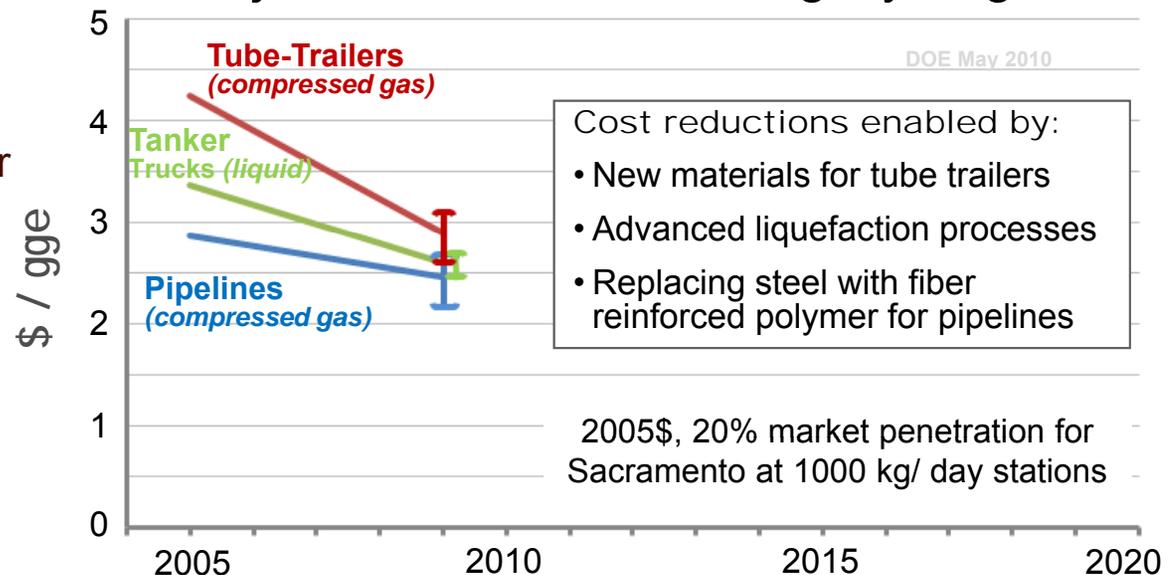
We've reduced the cost of hydrogen delivery* —

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

Cost targets under revision

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

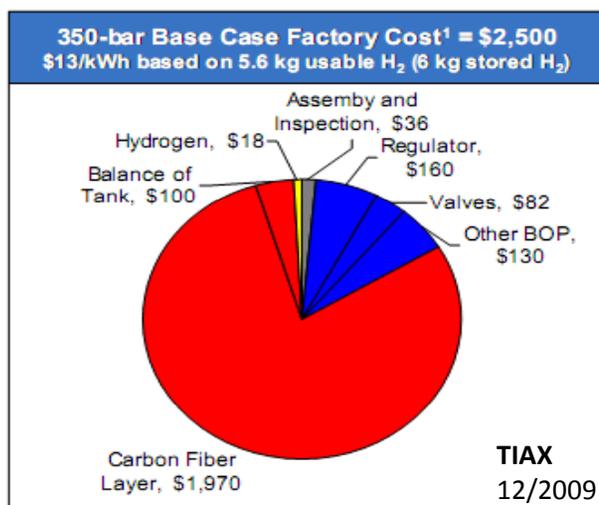
Projected Cost of Delivering Hydrogen



Compressed gas offers a near-term option, but cost is an issue

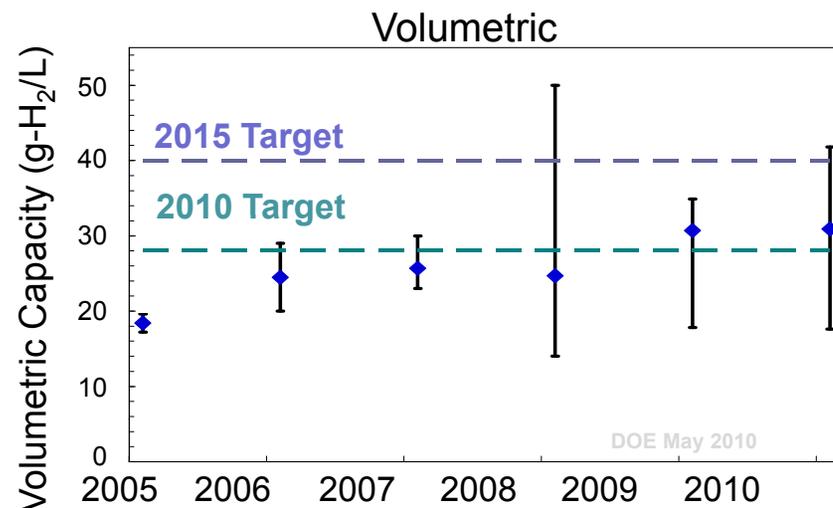
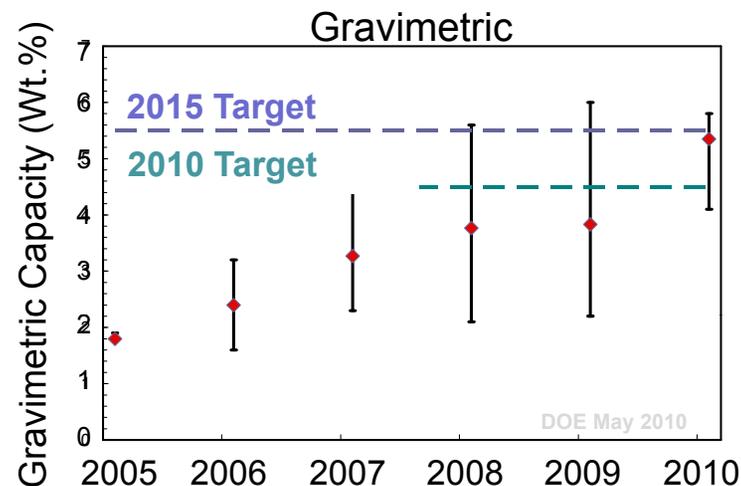
Compressed gas storage offers a near-term option for initial vehicle commercialization and early markets

- 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



¹ Cost estimate in 2005 USD. Includes processing costs.

Projected Capacities for Complete 5.6-kg H₂ Storage Systems

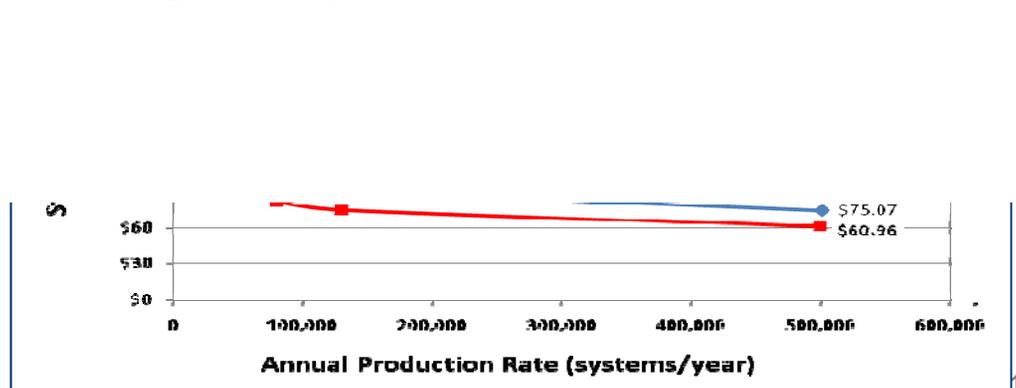
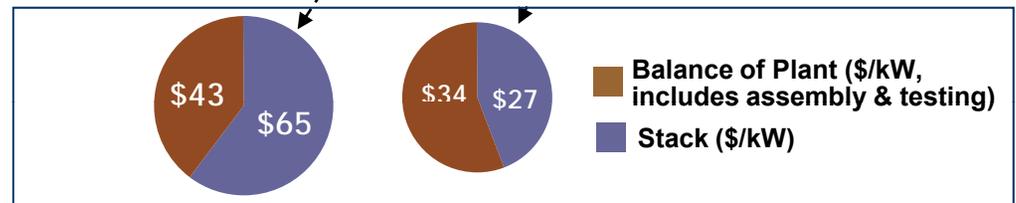
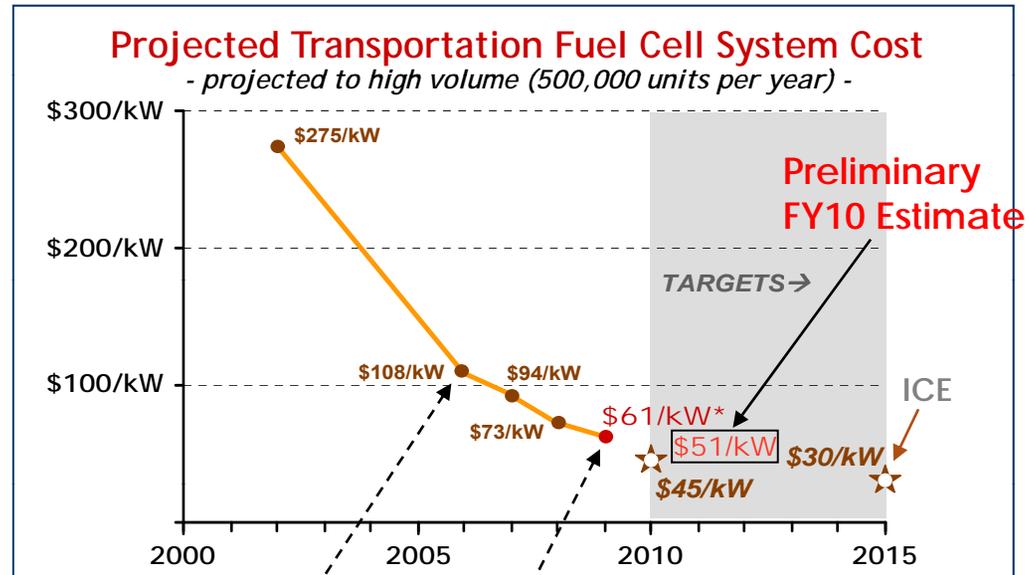


Fuel Cell R&D — Progress: Cost

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



(500,000 units/year).

**Panel found \$60 – \$80/kW to be a “valid estimate”:
http://hydrogen.doedev.nrel.gov/peer_reviews.html

The Program has reduced PGM content and increased power density, resulting in a decrease in system cost.

From 2008 to 2009, key cost reductions were made by:

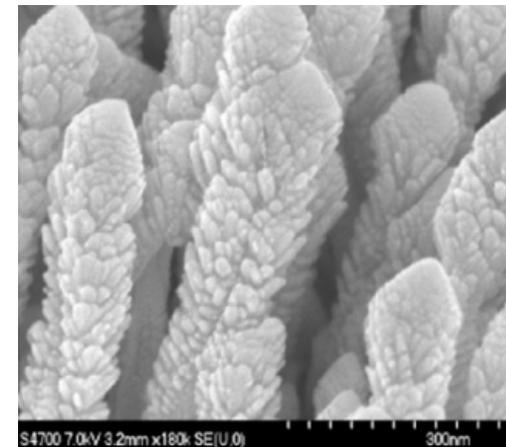
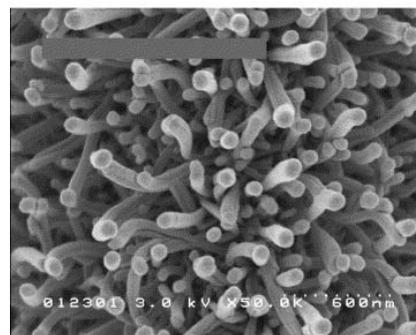
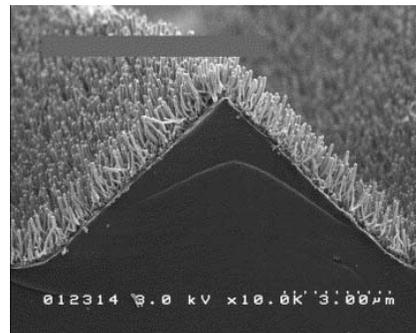
- Reducing platinum group metal content from 0.35 to 0.18 g/kW
- Increasing power density from 715 to 833 mW/cm²

→ These advances resulted in a \$10/kW cost reduction.

Key improvements enabled by using novel organic crystalline whisker catalyst supports and Pt-alloy whiskerettes.

There are ~ 5 billion whiskers/cm².

Whiskers are ~ 25 X 50 X 1000 nm.



Whiskerettes:
6 nm x 20 nm

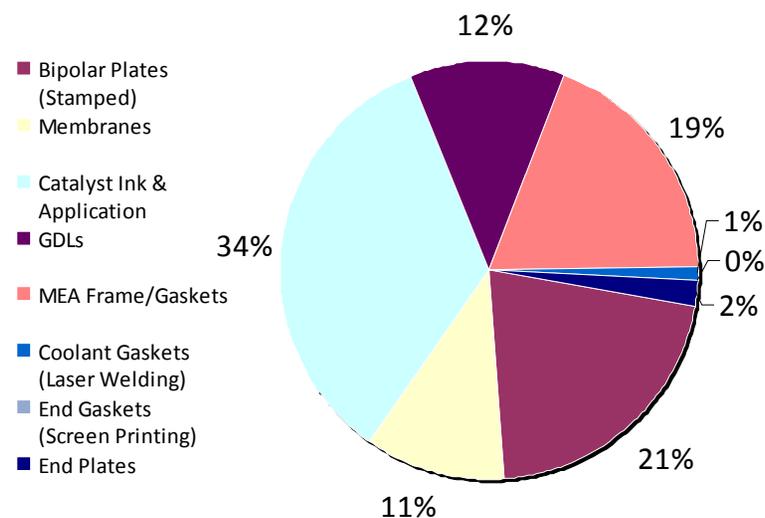
Challenges:

- Platinum (Pt) cost is ~34% of total stack cost
- Catalyst durability needs improvement

Four Strategies for Catalysts & Supports R&D:

- **Lower PGM Content**
 - Improved Pt catalyst utilization and durability
- **Pt Alloys**
 - Pt-based alloys with comparable performance to Pt and cost less
- **Novel Support Structures**
 - Non-carbon supports and alternative carbon structures
- **Non-PGM catalysts**
 - Non-precious metal catalysts with improved performance and durability

Stack Cost - \$26/kW

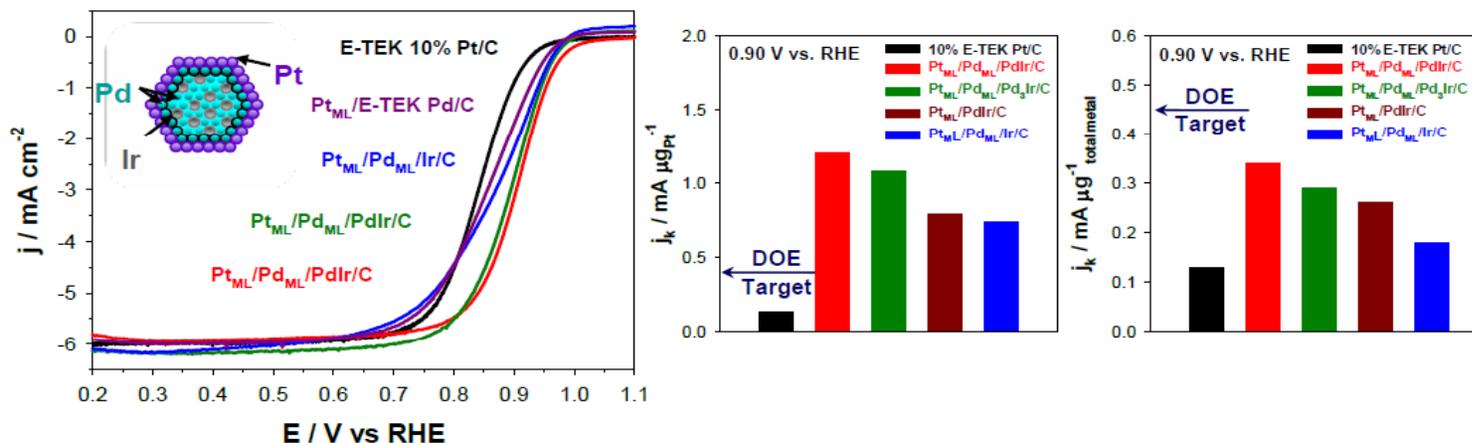


DTI, 2009 analysis, scaled to high volume production of 500,000 units/yr

Used \$1100/Troy Ounce for Pt Cost

Ultra-low Pt Content Catalysts

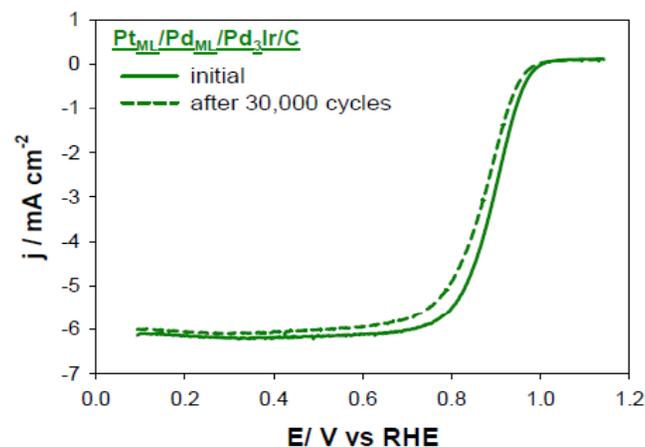
Pd Interlayer Effect on ORR Activity



•**Highlight:** **0.35 A/mg_{PGM}** at **0.90 V** – an improvement of 0.08 A/mg_{PGM} due to Pd interlayer (better lattice constant for Pt overlayer)

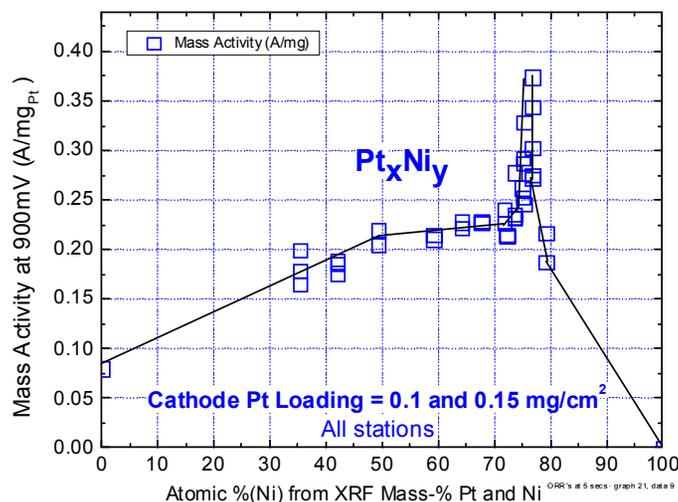
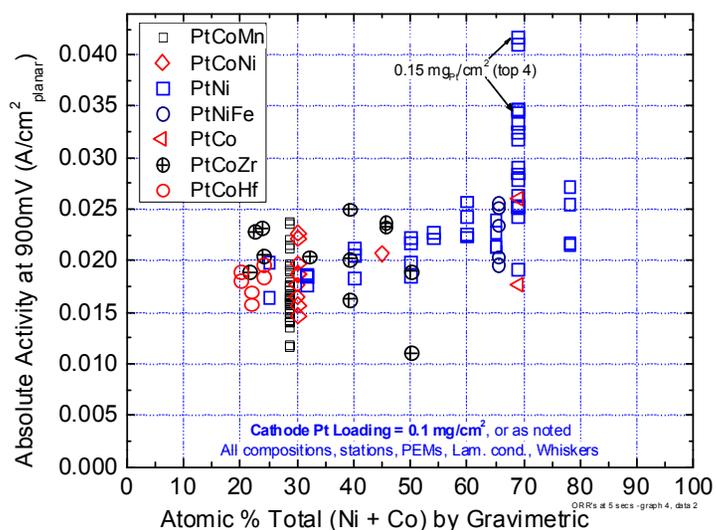
•**Highlight:** $E_{1/2}$ loss after 30,000 cycles of only 19 mV vs. 39 for Pt/C

•Pd not significantly oxidized (XAS); good substrate for Pt compared to other metals, e.g. iridium

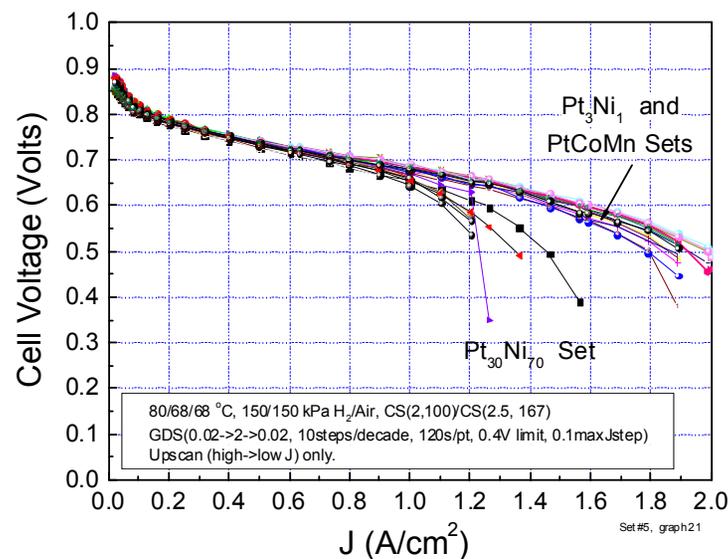


Next Steps: Improve activity and durability. In-cell testing.

High-Activity Binary PtNi Alloy Catalyst



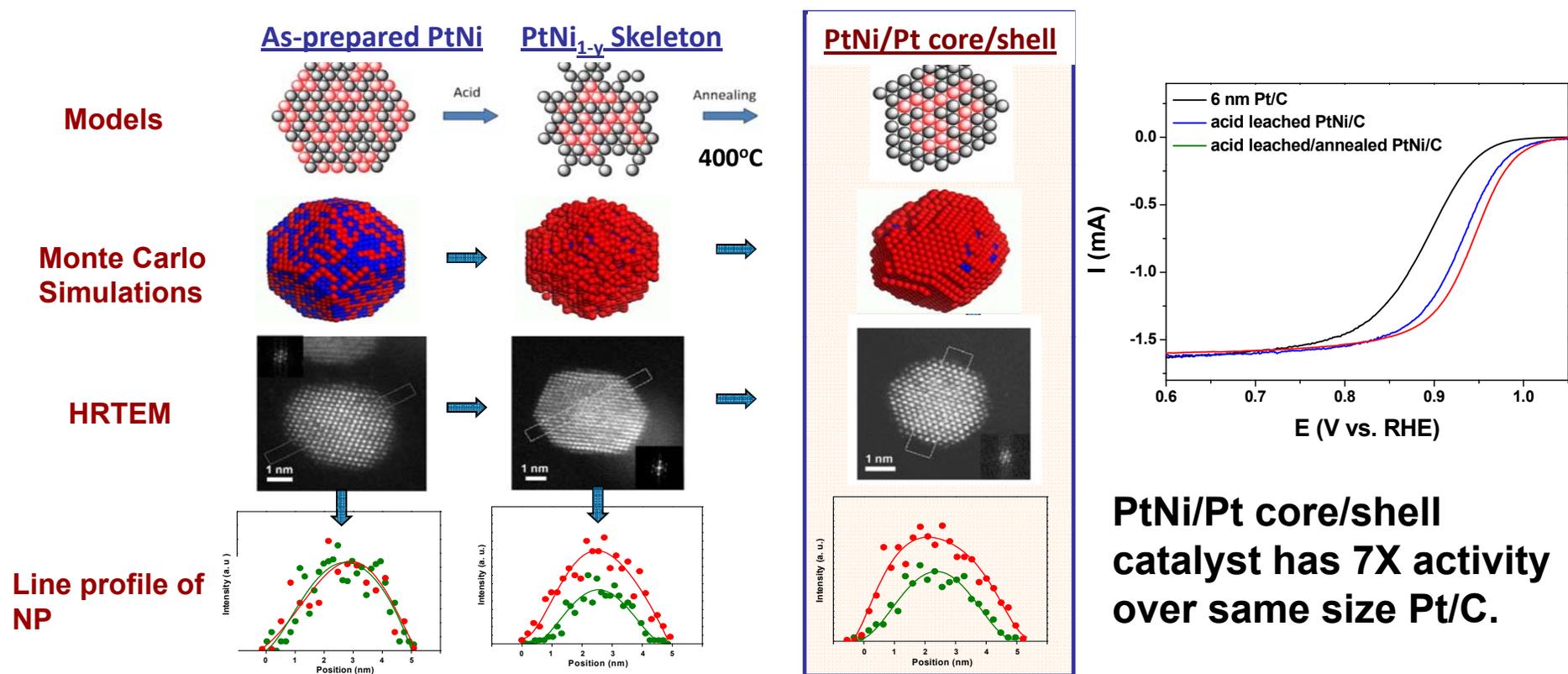
- Screening of multiple new alloys at 3M revealed anomalously high ORR activity for Pt_xNi_y at high Ni content.
- Dramatic and sharp mass activity peak at Pt_3Ni_7 (gravimetric) vs 60at% Ni and 76at% Ni by EMP and XRF respectively.
- Definite gains in kinetic performance but not a practical catalyst yet due to performance limitations above $1 A/cm^2$.



Next Steps: Improve high current density performance.

Nano-segregated Cathode Catalysts

Argonne National Laboratory approach: Materials by design to characterize, synthesize, and test nanosegregated multi-metallic nanoparticles and nanostructured thin metal films

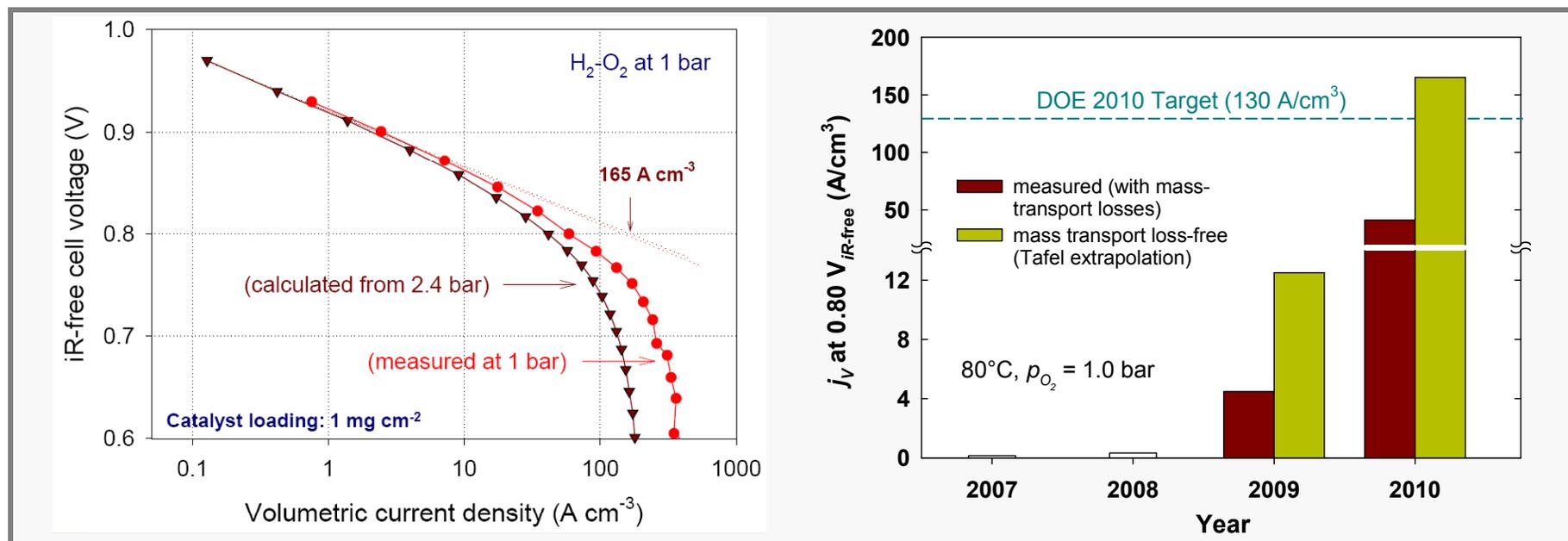


Next Steps: Evaluate in-cell durability, scale-up

N. Markovic, 2010 DOE Hydrogen Program Review

PGM-Free Catalysts

Los Alamos National Laboratory Approach: Cyanamide-Fe-C Catalysts



- High ORR activity reached with several non-PGM catalysts by LANL, including cyanamide-Fe-C catalyst (shown).
- Intrinsic catalyst activity is projected to exceed DOE 2010 activity target of 130 A/cm³ at 0.80 V.

Next Steps: Determine active site. Improve activity to PGM catalyst level.

Fuel Cell Technologies — Catalysts

Technical Targets vs. Status

Electrocatalysts for Transportation Applications	Status ^a	Targets ^b	
	2009	2010	2015
Platinum group metal (PGM) total content (both electrodes)	0.2 g/kW	0.15 g/kW	0.125 g/kW
PGM Total Loading	0.15 mg/cm ²	0.15 mg/cm ²	0.125 mg/cm ²
Loss in catalytic (mass) activity ^c	TBD	<40% loss of initial	<40% loss of initial
Catalyst support loss ^d	TBD	< 10% mass loss	< 10% mass loss
Mass activity ^e	0.16 A/mg Pt in MEA >0.44 A/mg Pt new alloy in RDE	0.44 A/mg PGM	0.44 A/mg PGM
Activity per volume of supported catalyst (non-PGM) ^f	155 A/cm ³	>130 A/cm ³	>300 A/cm ³

^a single cell status – will require scale-up

^b preliminary targets – approval pending

^c after 30,000 cycles from 0.6 – 1.0 V;

after 400 hours at 1.2 V

^d after 400 hours at 1.2 V

^e baseline @ 900mV_{IR-free}

^f baseline @ 800mV_{IR-free}

H	= High (significant challenge)	M	= Medium
M/H	= Medium/High	L	= Low (minimal challenge)

Update of Multiyear RD&D Plan in process

Challenges:

- Membranes account for 48% of stack cost at low volume
- Limits on operating range
- Chemical and mechanical durability

Membrane R&D:

High-Temperature, Low Humidity Conductivity

Phase segregation (polymer & membrane)

Non-aqueous proton conductors

Hydrophilic additives

High Conductivity and Durability Across Operating Range with Cycling

Mechanical support or membrane
reinforcement

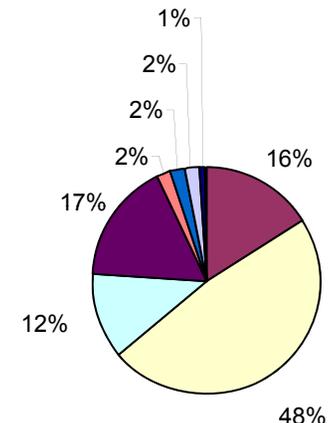
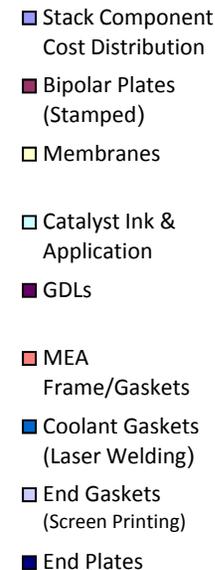
Chemical stabilization (additives, end-
group capping)

Polymer structure (side chain length,
grafting, cross-linking, backbone
properties, blends, EW)

Processing parameters (temperature,
solvents)

New materials

Stack Cost - \$137/kW



DTI, 2009 analysis, production of 1,000
units/yr

Used \$453/m² for membrane Cost

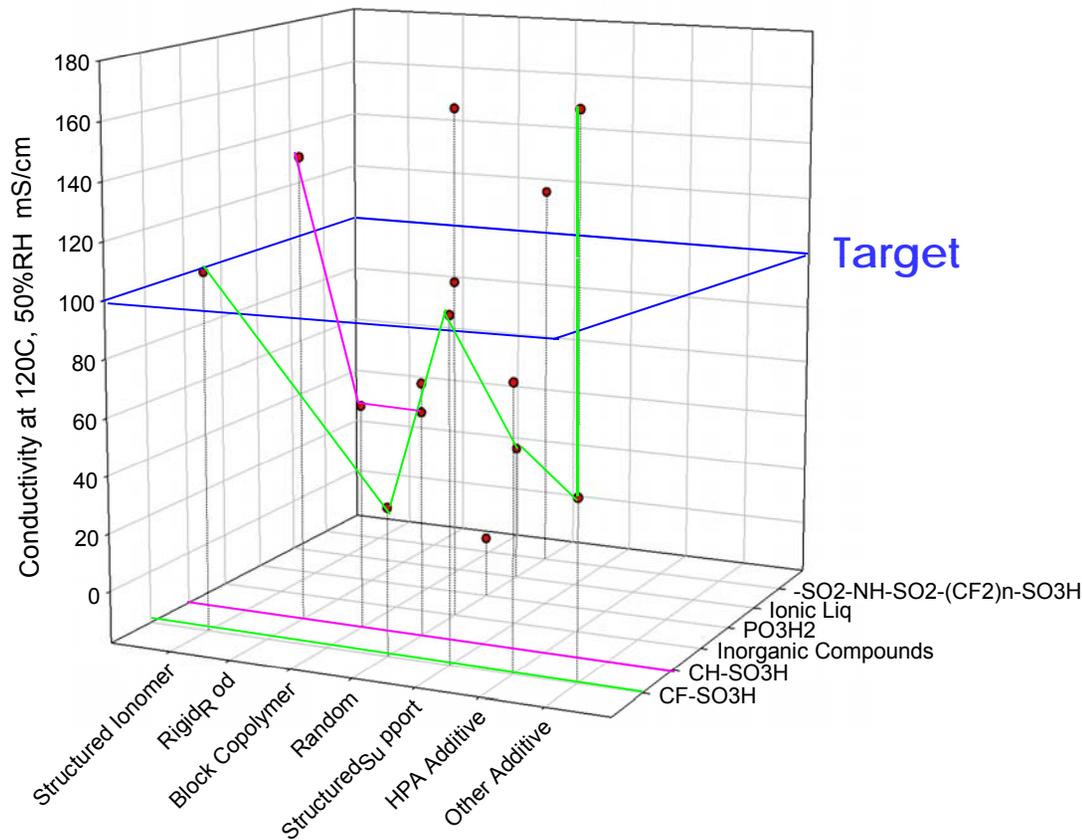
Strategies for Hi-T Membrane R&D

High conductivity at 120°C 50% RH achieved with a variety of approaches

		Morphology	Molecular Approach			Additive Approach				Micro/nano engineering approach	
			Other Polymer	Block Copolymer	Rigid Rods	ZrPhosphate	HPA	Zeolite	Other	Structured Support	Structured Ionomer
Conduction Mechanism											
Aqueous											
	FC-SO3H	Yellow			Orange	Yellow			Green	Green	Green
	HC-SO3H	Yellow	Yellow	Green	Orange	Orange					
	Hydrous Metal Oxides										
	Perfluoro imide acid	Green									
Potential Non Aqueous											
	polyPOMs	*									
	Phosphates	**									
	Phosphonic acids	Orange									
	Phosphoric acid		Yellow								
	Heterocyclic bases										
	Ionic liquids	Orange									
		Green	≥ 0.1 S/cm at 120C and 50%RH								
		Yellow	> 50% of target								
		Orange	Less than 50% of target			NRE 212 < 50% of target					
	*	Measured in-house and by a second party									
	**	Measured in-house									

Conductivity Results (120° C, 50% RH)

Need to go to even lower humidity to simplify fuel cell system designs: Need high conductivity at low RH



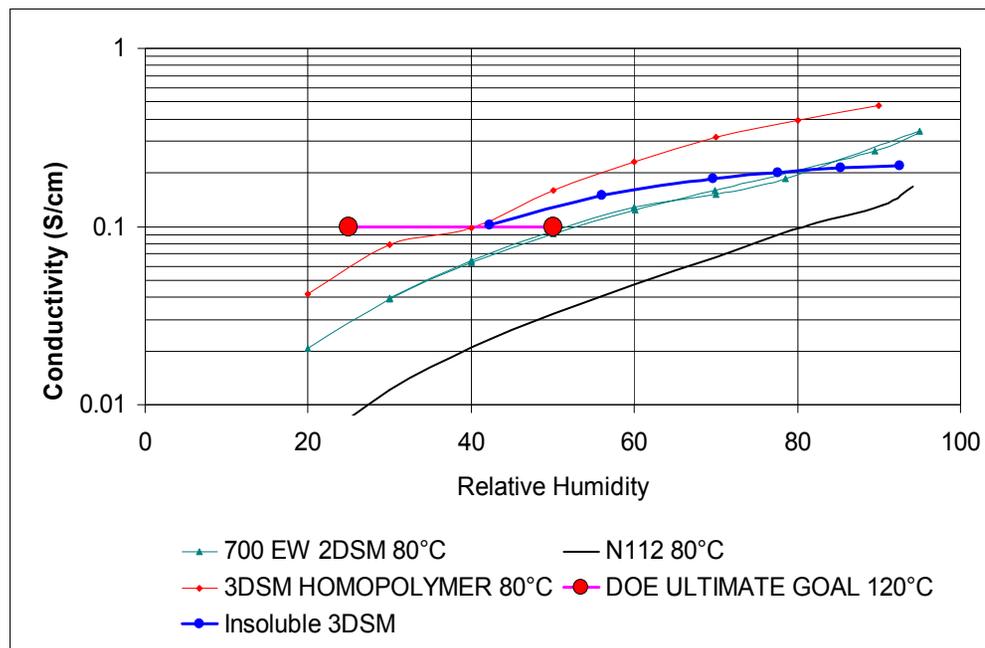
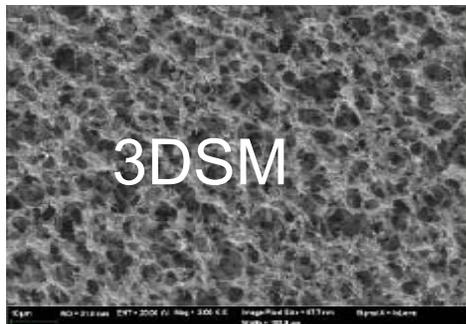
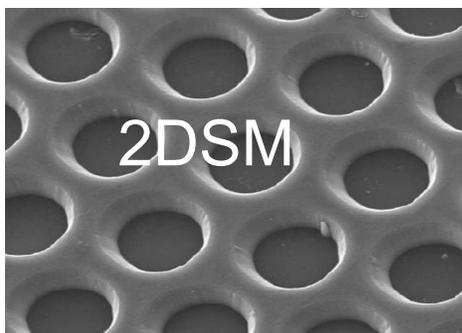
Exceeded 0.1 S/cm at 120°C and 50% RH using several conducting groups.

For a given conducting group, morphology can have a large effect on conductivity.

Additives can also have a large effect.

Dimensionally Stabilized Membranes

Giner Electrochemical Systems approach: Engineering polymer matrix provides mechanical properties. Low-EW ionomer provides conductivity

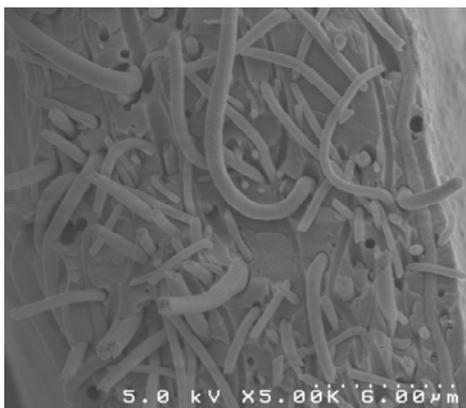


Next Steps: Impregnation of thin porous mats with low-EW ionomer. Fabricate large-area films. Improve fuel cell performance.

Nanocapillary Network Membranes

Vanderbilt University approach: Simultaneously electrospin dual nanofiber mat, one fiber is ionomer, the other is an inert polymer. Melt one fiber around other.

Generation 2: Co-spin PFSA and polysulfone nanofibers then process into membrane



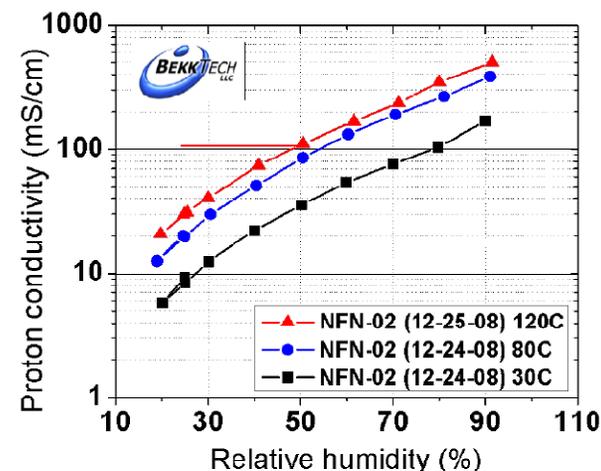
Nafion® matrix (~70 vol%), polyphenylsulfone nanofibers

Simultaneous electro-spinning of PFSA and polyphenylsulfone (inert matrix) – eliminates need for impregnation step; also can create PFSA nanofibers with polysulfone matrix from the same dual fiber mat.

Next Steps: Establish water retention at low RH, improve performance.

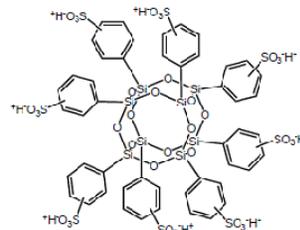
P. Pintauro, 2009, 2010 DOE Hydrogen Program Review

Generation 1: PFSA/SPOSS nanofiber mat that is impregnated with inert polymer



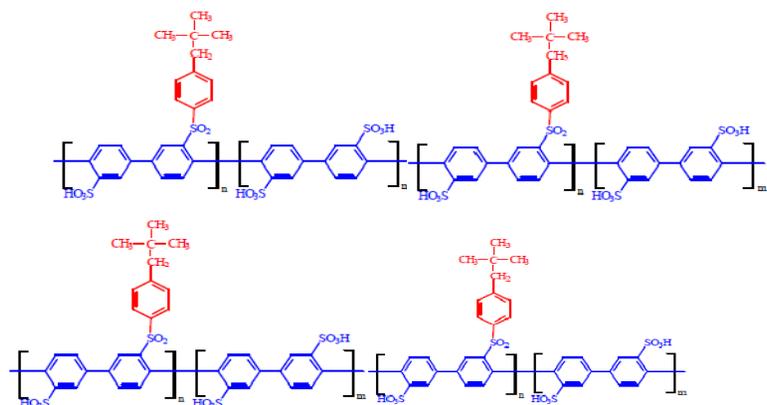
Membrane: 60 wt% 3M PFSA (825EW) + 35 wt% SPOSS + 5 wt% poly(acrylic acid) with NAO63 (inert matrix)

SPOSS = sulfonated polyhedral oligomeric silsesquioxanes

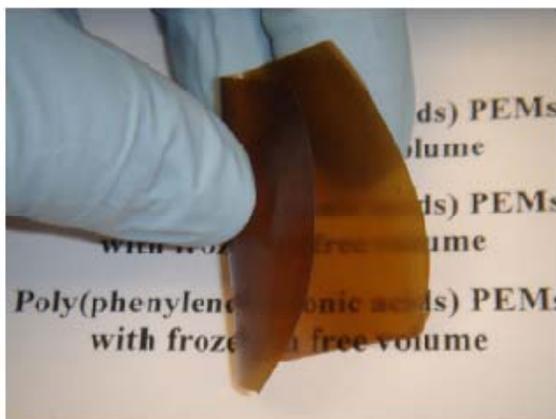


Rigid-rod Structure

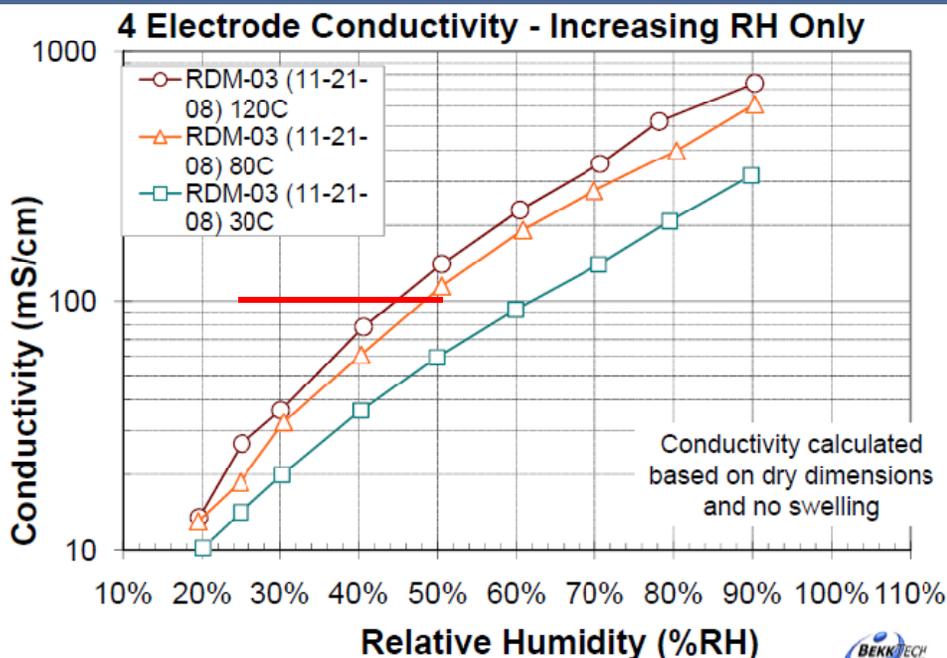
Case Western Reserve University approach: Molecular design with frozen-in free volume retains H₂O at low RH



Neopentyl benzene graft (4%) provides water insoluble film with decent mechanical properties



M. Litt, 2010 DOE Hydrogen Program Review

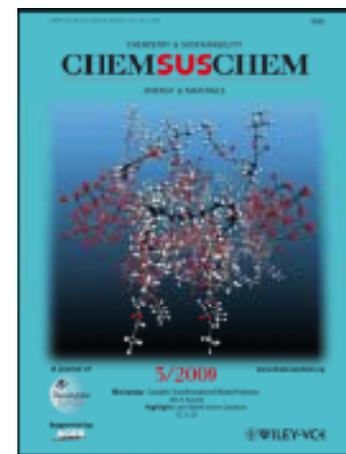
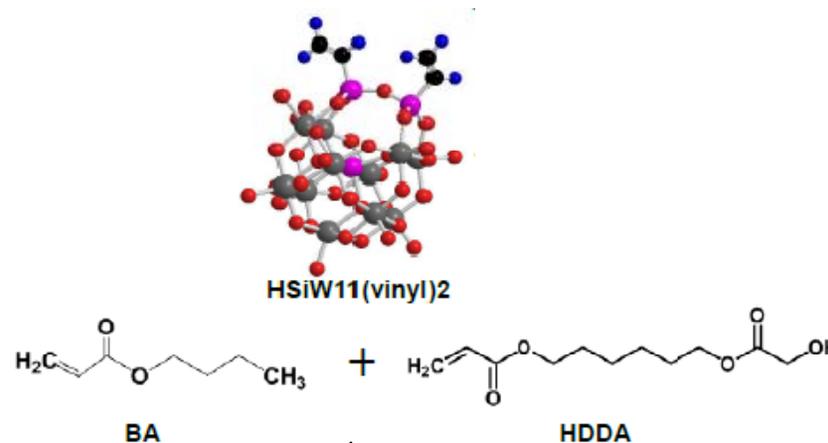
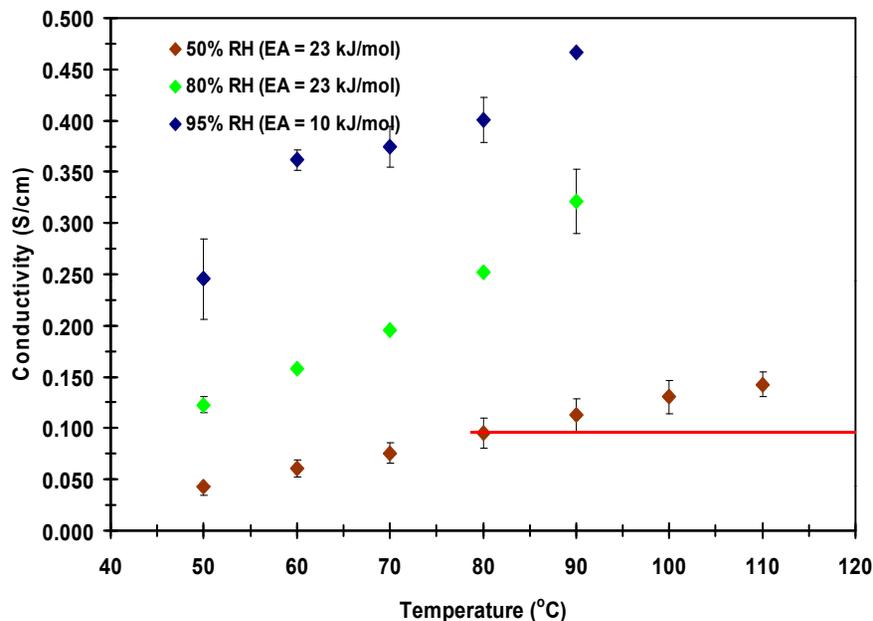


Demonstrates good conductivity at low RH

Next Steps: Improve mechanical properties. Homopolymers are water soluble. Grafting with non-polar moieties yields insoluble polymers with high conductivity at low RH. Grafting not easily scaled-up.

HPA-based Polymeric Ionomers

Colorado School of Mines approach: Tethered hetero-poly acids for high conductivity in dry conditions



HSiW11(vinyl)2/BA/HDDA co-polymer
(PolyPOM85V/BA)



Demonstrated concept of HPA-based polymeric ionomers for high conductivity at low RH.

Next Steps: Improve mechanical properties and oxidative stability. Currently developing chemistry to attach POM to more robust polymers.

DOE membrane targets

Characteristic	Units	2010	2015	Nafion®
		target	target	NRE211
Maximum operating temperature	°C	120	120	120
Area specific resistance at:				
Maximum operating temp and water partial pressures from 40 to 80 kPa	ohm cm ²	0.02	0.02	0.186
80°C and water partial pressures from 25 - 45 kPa	ohm cm ²	0.02	0.02	0.03-0.12
30°C and water partial pressures up to 4 kPa	ohm cm ²	0.03	0.03	0.049
-20°C	ohm cm ²	0.2	0.2	0.179
Oxygen crossover	mA/cm ²	2	2	2.7
Hydrogen crossover	mA/cm ²	2	2	2.2
Cost	\$/m ²	20	20	
Durability				
Mechanical	Cycles w/<10 sccm crossover	20,000	20,000	5000
Chemical	H ₂ crossover mA/cm ²	20	20	6

- **Catalysts**
 - Durability of low-PGM and non-PGM catalysts
 - Effects of impurities on low-PGM and non-PGM catalysts
 - Durability of catalyst supports
 - Water management with high-activity catalysts
 - Cost of PGM catalysts
- **Membranes**
 - Low RH performance
 - Durability of new membranes
 - Cost at low volumes
- **MEAs**
 - Low-temperature performance
 - Water management
 - High-current operation

This talk covered only some of the technical challenges and aspects of the DOE portfolio. Other areas being addressed by DOE are:

Water management – freeze issues, materials properties

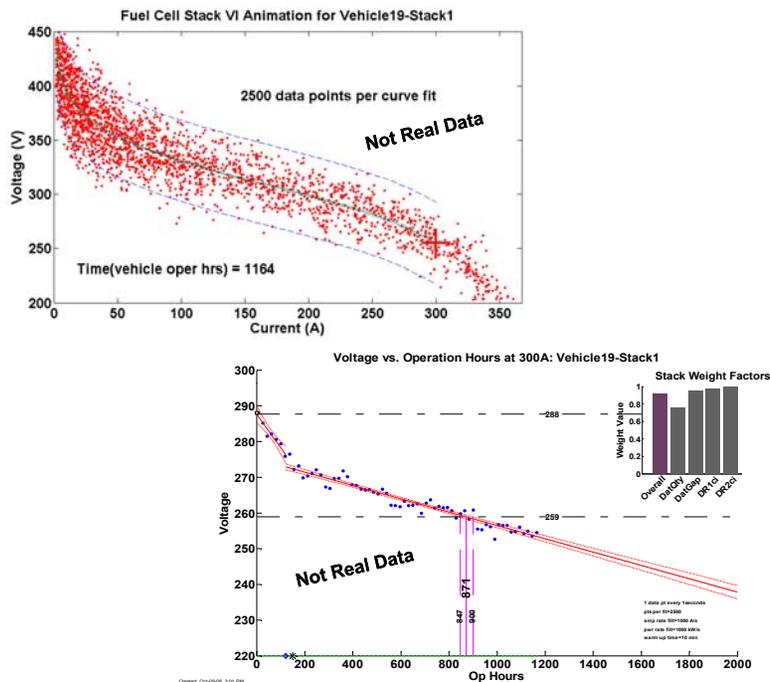
Modeling – durability, transport

Impurity effects – fuel, air, system-generated

Cell hardware – plates, seals

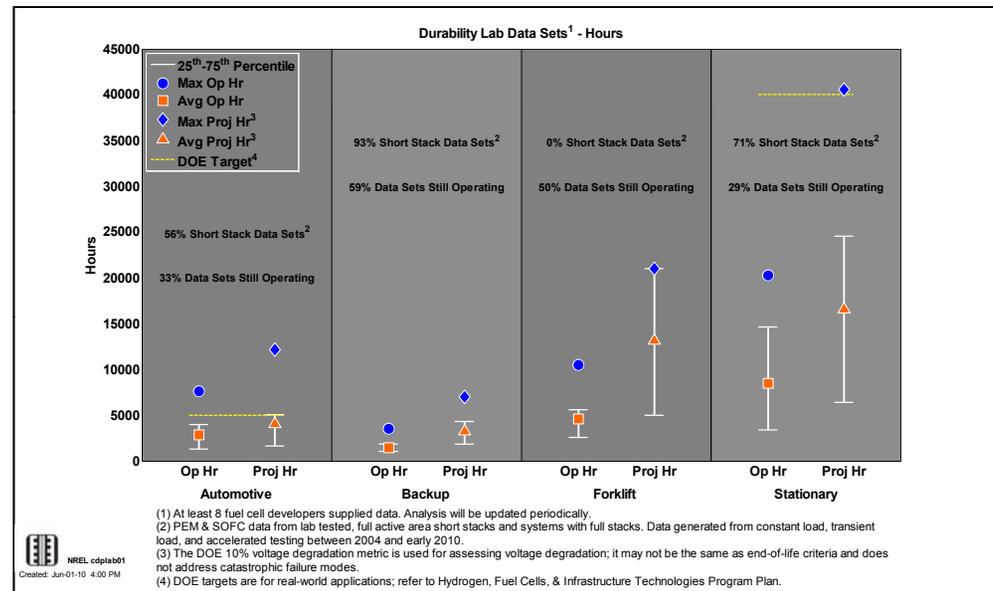
Stationary fuel cells – APUs, CHP

Process and analyze fuel cell stack data



Report to data provider and publish Composite Data Products

http://www.nrel.gov/hydrogen/proj_tech_validation.html



Contact Info
 Jennifer Kurtz
 jennifer.kurtz@nrel.gov
 303-275-4061

Example: CDP Lab#01 - Operation data from lab testing for automotive, backup, material handling, and stationary power applications

Demonstrations are essential for validating the performance of technologies in integrated systems, under real-world conditions.

RECENT ACCOMPLISHMENTS

Vehicles & Infrastructure

- 144 fuel cell vehicles and 23 hydrogen fueling stations have reported data to the project
- Over 2.5 million miles traveled
- Over 150,000 kg- H₂ produced or dispensed*
- Fuel cell durability- 2,500 hours (nearly 75K miles)
- Fuel cell efficiency 53-59%
- Vehicle Range: ~196 – 254 miles

Buses

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

Forklifts

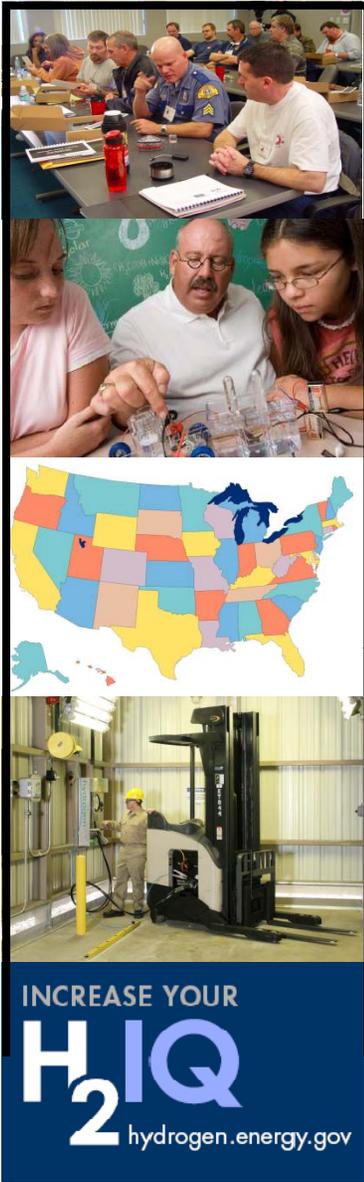
- Forklifts at Defense Logistics Agency site have completed more than 10,000 refuelings

Recovery Act

- NREL is collecting data (backup power, forklifts, etc.)



* Not all hydrogen produced is used in vehicles



- **Safety & Code Officials**

- Trained >90 first responders in 3 advanced-level first responder training courses in 18 states and deployed an Intro to Hydrogen web course for code officials

- **Schools & Universities**

- Working with 5 universities to finalize & teach >25 university courses & curriculum modules specializing in H₂ and fuel cells

- **End Users**

- Provided day-long educational seminars to lift truck users, including hands-on forklift demos and real-world deployment data

- **State & Local Governments**

- Conducted >19 workshops and seminars across the country to educate decision-makers on fuel cell deployments

- **CNG H₂ Fuels Workshop**

- Brazil, Canada, China, India and U.S. identified critical gaps and lessons learned from CNG vehicles

- **H₂ Fuel Quality Specification**

- Technical Specification published and harmonized with SAE J2719

- **Separation Distances**

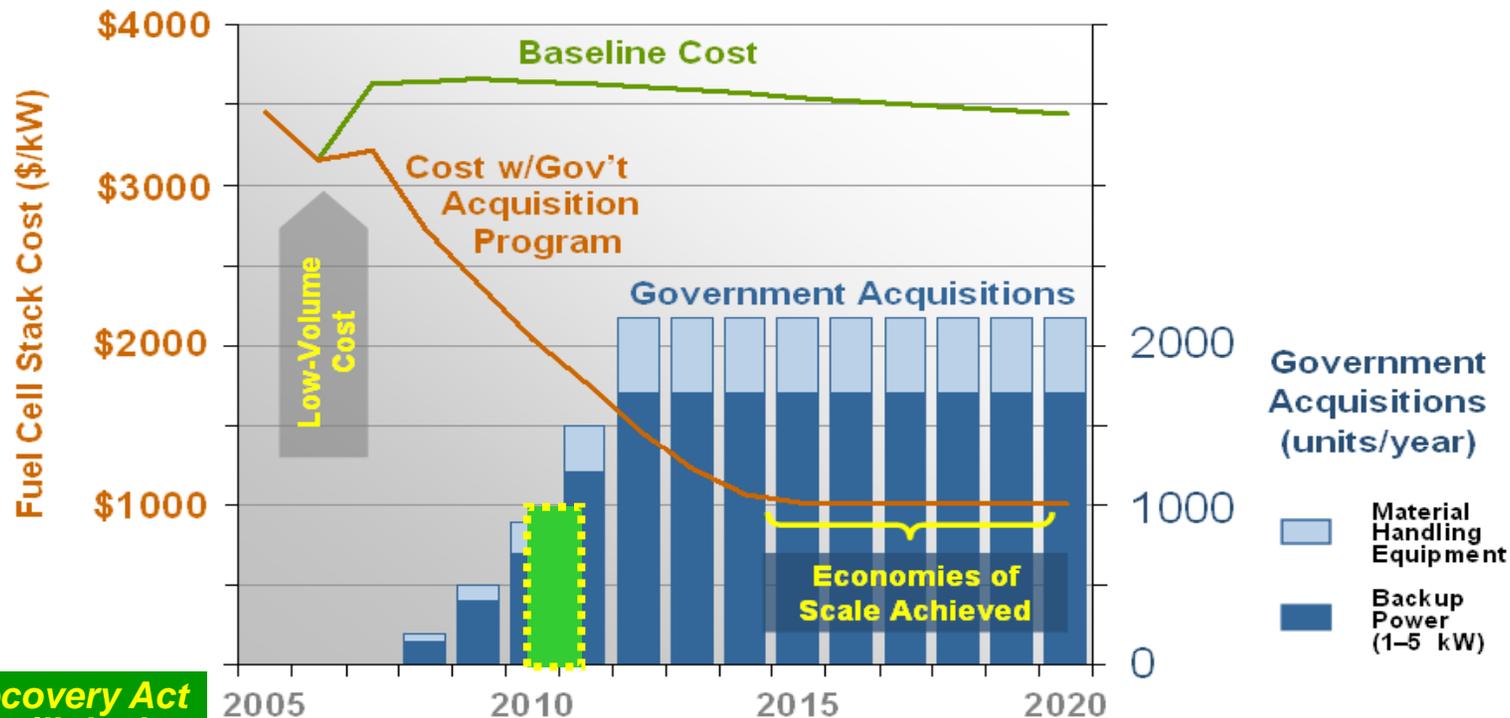
- Incorporated Quantitative Risk Assessment for separation distances into codes (NFPA2)

- **Materials & Components Compatibility**

- Completed testing to enable deployment of 100 MPa stationary storage tanks
- Forklift tank lifecycle testing program underway to support the development of CSA HPIT1

Example: Government acquisitions could significantly reduce the cost of fuel cells through economies of scale, and help to support a growing supplier base.

Impact of Government Acquisitions on Fuel Cell Stack Costs (for non-automotive fuel cells)



Recovery Act funding will deploy up to 1000 fuel cells, in the private sector, by 2012.

Source: ORNL

We are facilitating the adoption of fuel cells across government and industry:

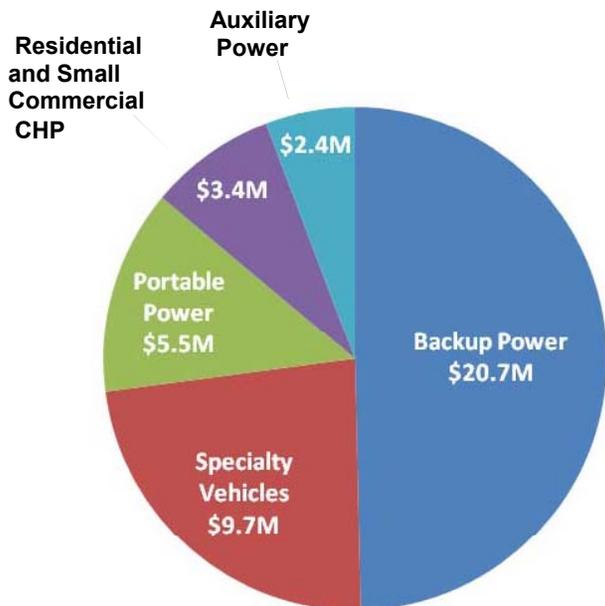
- >100 fuel cells are being deployed, through interagency agreements.
- More interagency agreements under development.

Recovery Act Deployments

DOE announced ~\$42 million from the American Recovery and Reinvestment Act to fund 12 projects to deploy more than 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.

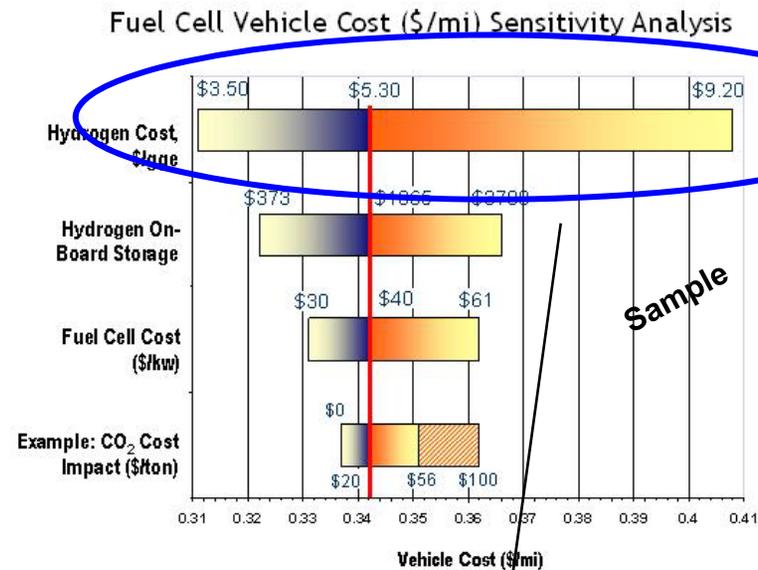
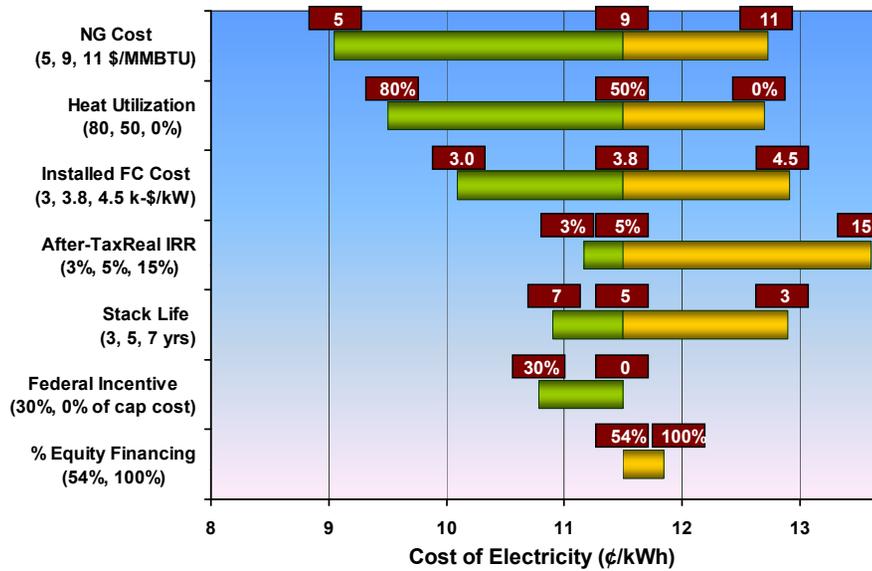


Approximately \$51 million in cost-share proposed by industry participants—for a total of nearly \$93 million.

COMPANY	AWARD	APPLICATION
Delphi Automotive	\$2.4 M	Auxiliary Power
FedEx Freight East	\$1.3 M	Specialty Vehicle
GENCO	\$6.1 M	Specialty Vehicle
Jadoo Power	\$2.2 M	Backup Power
MTI MicroFuel Cells	\$3.0 M	Portable
Nuvera Fuel Cells	\$1.1 M	Specialty Vehicle
Plug Power, Inc. (1)	\$3.4 M	CHP
Plug Power, Inc. (2)	\$2.7 M	Backup Power
University of North Florida	\$2.5 M	Portable
ReliOn Inc.	\$8.5 M	Backup Power
Sprint Comm.	\$7.3 M	Backup Power
Sysco of Houston	\$1.2 M	Specialty Vehicle

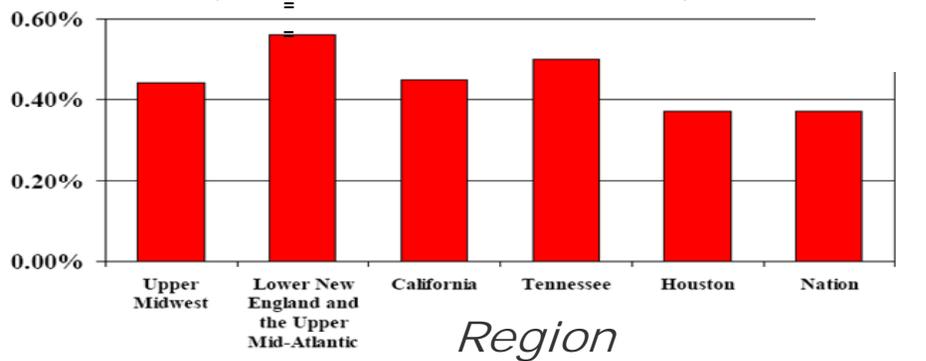
Systems Analysis: *Examples*

We are assessing the costs and benefits of various technology pathways and conducting a range of analyses including sensitivity analysis, life cycle analysis and job creation analysis.



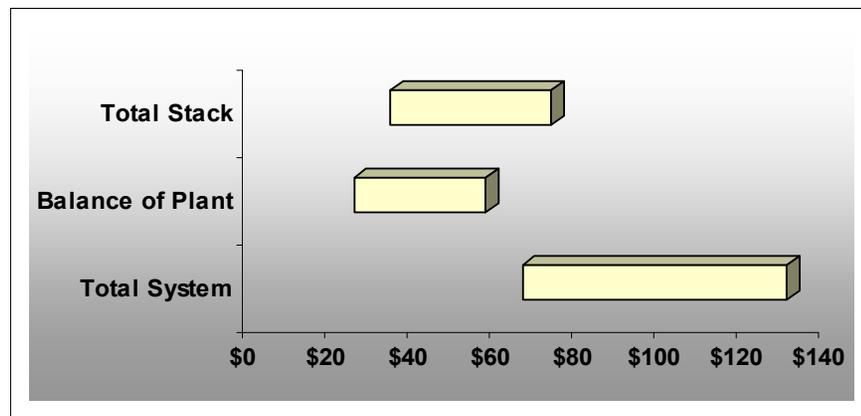
Example:
Need to reduce H₂ cost (production, delivery & storage)

Successful Commercialization Will Have Significant Impact on Employment
(% increase from base case)

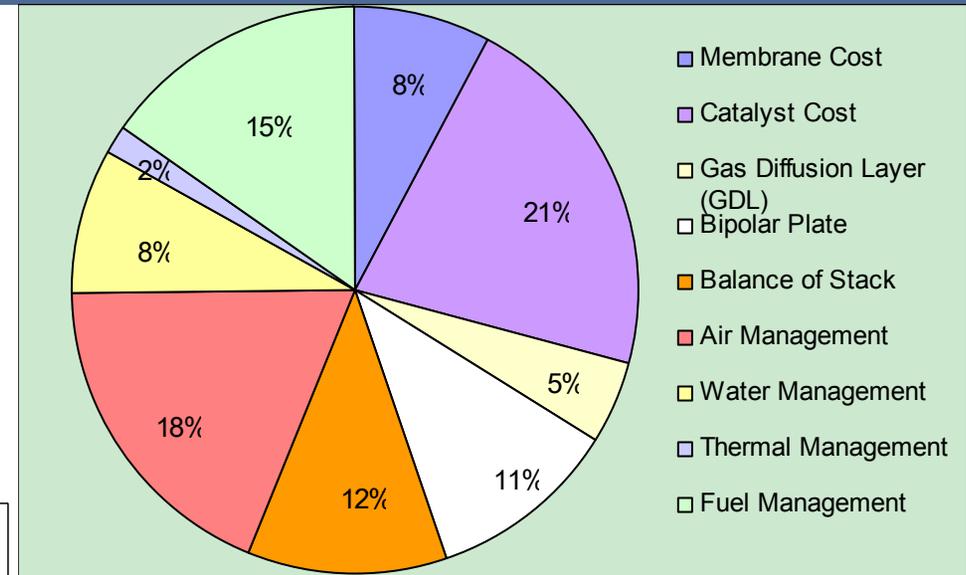


Stakeholder Cost Analyses

Representatives from the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) compiled fuel cell cost estimates for automotive applications to identify potential R&D focus areas

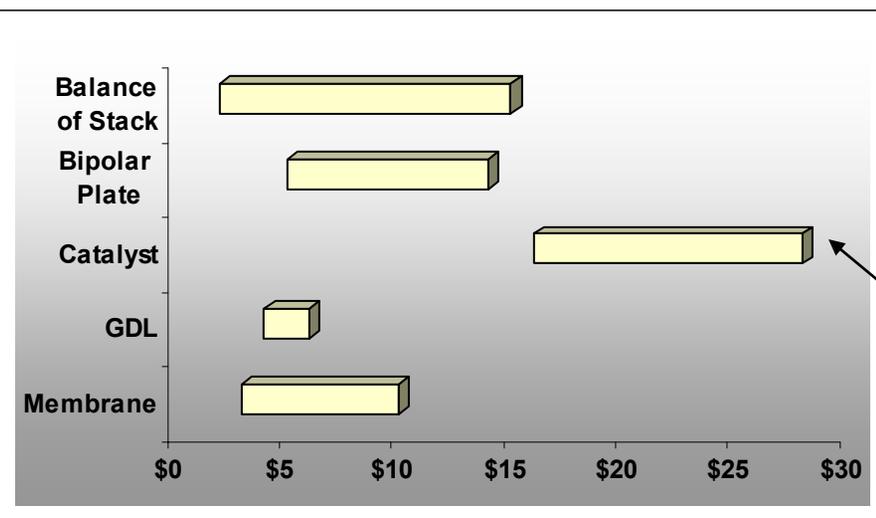


Cost range for 500,000 – 1M units/year: system status



Example of cost breakdown from China IPHE reference (500,000 units)

- Range of cost estimates varies widely for some components
- Catalyst cost reduction is clearly required



Cost range for 500,000 units/year: stack status

Working Group (WG)	DOE Representative	Leads
High Temp Membrane	Nancy Garland	Jim Fenton (UCF/FSEC) John Kopasz (ANL)
Durability	Donna Ho	Debbie Myers (ANL) Rod Borup (LANL)
Transport Modeling	Dimitrios Papageorgopoulos	Adam Weber (LBNL) R. Mukundan (LANL)
Stationary	Jason Marcinkoski	TBD

Examples of Workshops

Analysis, Tank Safety- China, 9/10

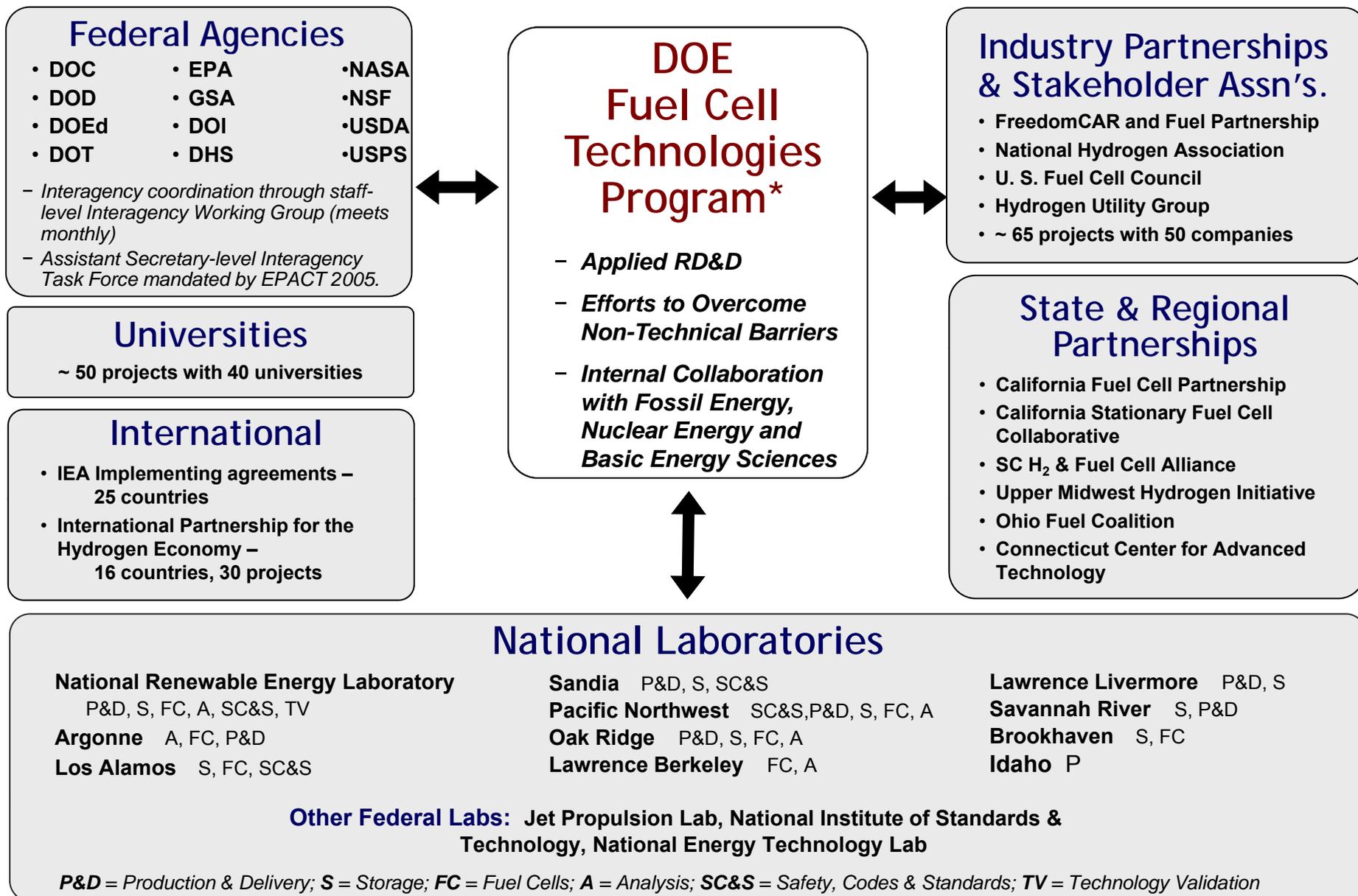
Reversible Fuel Cells- TBD

Product/Component Validation- TBD

Energy Storage-TBD

Other Ideas?

What more can DOE be doing to help accelerate progress and maximize value?



* Office of Energy Efficiency and Renewable Energy

Analysis & Testing

ANL
DTI
TIAX
LANL
NIST
ORNL
Battelle

Catalysts & Supports

3M
General Motors
ANL
BNL
LANL
LBNL
NREL
PNNL
UTC Power
Illinois Institute of Technology
University of South Carolina
Northeastern University

Cross-cutting

Case Western Reserve University
Kettering University
Stark State
University of Connecticut

Distributed Energy Systems

Acumentrics
Intelligent Energy
Plug Power
IdaTech
Versa Power Systems

Durability

UTC Power
LANL
Ballard Power Systems
ANL
Nuvera Fuel Cells
DuPont

Hardware

ANL
Treadstone
ORNL
UTC Power

Impurities

Clemson University
LANL
NREL
University of Hawaii
University of Connecticut

Membranes

3M
Arizona State University
Arkema
Case Western Reserve University
Colorado School of Mines
FuelCell Energy
Giner Electrochemical Systems
LBNL
University of Central Florida
Vanderbilt University
LANL
Ion Power

Portable Power

LANL
NREL
Arkema
University of North Florida

Transportation Systems

ANL
Cummins
Delphi
Honeywell
W.L. Gore

Water Transport and Freeze

CFD Research Corp.
LANL
Nuvera Fuel Cells
Rochester Institute of Technology
SNL
LBNL
Giner Electrochemical Systems
Plug Power
General Motors

Hydrogen Posture Plan

An Integrated Research, Development and Demonstration Plan

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**

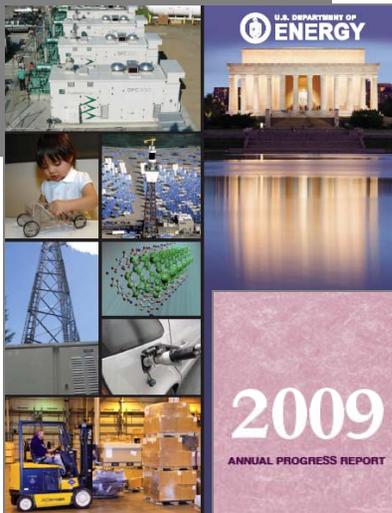
www.hydrogen.energy.gov/annual_review10_proceedings.html

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



2009
ANNUAL PROGRESS REPORT
DOE
Hydrogen
Program



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

<http://www.eere.energy.gov/hydrogenandfuelcells>

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