DOE Hydrogen and Fuel Cell Overview

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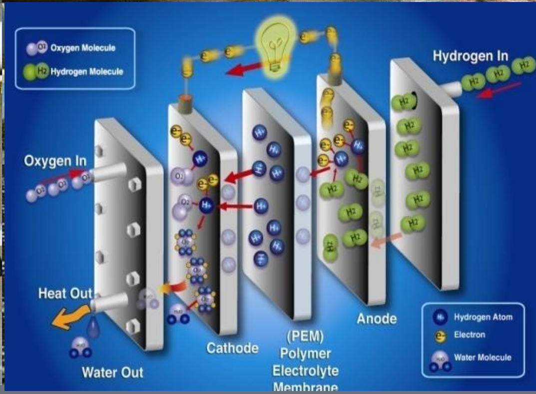


ASME 2011- Plenary

5th International Conference on Energy Sustainability, Washington, DC

August 8, 2011

Dr. Sunita Satyapal

U.S. Department of Energy
Fuel Cell Technologies Program
Program Manager

Agenda

- **Overview**
- **Status, Progress and Key Challenges**
- **Recent Analyses & Publications**
- **Future Plans**

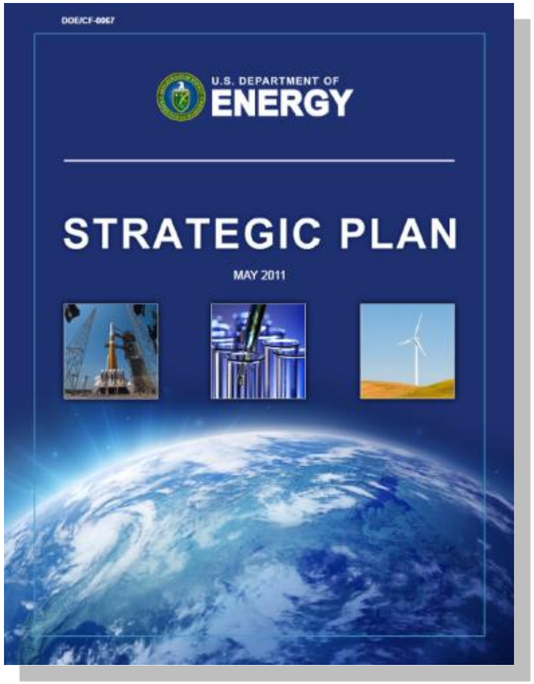
Key Goals

Goal 1: Catalyze the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in clean energy technologies.

Goal 2: Maintain a vibrant U.S. effort in science and engineering as a cornerstone of our economic prosperity with clear leadership in strategic areas.

Goal 3: Enhance nuclear security through defense, nonproliferation, and environmental efforts.

Goal 4: Establish an operational and adaptable framework that combines the best wisdom of all Department stakeholders to maximize mission success.



http://energy.gov/media/DOE_StrategicPlan.pdf

U.S. Energy Consumption

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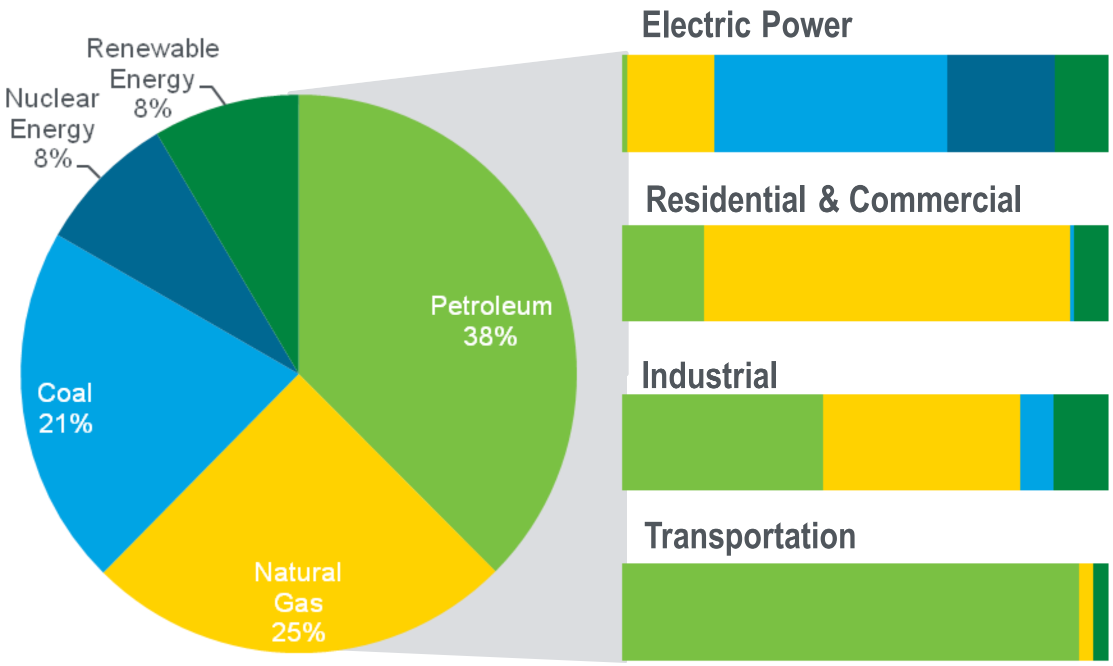
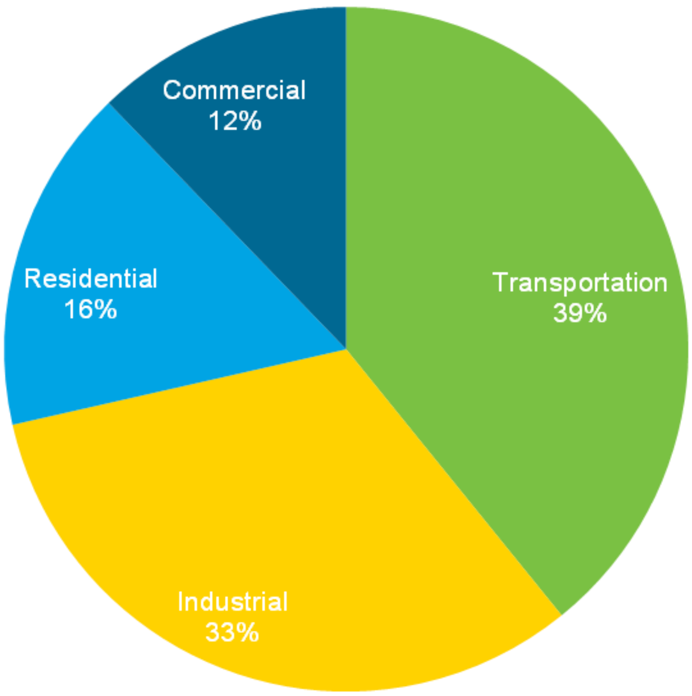
U.S. Primary Energy Consumption by Source and Sector



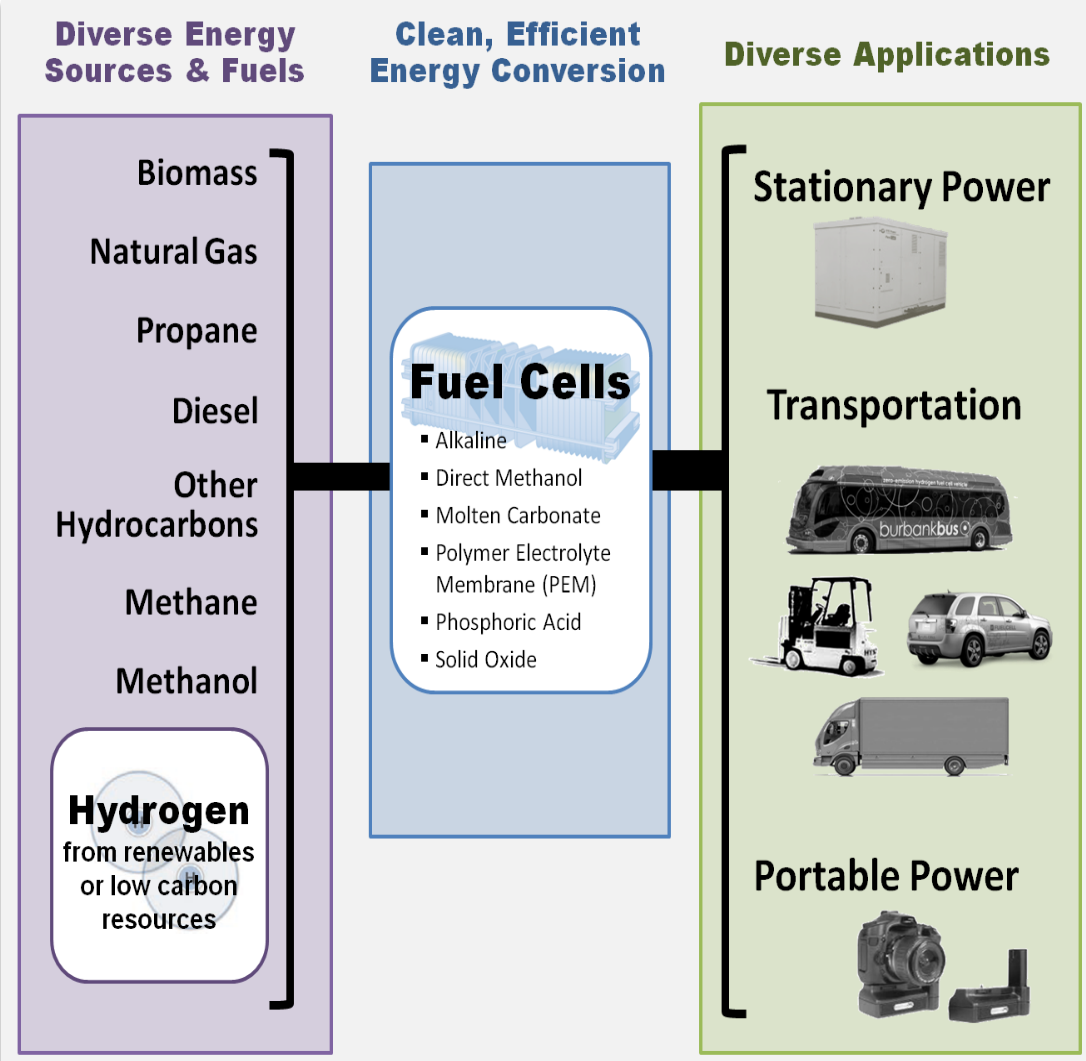
Share of Energy Consumed by Major Sectors of the Economy, 2009



Total U.S. Energy = 94.6 Quadrillion Btu

Source: Energy Information Administration, *Annual Energy Review 2009,* Figure 2.0

The Role of Fuel Cells



Key Benefits

Very High Efficiency
- **up to 60%** *(electrical)*
- **up to 70%** *(electrical, hybrid fuel cell / turbine)*
- **up to 85%** *(with CHP)*

Reduced CO_2 Emissions
- **35–50%+ reductions** *for CHP systems (>80% with biogas)*
- **55–90% reductions** *for light-duty vehicles*

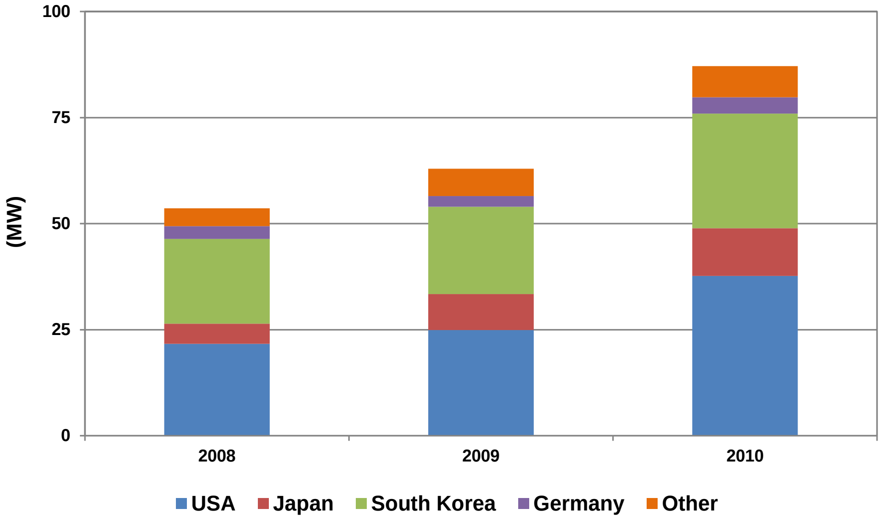
Reduced Oil Use
- **>95% reduction** *for FCEVs (vs. today's gasoline ICEVs)*
- **>80% reduction** *for FCEVs (vs. advanced PHEVs)*

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

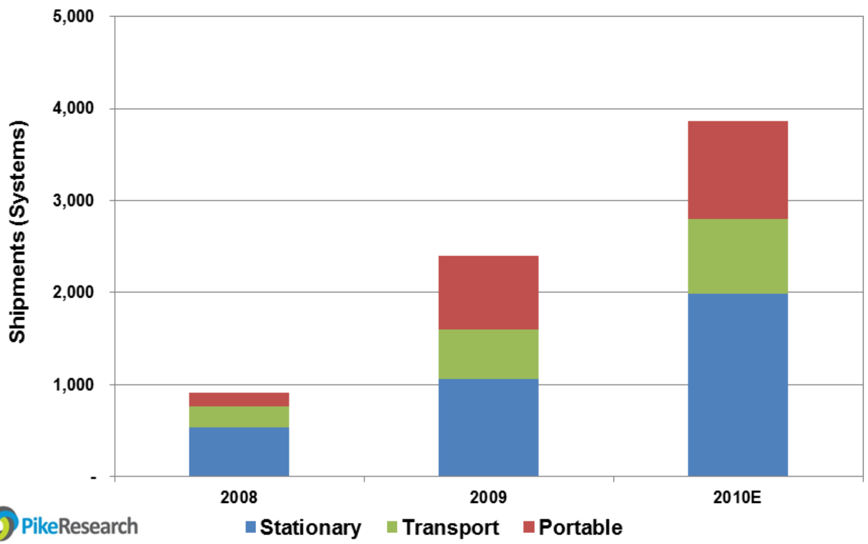
Fuel Flexibility
- **Clean fuels** — *including biogas, methanol, H_2*
- **Hydrogen** — *can be produced cleanly using sunlight or biomass directly, or through electrolysis, using renewable electricity*
- **Conventional fuels** — *including natural gas, propane, diesel*

Fuel Cell Market Overview

Megawatts Shipped, Key Countries: 2008-2010



North American Shipments by Application



PikeResearch

Fuel cell market continues to grow
- **~36% increase in global MWs shipped**
- **~50% increase in US MWs shipped**

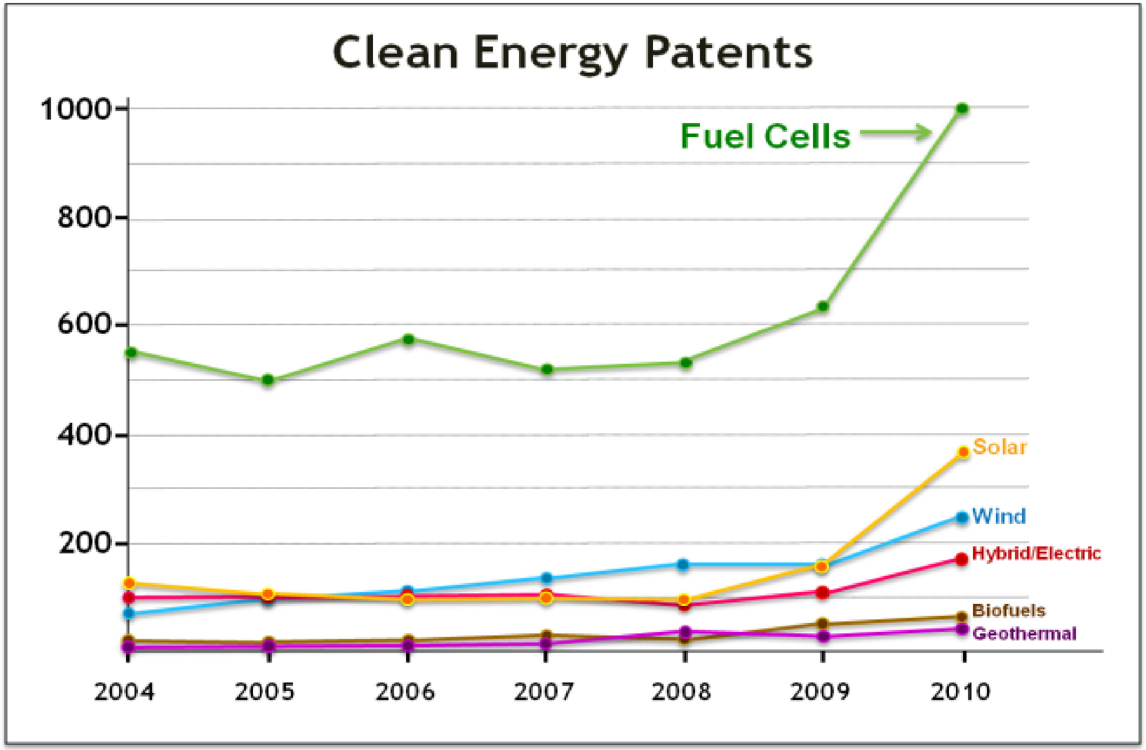
Various analyses project that the global fuel cell/hydrogen market could reach maturity over the next 10 to 20 years, producing revenues of:
- **$14 – $31 billion/year for stationary power**
- **$11 billion/year for portable power**
- **$18 – $97 billion/year for transportation**

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 Cell Patents Reflect Emerging Growth



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} http://cepgi.typepad.com/heslin_rothenberg_farley_/

Fuel Cell Patents per Country

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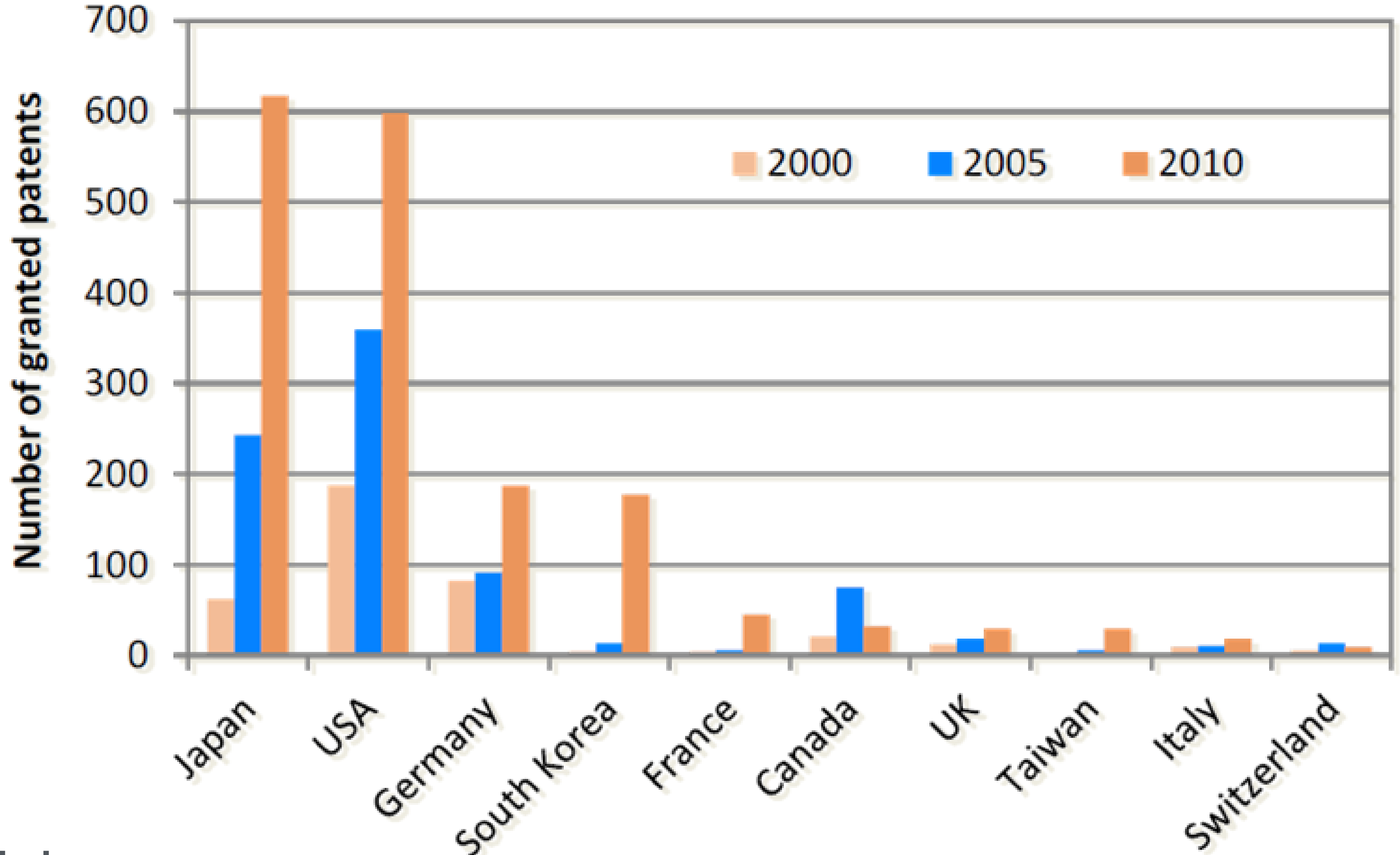
Overall patents led by USA and Japan. Significant growth and acceleration of fuel cell patents by Japan, USA, Germany, and Korea.

Annual granted fuel cell patents per country of origin (top ten)



FuelCell Today

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.*

***>15,000** fuel cells shipped in 2009*

Fuel cells can be a cost-competitive option for critical-load facilities, backup power, and forklifts.

Production & Delivery of Hydrogen

In the U.S., there are currently:

***~9 million metric tons** of H_2 produced annually*

*> **1,200 miles** of H_2 pipelines*

Source: US DOE 09/2010

Fuel Cells for Transportation

In the U.S., there are currently:

- *> 200 fuel cell vehicles*
- *~ 20 active fuel cell buses*
- *~ 60 fueling stations*

Sept. 2009: Auto manufacturers from around the world signed a letter of understanding supporting fuel cell vehicles in anticipation of widespread commercialization, beginning in 2015.

Well-to-Wheels CO_2 Analysis

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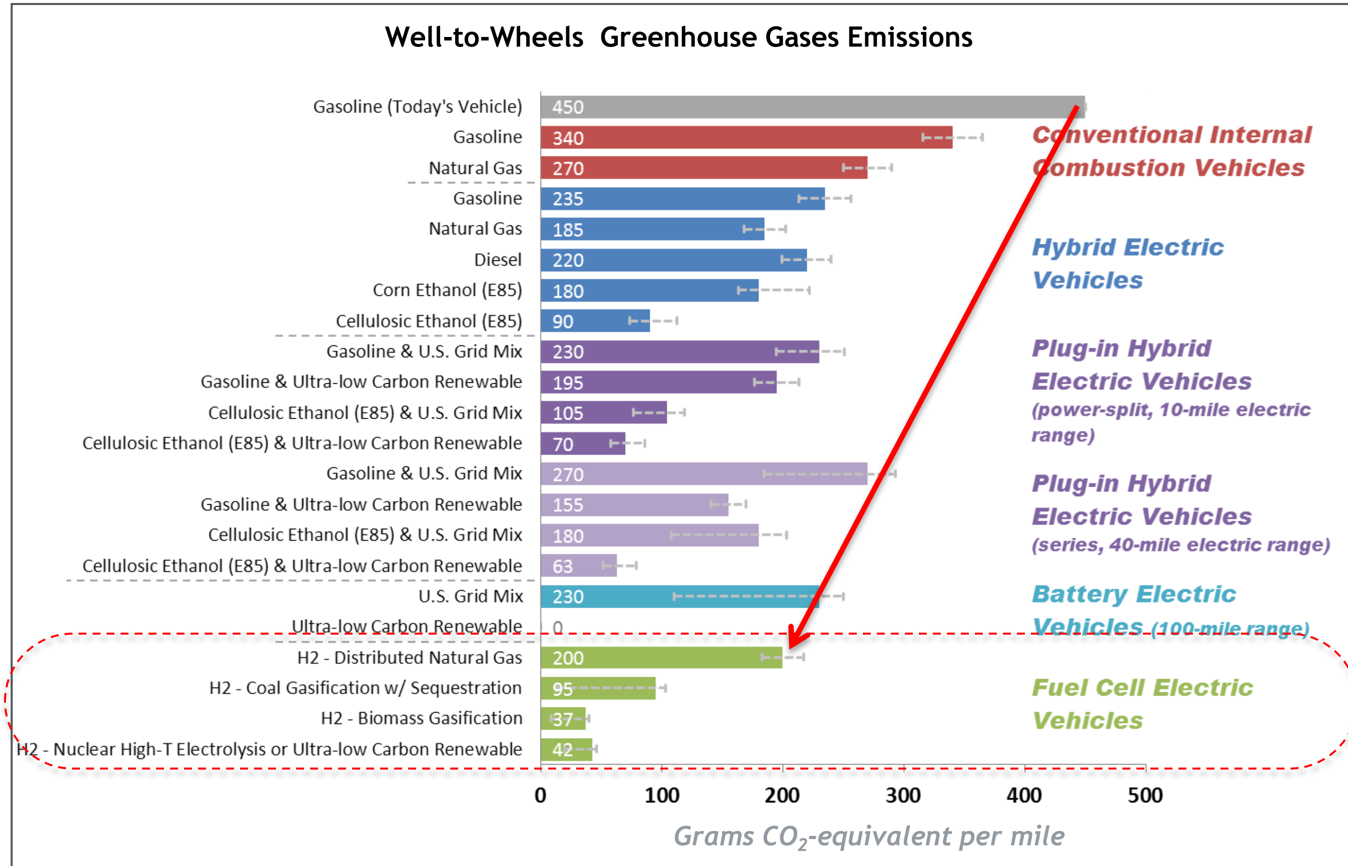
Analysis by Argonne National Lab, DOE Vehicle Technologies Program, and FCT Program shows benefits from a portfolio of options



H_2 from Natural Gas

Even FCEVs fueled by H_2 from distributed NG can result in a >50% reduction in GHG emissions from today's vehicles.

Use of H_2 from NG decouples carbon from energy use—i.e., it allows carbon to be managed at point of production vs at the tailpipe.

Even greater emissions reductions are possible as hydrogen from renewables enter the market.

Notes:

For a projected state of technologies in 2035-2045. Ultra-low carbon renewable electricity includes wind, solar, etc. Does not include the lifecycle effects of vehicle manufacturing and infrastructure construction/decommissioning.

Analysis & Assumptions at: http://hydrogen.energy.gov/pdfs/10001_well_to_wheels_gge_petroleum_use.pdf

Well-to-Wheels Petroleum Analysis

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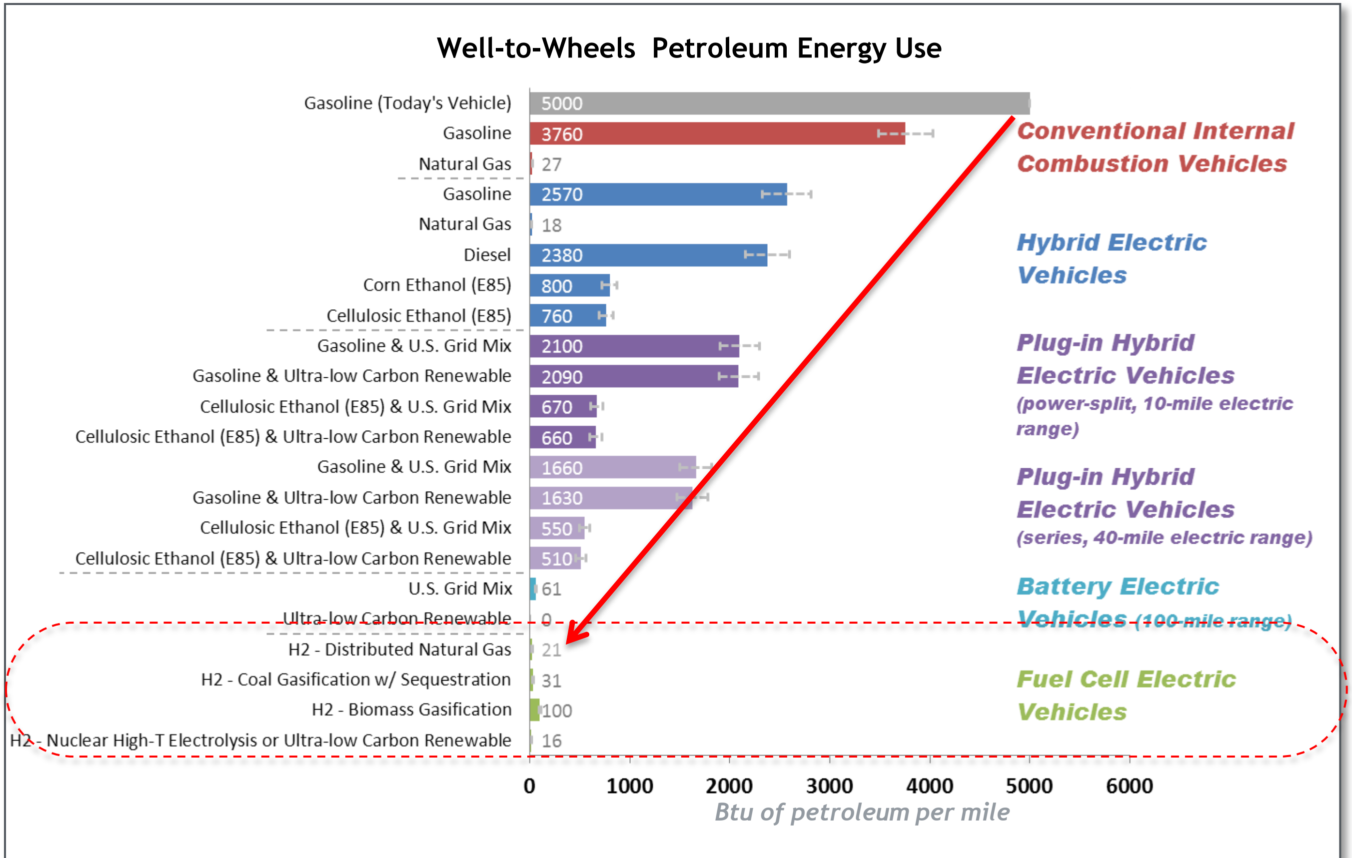
Analysis by Argonne National Lab, DOE Vehicle Technologies Program, and FCT Program shows benefits from a portfolio of options.



H_2 from Natural Gas

FCEVs fueled by H_2 from distributed natural gas can almost completely eliminate petroleum use.

1 million FCEVs would only increase current natural gas consumption by less than 0.2%*

** 1 million FCEVs would require ~1 billion cubic meters/year of NG; current NG consumption is about 600 billion cubic meters/yr*

Notes:
For a projected state of technologies in 2035-2045. Ultra-low carbon renewable electricity includes wind, solar, etc. Does not include the life-cycle effects of vehicle manufacturing and infrastructure construction/decommissioning.
Analysis & Assumptions at: http://hydrogen.energy.gov/pdfs/10001_well_to_wheels_gge_petroleum_use.pdf

Key Challenges

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

Technology Barriers*

Fuel Cell Cost & Durability

Targets*:

***Stationary Systems:* $750 per kW, 40,000-hr durability**

***Vehicles:* $30 per kW, 5,000-hr durability**

Hydrogen Cost

Target*: $2 – 4 /gge, (dispensed and untaxed)

Hydrogen Storage Capacity

Target: > 300-mile range for vehicles—without compromising interior space or performance

Technology Validation:

Technologies must be demonstrated under real-world conditions.

Economic & Institutional Barriers

Safety, Codes & Standards Development

Domestic Manufacturing & Supplier Base

Public Awareness & Acceptance

Hydrogen Supply & Delivery Infrastructure

Market Transformation

Assisting the growth of early markets will help to overcome many barriers, including achieving significant cost reductions through economies of scale.

Program R&D – Federal Role

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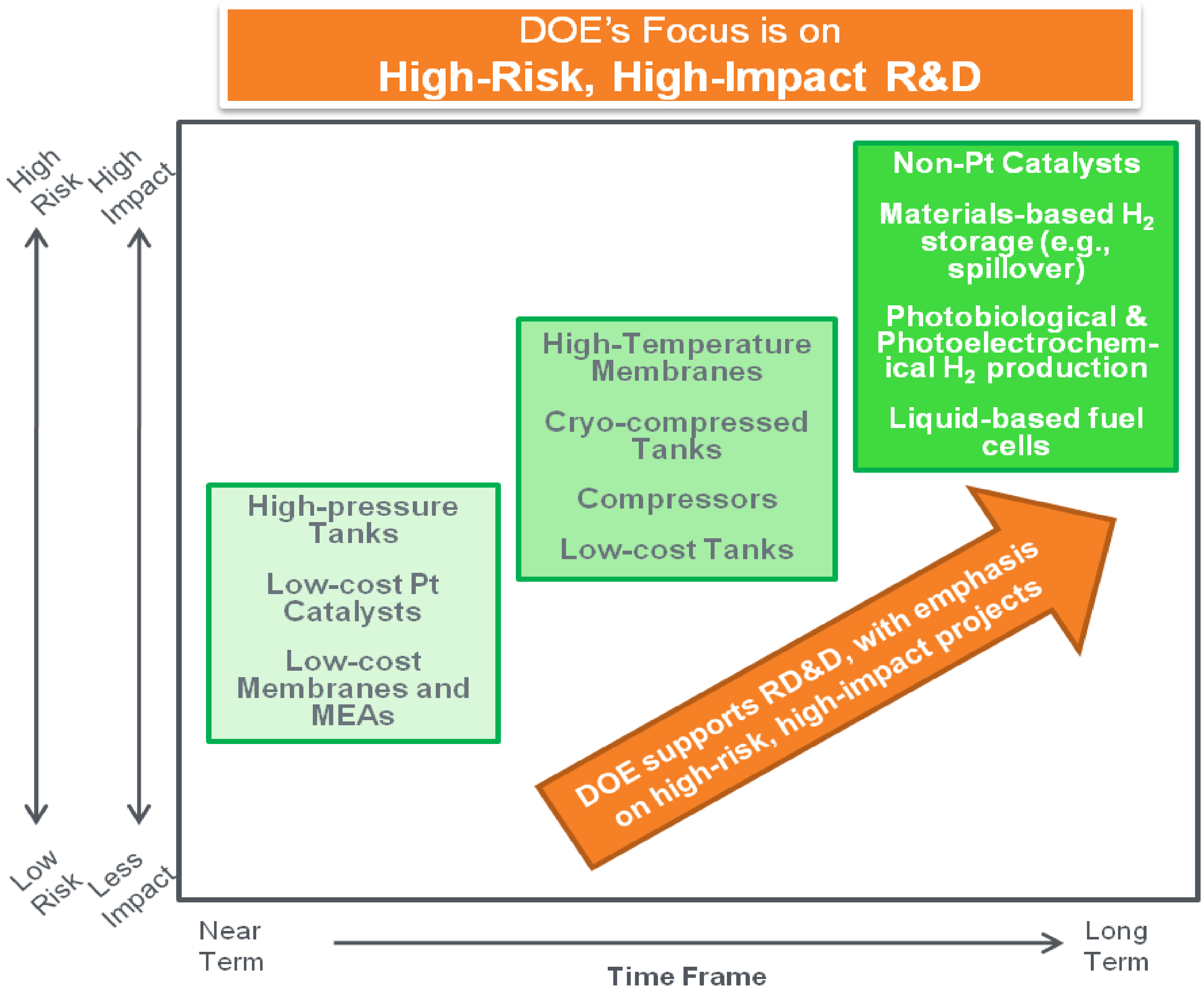

SC-EERE-ARPA-E Collaborations

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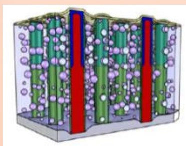
Examples of Cross-Office Collaborative Successes

Office of Science – U.S. DEPARTMENT OF ENERGY

Advancing fundamental science knowledge base

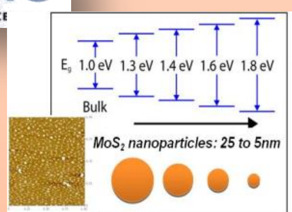
JCAP

Solar Fuels Hub



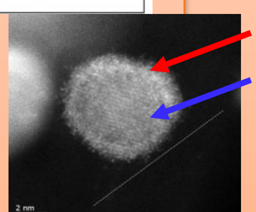
Nanowire based solar fuels generation (CalTech)

EFRC – ENERGY FRONTIER RESEARCH CE[NTERS]



Bandgap tailoring (Stanford)

Mechanistic understanding of catalysts



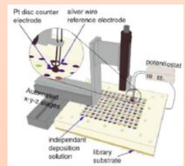
Pt monolayer

Pd core

U.S. Department of Energy EERE

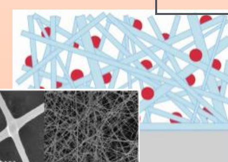
Applied RD&D of innovative technologies

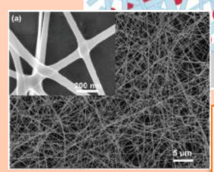
High Throughput Processes (UCSB)



Standard protocols and benchmarking

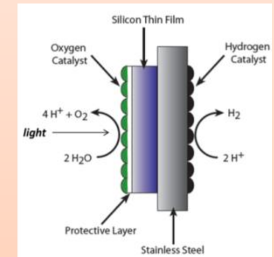
Working Groups PEC, Biological, High T Membranes, Storage Systems





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)

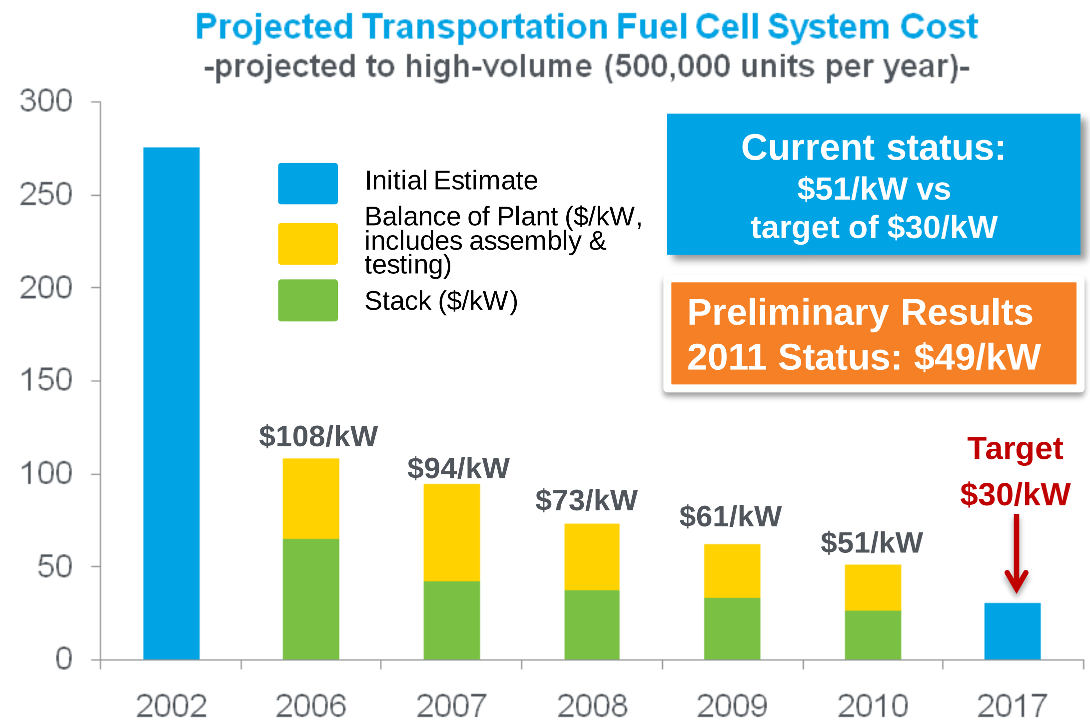
Biological H_2 production

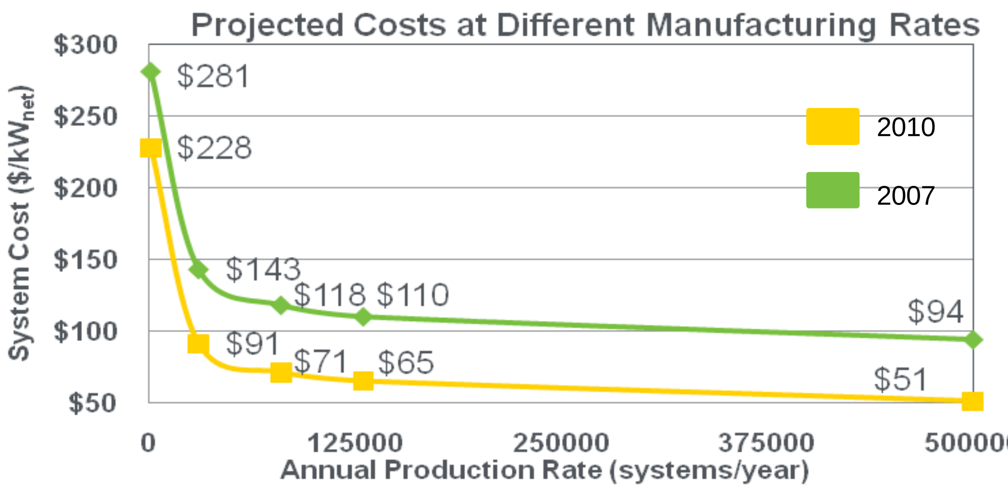
Materials-based H_2 storage

Progress – Fuel Cells

Projected high-volume cost of fuel cells has been reduced to $51/kW (2010)*

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





***Based on projection to high-volume manufacturing (500,000 units/year).**

*****Panel found $60 – $80/kW to be a "valid estimate": http://hydrogendoedev.nrel.gov/peer_reviews.html***

Fuel Cell Challenges: Catalysts and Supports

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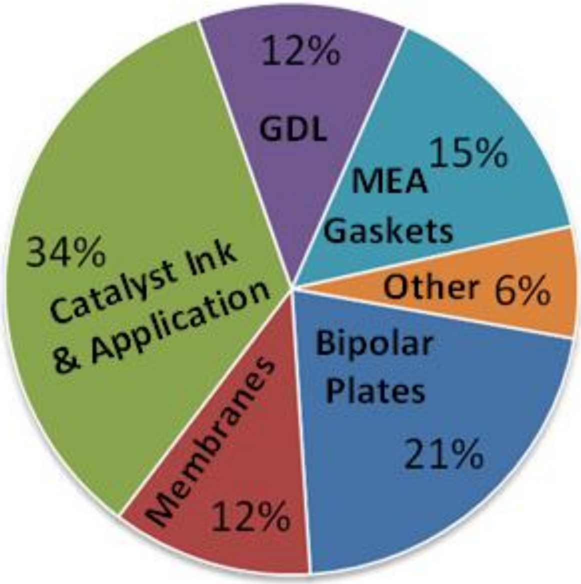
Challenges:

- ***Platinum (Pt) cost is ~34% of total stack cost at high volume***
- ***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 - $25/kW



DTI, 2010 analysis, scaled to high volume production of 500,000 units/yr

Used $1100/Troy Ounce for Pt Cost

Fuel Cell Catalysts
Technical Targets vs. Status

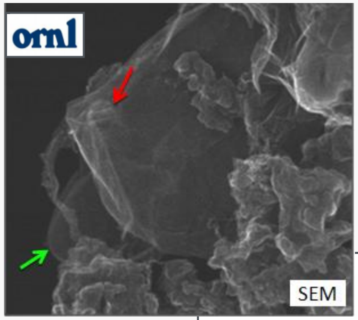
Electrocatalysts for Transportation Applications	Status[a]	Targets[b]
	2011	2017
Platinum group metal (PGM) total content (both electrodes)	**0.19 g/kW**	**0.125 g/kW**
PGM Total Loading	**0.15 mg/cm²**	**0.125 mg/cm²**
Loss in catalytic (mass) activity[c]	**<40%**	**<40% loss of initial**
Catalyst support loss[d]	**<10% mass loss**	**< 10% mass loss**
Mass activity[e]	**0.24 A/mg Pt in MEA >0.44 A/mg Pt new alloy in RDE**	**0.44 A/mg PGM**
Activity per volume of supported catalyst (non-PGM)[f]	**60 A/cm³ (measured) 160 A/cm³ (extrapolated)**	**>300 A/cm³**

[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 @ $900mV_{IR\text{-}free}$
[f] baseline @ $800mV_{IR\text{-}free}$

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

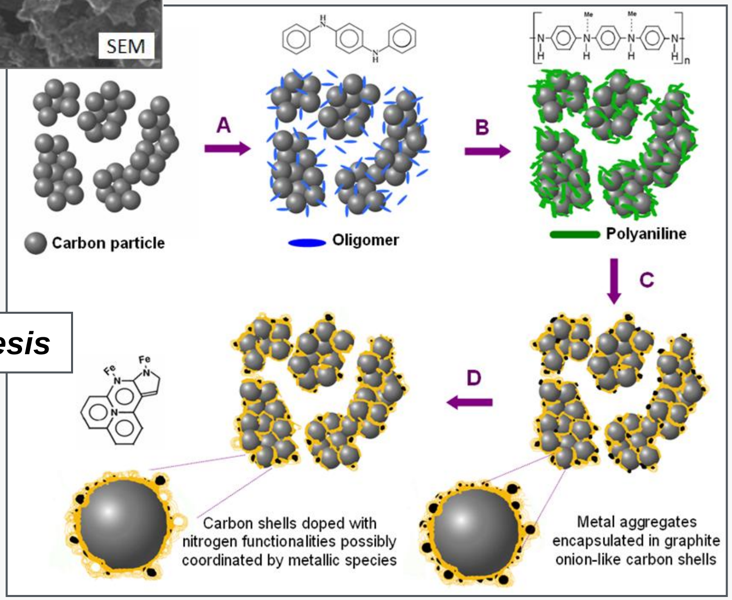
Update of Multiyear RD&D Plan in process

Catalysts: Non-PGM catalysts demonstrate activity approaching that of Pt

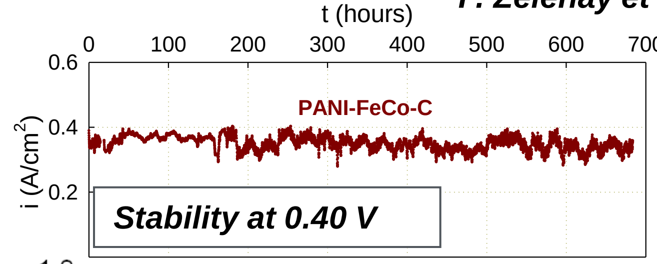


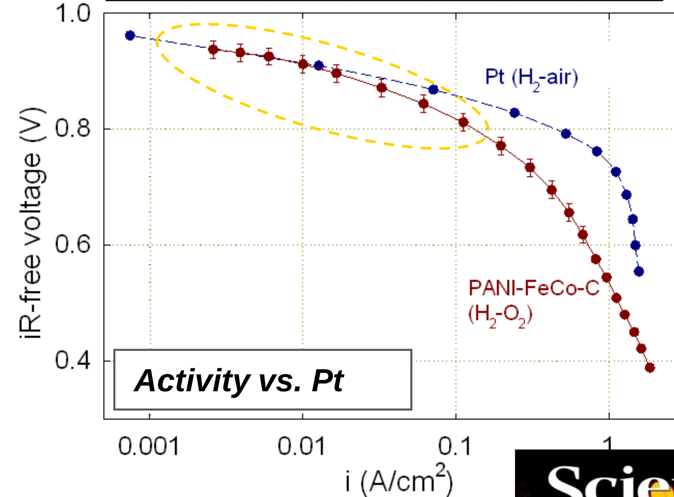
Catalyst SEM: *Layered-graphene sheet marked with green arrow; FeCo-containing nanoparticle shown with red arrow.*

The Synthesis

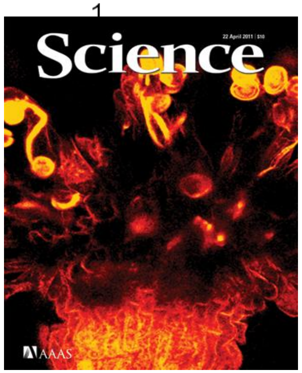


P. Zelenay et al., LANL





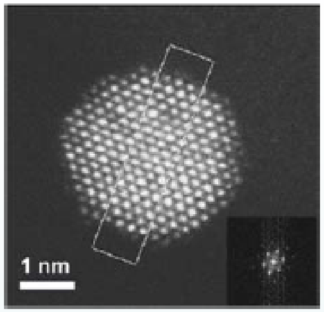
G. Wu, K. L. More, C. M. Johnston, P. Zelenay, *Science*, **332**, 443-7 (2011)

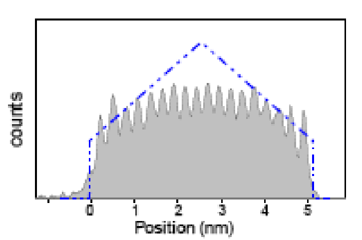


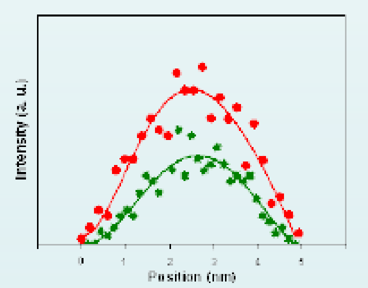
- **High ORR activity reached with polyaniline-based and cyanamide-based catalysts**
- **Intrinsic activity getting close that of Pt, but electrode structure needs improvement**

Catalysts: Nano-segregated binary and ternary catalysts demonstrate performance more than 6X in 2011 that of platinum

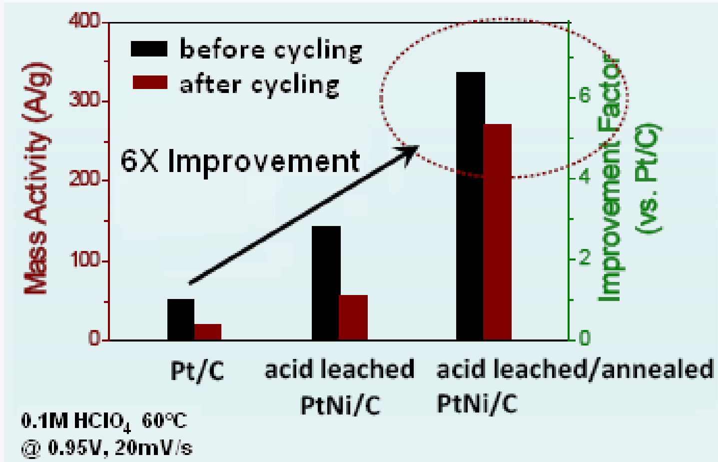
Nanosegregated Binary (PtNi)







Multilayered Pt-skin surfaces confirmed for PtNi annealed NPs

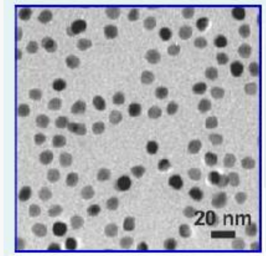


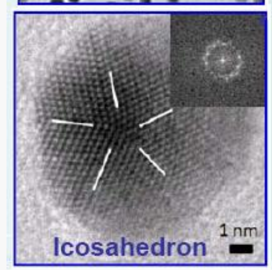
Performance: Nanosegregated PtNi/C catalysts have ORR mass activity **~0.35 A/mg** in MEA testing – *approaching 0.44 A/mg target*

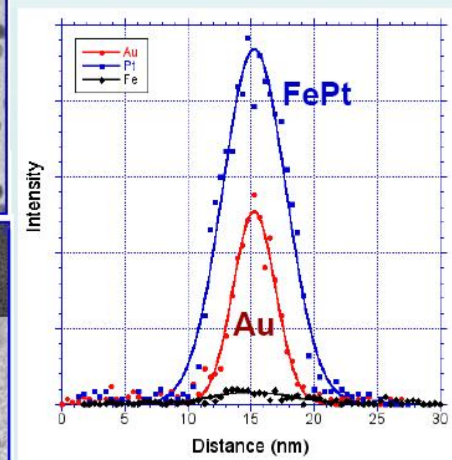
Durability: 3X improved retention of mass activity after 20,000 potential cycles compared to Pt/C

N. Markovic et al., ANL

NanosegregatedTernary (PtFeAu)







Performance:
FePt(shell)/Au(core) demonstrates ORR mass activity more than 3X that of Pt/C

Durability:
Maintains 80% of initial activity after 80,000 potential cycles (cf. less than 20% for Pt/C)

Fuel Cell Challenges: Membranes

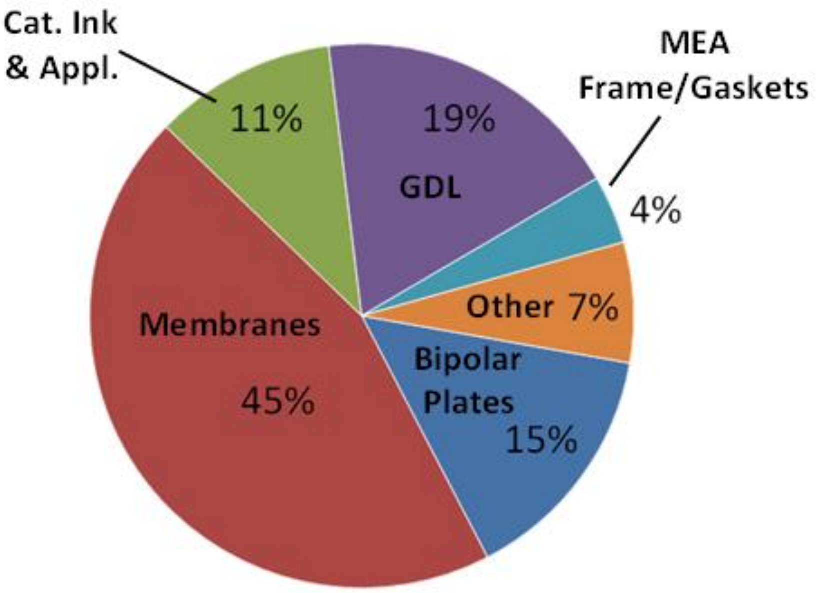
Challenges:

- ***Membranes account for 45% 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 - $144/kW



DTI, 2010 analysis, production of 1,000 units/yr

Fuel Cell Membrane Targets

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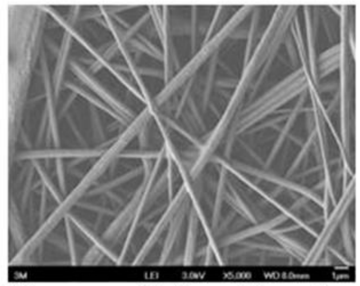
Characteristic	Units	2011 status	2017 target	Nafion® NRE211
Maximum oxygen crossover	mA/cm^2	<1	2	2.7
Maximum hydrogen crossover	mA/cm^2	<1.8	2	2.2
Area specific resistance at:				
Max operating temp and 40 – 80 kPa water partial pressure	ohm cm^2	0.023 (40 kPa) 0.012 (80 kPa)	0.02	0.186
80 C and water partial pressures from 25 - 45 kPa	ohm cm^2	0.017 (25 kPa) 0.006 (44 kPa)	0.02	0.03-0.12
30 C and water partial pressures up to 4 kPa	ohm cm^2	0.02 (3.8 kPa)	0.03	0.049
-20 C	ohm cm^2	0.1	0.2	0.179
Operating temperature	C	<120	≤120	120
Minimum electrical resistance	ohm cm^2		1000	
Cost	\$/m^2		20	
Durability				
Mechanical	Cycles w/<10 sccm crossover	>20,000	20,000	5,000
Chemical	hours	>2,300	500	

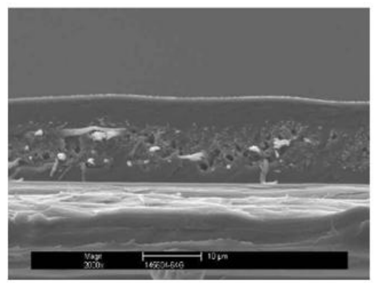
Progress - Fuel Cell R&D

Innovative membranes demonstrate high conductivity at low RH

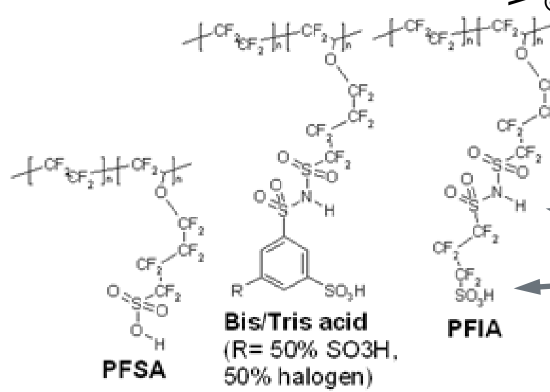
- **PFIA membranes meet most DOE targets for performance and durability**
- **PFIA maintains high crystallinity at lower equivalent weight than PFSAs → better mechanical properties**
- **High conductivity with PFIA under dry conditions: 0.087 S/cm @ 120 C, 25% RH**
- **Supported and stabilized membranes are durable: >2,300 hours chemical stability test; >20,000 RH cycles**

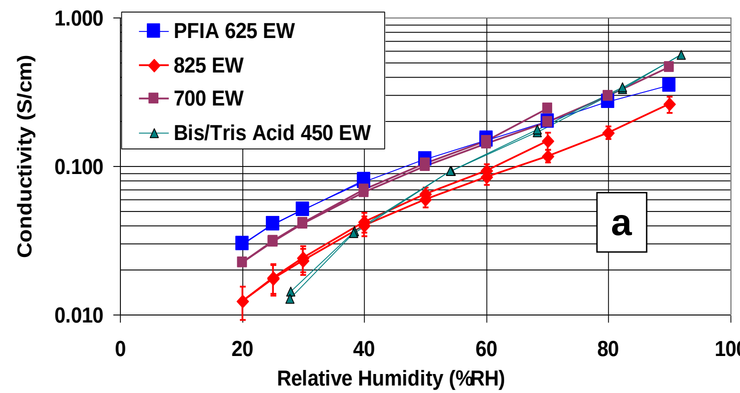


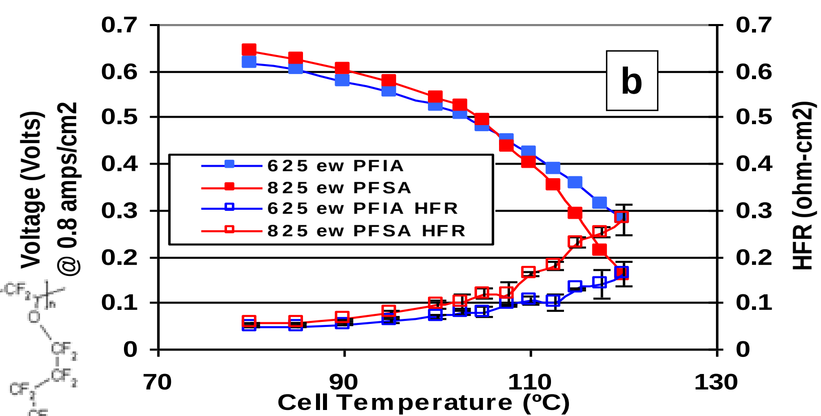
SEM Image of Nanofiber Support



Freeze Fracture





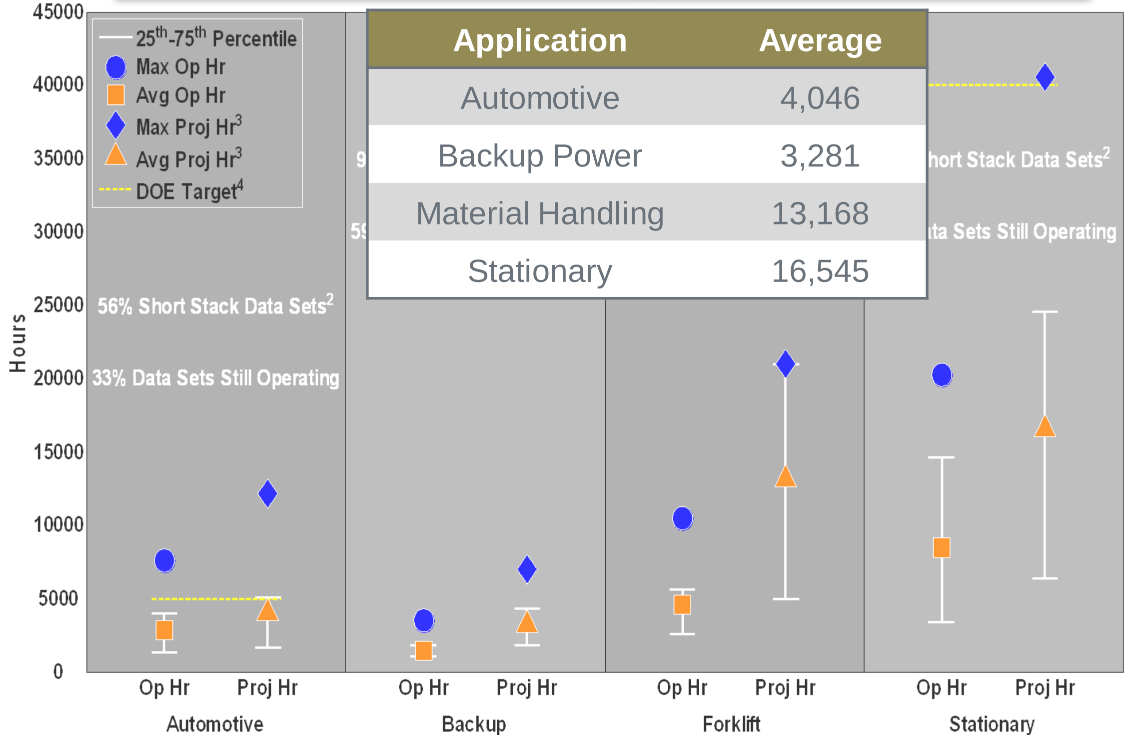


Two superacid sites per side chain

S. Hamrock et al., 3M

Tracking durability for diverse applications. Maximum projected durability exceeds some DOE targets.

Application	Average
Automotive	4,046
Backup Power	3,281
Material Handling	13,168
Stationary	16,545



Tracking durability data from multiple companies (NREL)

Challenges – Continue to decrease cost and increase durability without compromising performance.

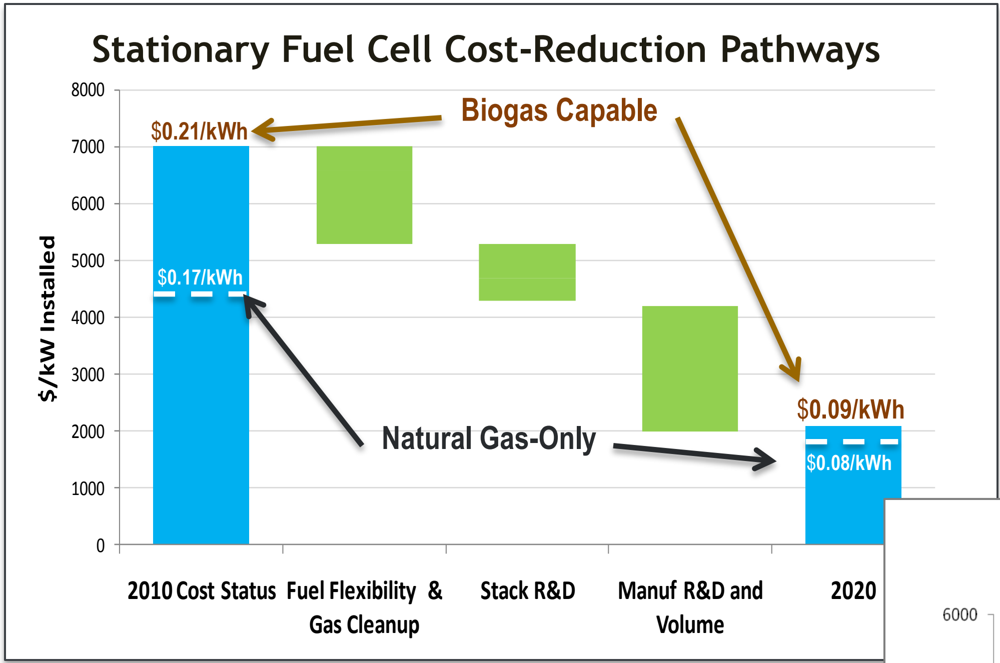
Fuel Cells: Summary of Key Issues

- 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

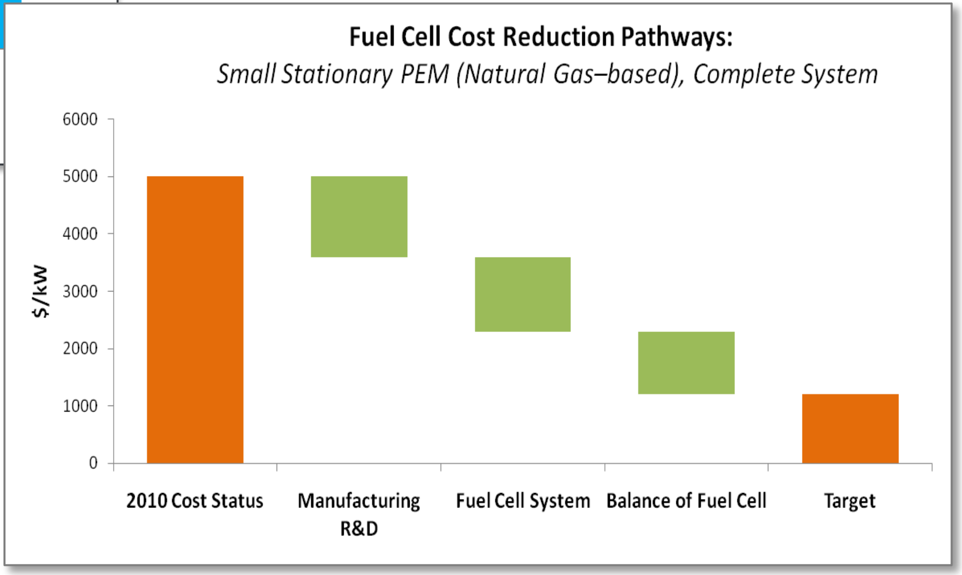
Cost Reduction Roadmap for Stationary Fuel Cells (using biogas or natural gas)

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

Technology advancements, advanced manufacturing, and economies of scale are required to achieve necessary cost reductions.

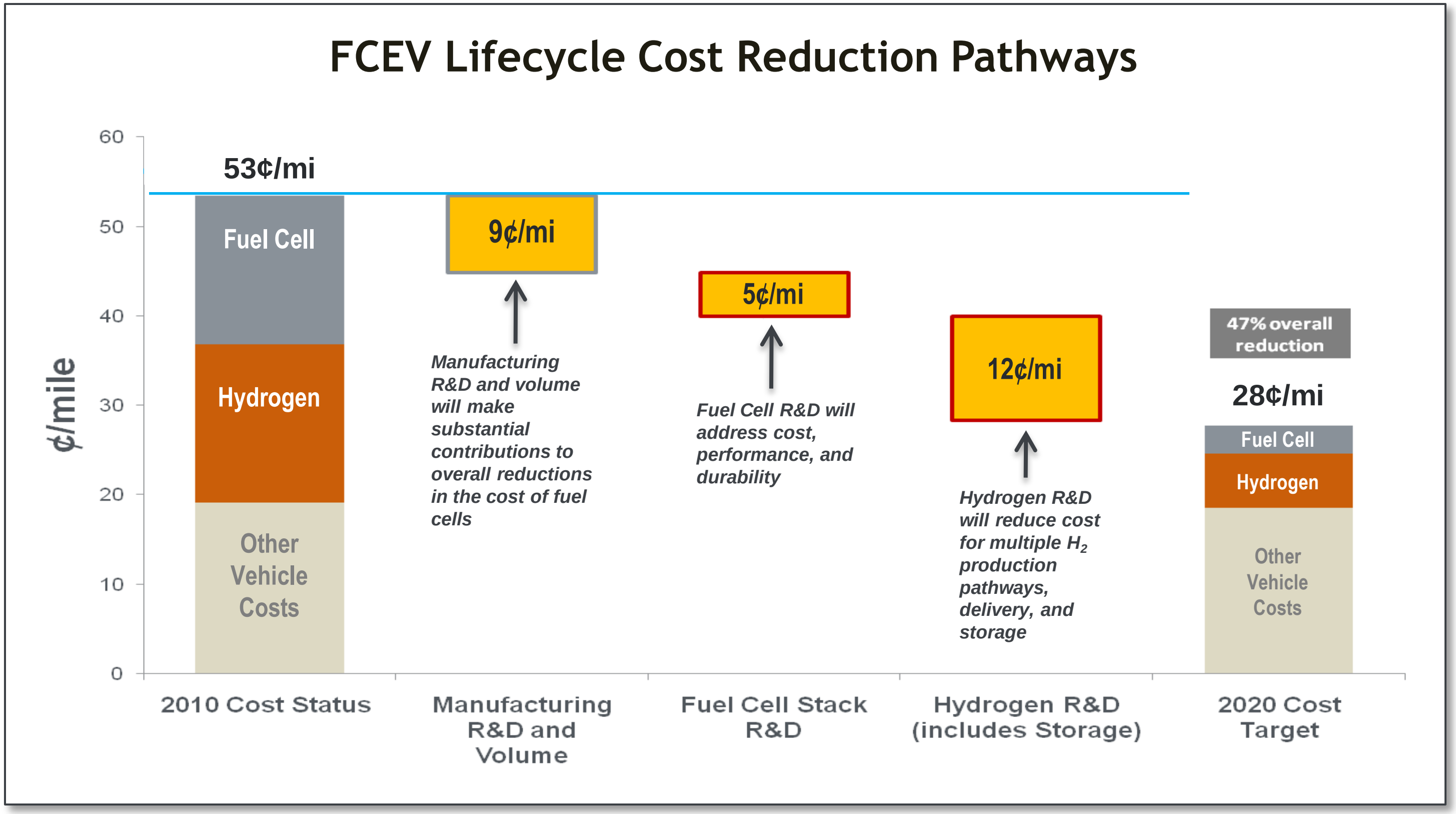


Example: Biogas contains impurities that must be removed before it can be used in fuel cells. Gas cleanup equipment and operation result in costs beyond those associated with systems that use only natural gas.



Cost Reduction Roadmap for Fuel Cell Electric Vehicles

Need to identify pathways to reduce cost for all key components in lifecycle cost.



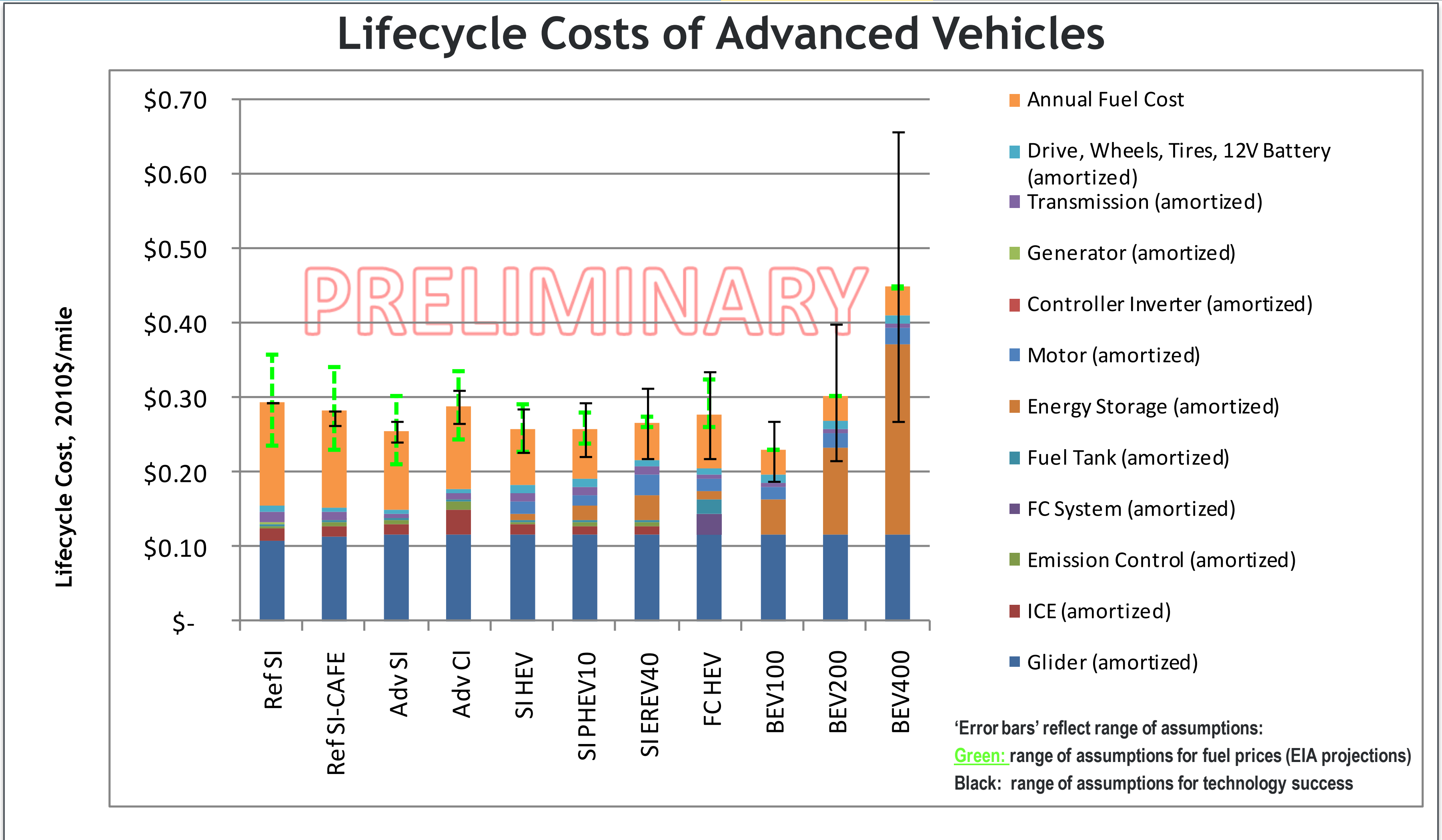
Assumptions

- **Fuel cells**
  Cost: $51/kW → $30/kW
  (low-volume cost is $100/kW)
  Durability: 75k → 150k miles
- **Hydrogen Production**
  Cost: $5.50/gge → $3.00/gge
- **On-board Hydrogen Storage**
  Cost: $5,050 → $1,100
- **FCEV fuel economy**
  50 mpgge → ~60 mpgge
- **Annual miles driven:**
  10,000 mi

Vehicle Lifecycle Cost Analysis

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

Preliminary DOE analysis



See pg 2-3 for range of assumptions for future state of technology (2030 timeframe)

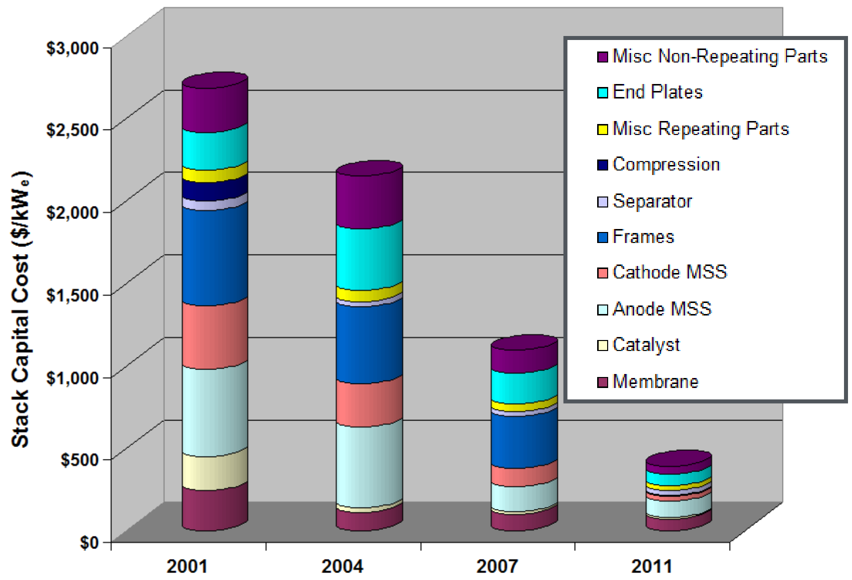
Progress - Hydrogen Production

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

Demonstrated continued progress in hydrogen cost reduction

Reduced electrolyzer cost by 80% since 2001

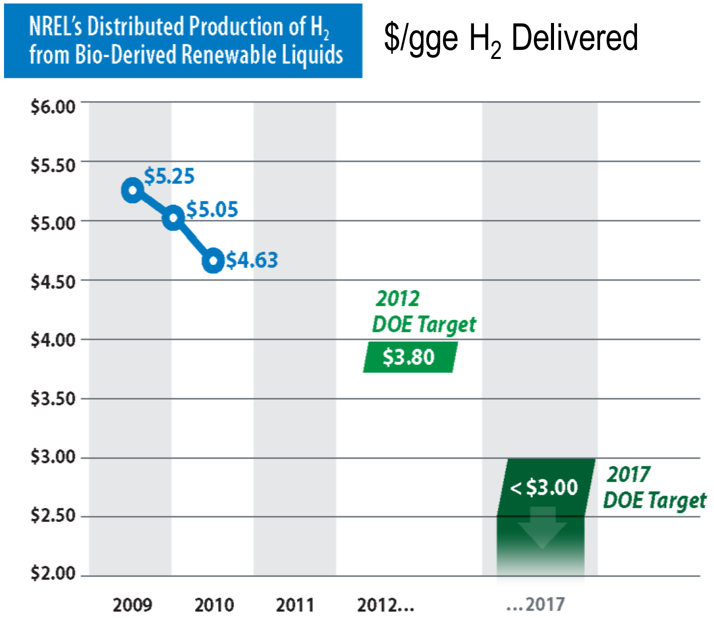
- 15% cost reduction in just the last year
- Projected high volume capital cost of $350/kW (vs. 2012 target $400/kW) (Proton, Giner)



Photoelectrochemical Conversion (PEC):

- Demonstrated potential to exceed 10% solar-to-hydrogen efficiency target >16% observed at lab scale (NREL)

Autothermal Reforming of Pyrolysis Oil



- Increased hydrogen yield by 65%
- Reduced production cost to an estimated $4.65/gge delivered

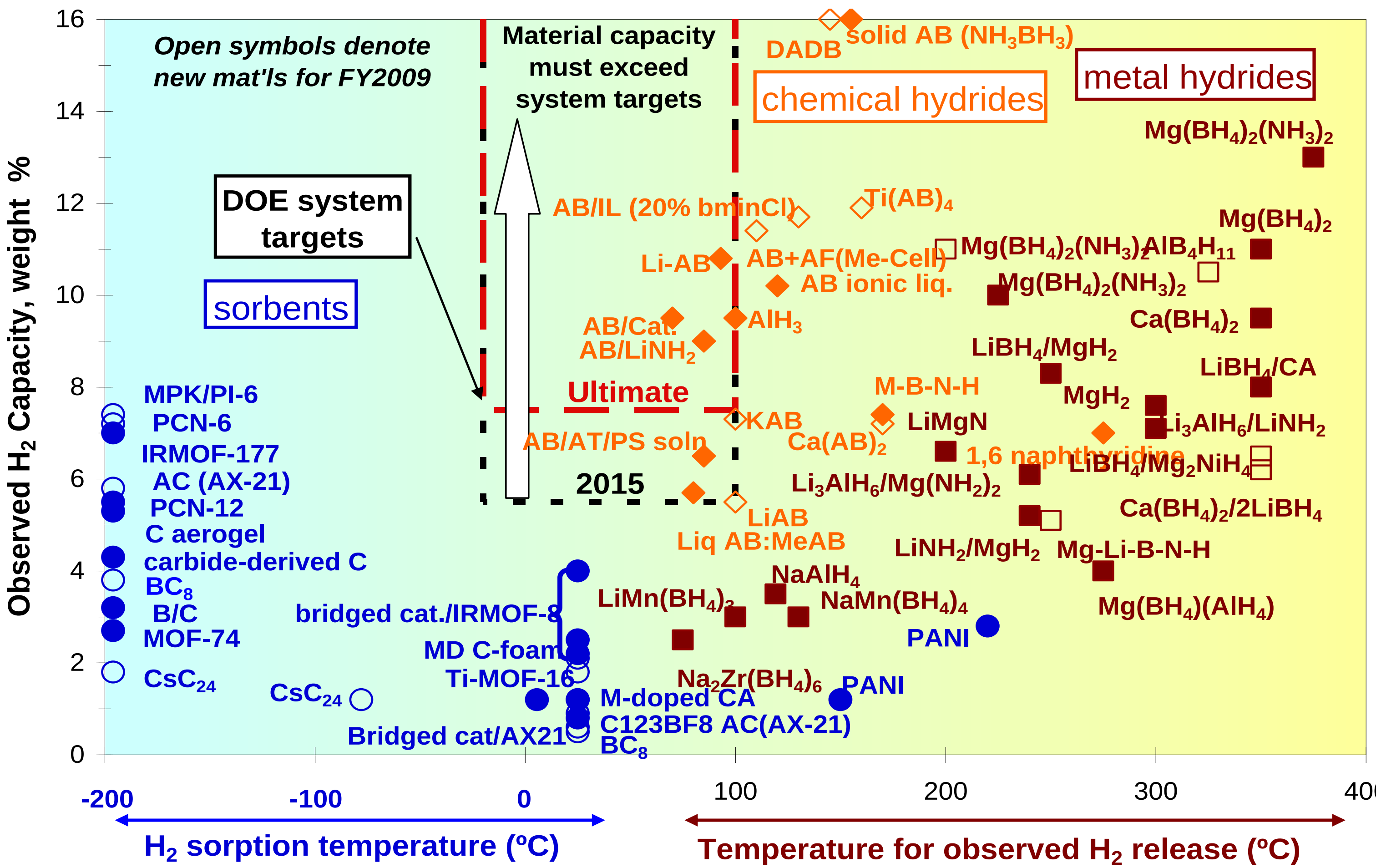
Note: costs depend on cost assumptions for pyrolysis oil

Progress - Hydrogen Storage

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

Tanks can achieve 430 mile range. Focus is on materials R&D but meeting all weight, volume, performance and cost requirements is still challenging.

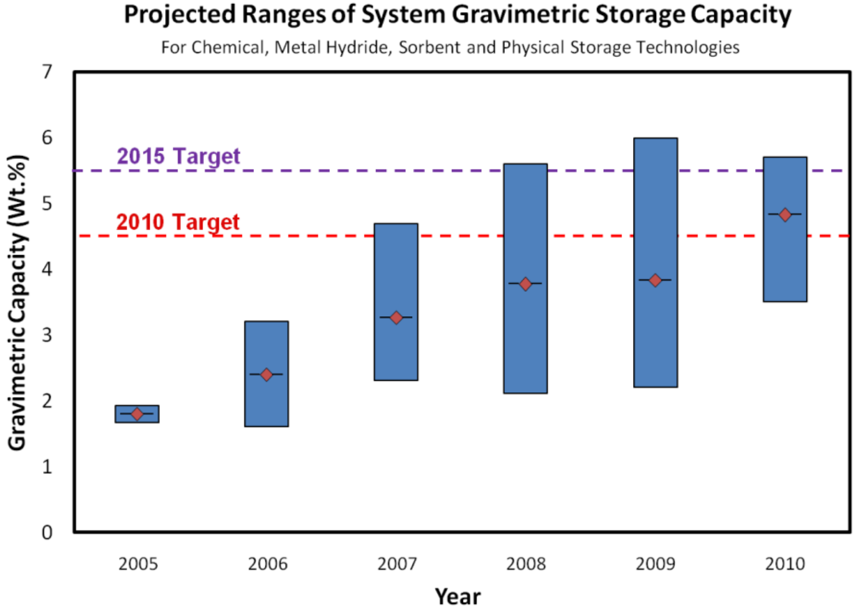
Developed > 420 new materials with potential to store hydrogen at low to moderate pressures

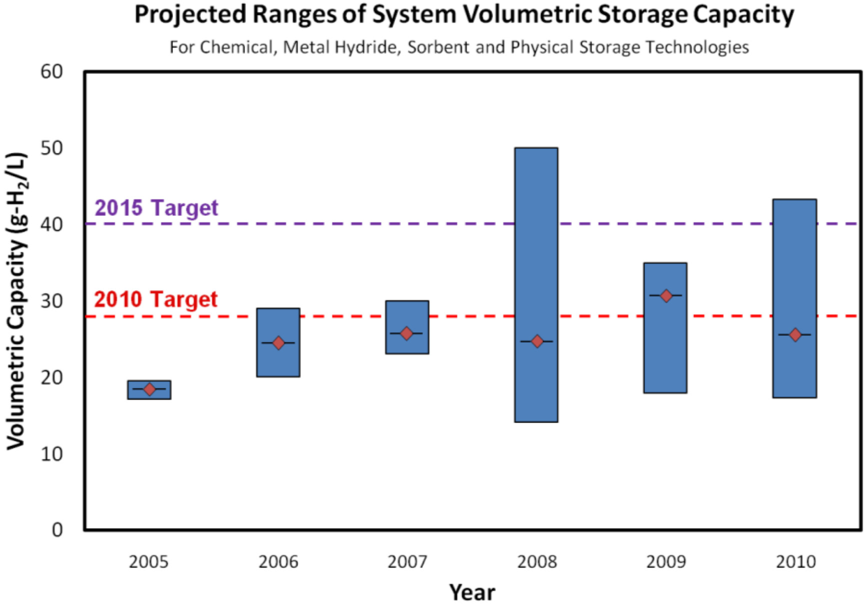


Storage Progress & Challenges

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

Projected Capacities for Complete 5.6-kg H_2 Storage Systems

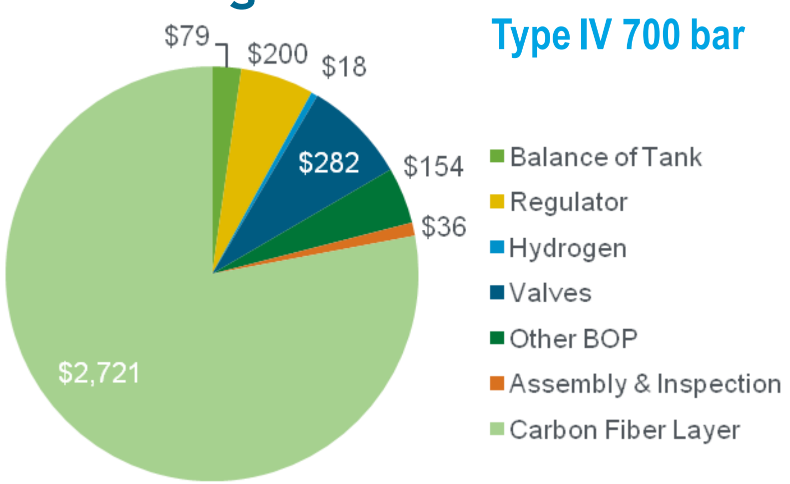




Based on analysis using the best available data and information for each technology analyzed in the given year.

- **Assessed and updated targets as planned** — based on real-world experience with vehicles, weight and space allowances in vehicle platforms, and needs for market penetration
- **Developed and evaluated more than 400 material approaches experimentally and millions computationally**

Challenge: Carbon fiber cost



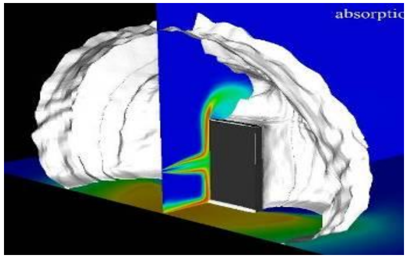
Safety, Codes & Standards R&D - Examples

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

Separation Distances

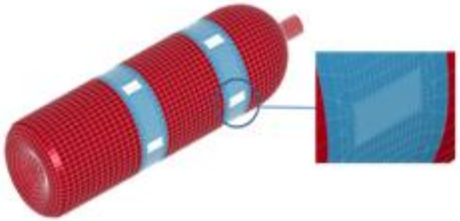
Provided technical data and incorporated risk-informed approach that enabled NFPA2 to update bulk gas storage separation distances in the 2010 edition of NFPA55

Barrier walls can be used to reduce separation distances



Materials and Components Compatibility

- Conducting cycle life testing of tanks to enable design qualification
- Testing continues for Materials Compatibility Technical Reference



Fuel Quality Specification

- Draft International Standard (DIS) was submitted to ISO TC197 Nov 2010
- Technical Specification (TS) published and harmonized with SAE J2719, Committee Draft (CD) prepared
- Developing standardized sampling and analytical methodologies with ASTM

Safety Sensor Development

- Completed extensive life testing - 4,000 hrs and 10,000 thermal cycles - of a robust, ceramic, electrochemical Hydrogen safety sensor with exceptional baseline stability and resistance to H2 signal degradation

Technical Performance Requirements	
Sensitivity: 1 vol% H_2 in air	Temperature: -40°C to 60°C
Accuracy: 0.04-4% ±1% of full scale	Durability: 5 yrs without calibration
Response time: <1 min at 1% And <1 sec at 4% Recovery <1 min	Low cross-sensitivity to humidity, H_2S, CH_4, CO, and VOCs

Progress – Technology Validation

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

Demonstrations are essential for validating technologies in integrated systems.

Real-world Validation

Vehicles & Infrastructure

- 155 fuel cell vehicles and 24 hydrogen fueling stations
- Over 3 million miles traveled
- Over 131 thousand total vehicle hours driven
- 2,500 hours (nearly 75K miles) durability
- Fuel cell efficiency 53-59%
- Vehicle Range: ~196 – 254 miles (430 miles on separate FCEV)

Buses (with DOT)

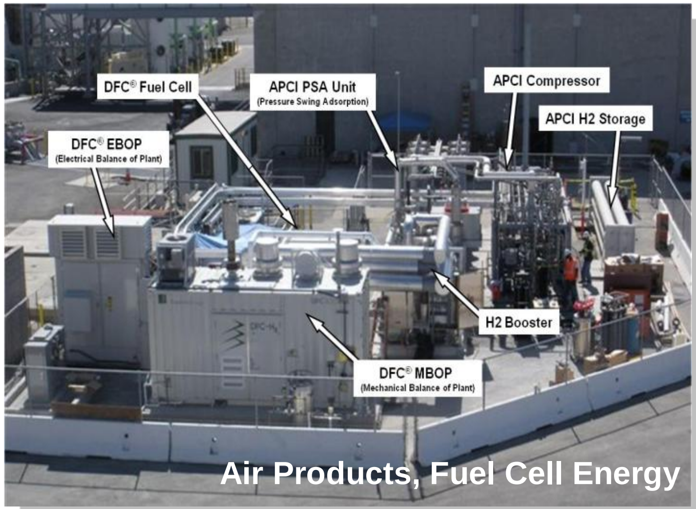
- H_2 fuel cell buses have a 42% to 139% better fuel economy when compared to diesel & CNG buses

Forklifts

- Over 45,000 refuelings at Defense Logistics Agency site

CHHP (Combined Heat, Hydrogen and Power)

- Achieved 54% (hydrogen + power) efficiency of fuel cell when operating in hydrogen co-production mode
- 100 kg/day capacity, renewable hydrogen supply



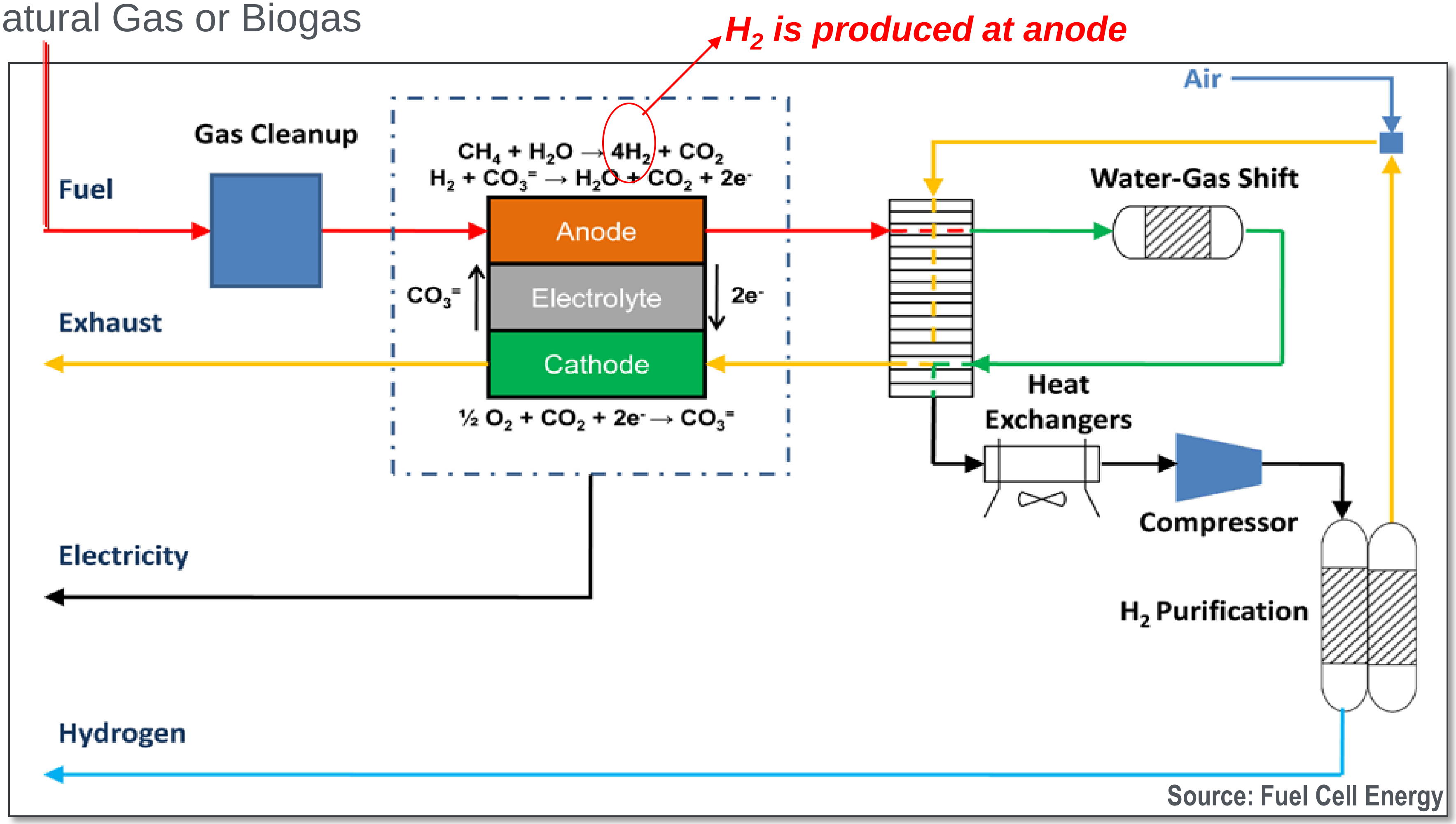
Air Products, Fuel Cell Energy

Early Option for Hydrogen Infrastructure — *Combined Heat, Hydrogen and Power (CHHP)*

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

High-temperature stationary fuel cells can co-produce hydrogen while providing power as well as heat for stationary applications . This offers an early supply of low-volumes of hydrogen without the need to commit to the capital cost of a dedicated fueling station.

Natural Gas or Biogas



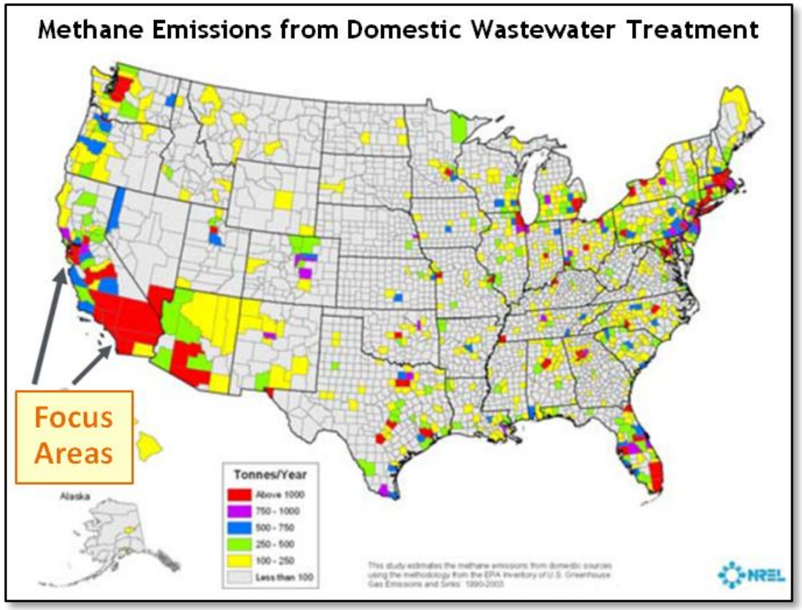
Biogas as a Potential Early Source of Renewable Hydrogen

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

- ***The majority of biogas resources are situated near large urban centers—ideally located near the major demand centers for hydrogen for FCEVs.***
- ***Hydrogen can be produced from this renewable resource using existing technology.***

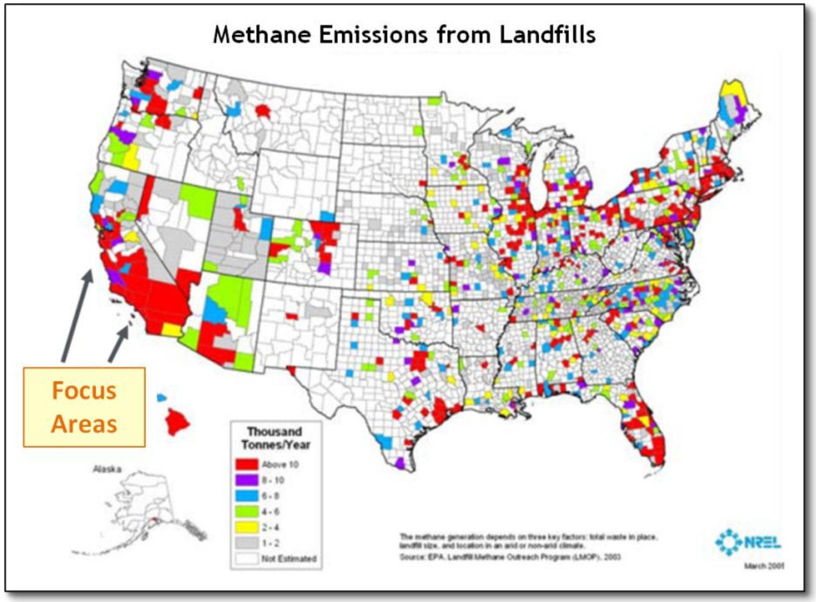
SOURCE: Wastewater Treatment, *could provide enough H_2 to refuel* ***100,000 vehicles per day.***

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



SOURCE: Landfills, *could provide enough H_2 to refuel* ***2–3 million vehicles/day****.*

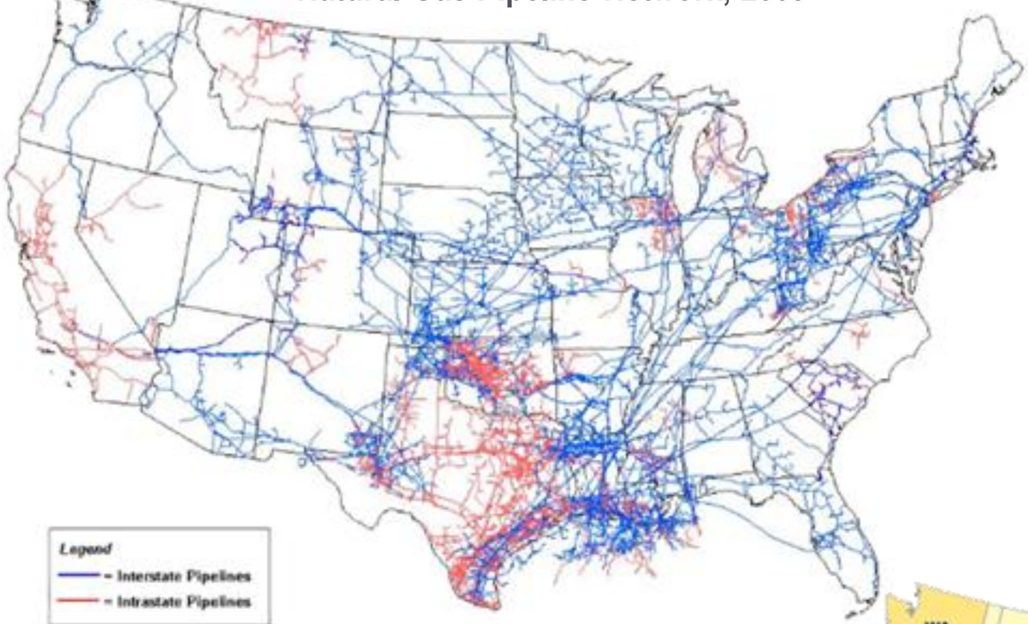
- 12.4 million MT per year of methane is available from landfills in the U.S.
- ~50% of this resource could provide **~8 million kg/day** of hydrogen.



Natural Gas Opportunities

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

Natural Gas Pipeline Network, 2009

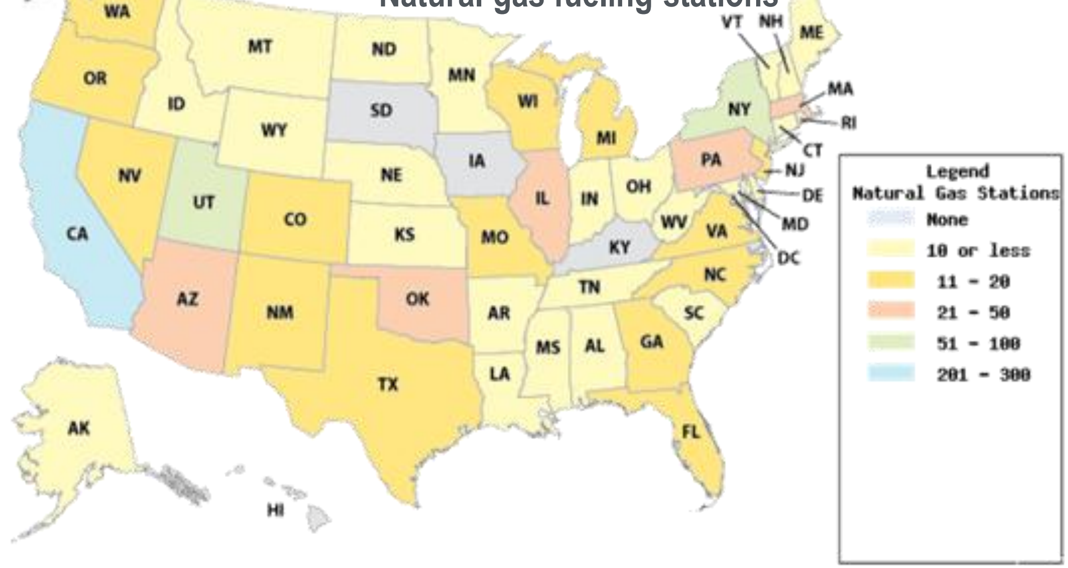


Source: Energy Information Administration, Office of Oil & Gas, Natural Gas Division, Gas Transportation Information System

Options for hydrogen production

1. **Distributed production/delivered hydrogen from natural gas (long term goal- hydrogen from renewables)**
2. **Co-produce hydrogen, heat, and power (tri-gen) with natural gas or biogas**
3. **Hydrogen from waste (industrial, wastewater, landfills)**

> 300,000 miles of interstate and intrastate transmission pipelines



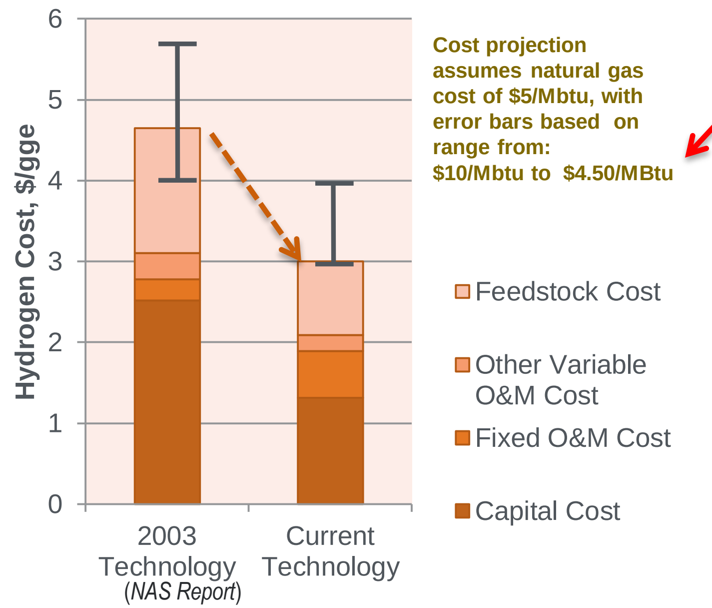
Hydrogen from Distributed Natural Gas

DOE-funded efforts have reduced the cost of hydrogen produced from natural gas (at the fueling station) to $3/gallon gasoline equivalent (gge), assuming high-volumes.

Program Success in Distributed NG Reforming:

- Completed R&D phase
- Achieved high volume $3/gge cost for H_2 dispensed at the station *(validated by independent panel*)*
- Near-term option for commercialization has potential to reduce transportation sector GHG emissions by > 50%

Cost of H_2 Produced from Natural Gas—at the Station
(projected to high-volume, includes all station costs)



DNG reforming is an affordable option for a range of natural gas prices.

Challenge
Low volume cost is still too high

Progress & Plans in Renewable Hydrogen *(all costs assume high-volume production**)*

- **$4.60 – $5.70/gge** for distributed production *(including all station costs)* from electrolysis, pyrolysis oil reforming
- As low as **$2.70/gge** for centralized production from renewables *(high-volume production, at plant gate)*
- **Direct solar conversion** — progress in several pathways *(photoelectrochemical, biological, and thermochemical)*
- **Renewable electrolysis** — **$5/gge or less** if Sunshot and other DOE renewable targets are met
  *(**<$4/gge** with improvements in catalysts and membranes and corrosion-resistant and more-durable materials)*

* Program Record #10001, www.hydrogen.energy.gov/program_records.html.
** Distributed costs assume station capacities of 1500 kg/day, with 500 stations built per year; costs for centralized production assume a range of production capacities, from 50,000 kg/day to 194,000 kg/day.

Deployed more than 630 fuel cells to date for use in forklifts and backup power at several companies including Sprint, AT&T, FedEX, Kimberly Clark, and Whole Foods

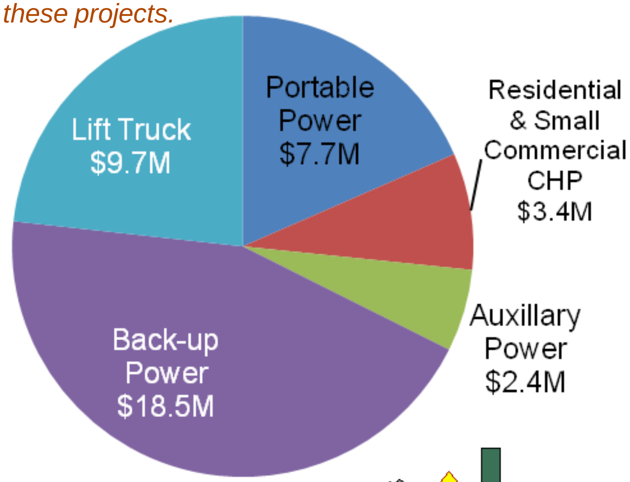
FROM the LABORATORY to DEPLOYMENT:

DOE funding has supported R&D by all of the fuel cell suppliers involved in these projects.

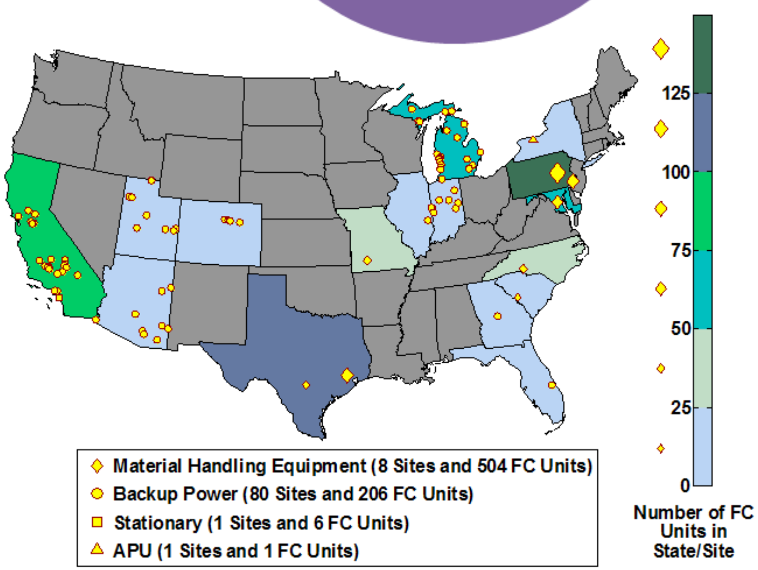
DOE: $42 M

Cost-share: $54 M

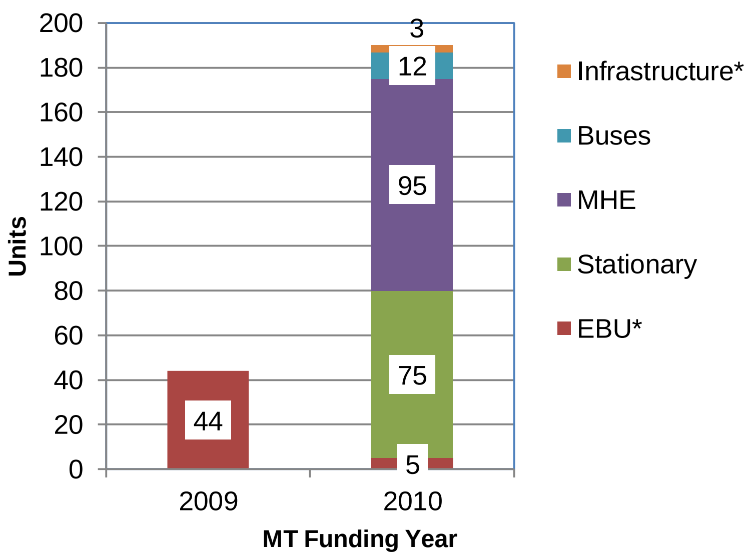
Total: $96 M.



- Forklifts
  - FedEX Freight East, GENCO, Nuvera Fuel Cells, Sysco Houston
- Back-up Power
  - Plug Power, Inc., ReliOn, Inc., Sprint Nextel
- Portable Power
  - Jadoo Power, MTI MicroFuel Cells, Univ. of N. Florida
- Auxiliary Power
  - Delphi Automotive



ARRA JOBS STATUS (Apr 2011) ~46 jobs reported on Recovery.gov



Deployments – Backup Power

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

$3.6M in a cost-shared effort to install more than 230 kW in fuel cell backup power across 8 DOD installations, 1 NASA Research Center, and DOE National Lab.

Locations

- Cheyenne Mountain AFB (CO)
- Fort Hood (TX)
- Fort Bragg (NC)
- Aberdeen Proving Ground (MD)
- Picatinny Arsenal (NJ)
- U.S. Military Academy West Point (NY)
- U.S. Marine Corps (CA)
- Ohio National Guard (OH)
- NASA Ames (CA)
- Argonne National Laboratory (IL)

LOGANEnergy will install three PEM fuel cell backup power units at Argonne National Laboratory.

•6kW system by ReliOn

•10kW system by Hydrogenics

•15kW system by Altergy

Projected installation date is planned for December 2011.

The fuel cells will ensure the availability of electric power for critical applications during outages.

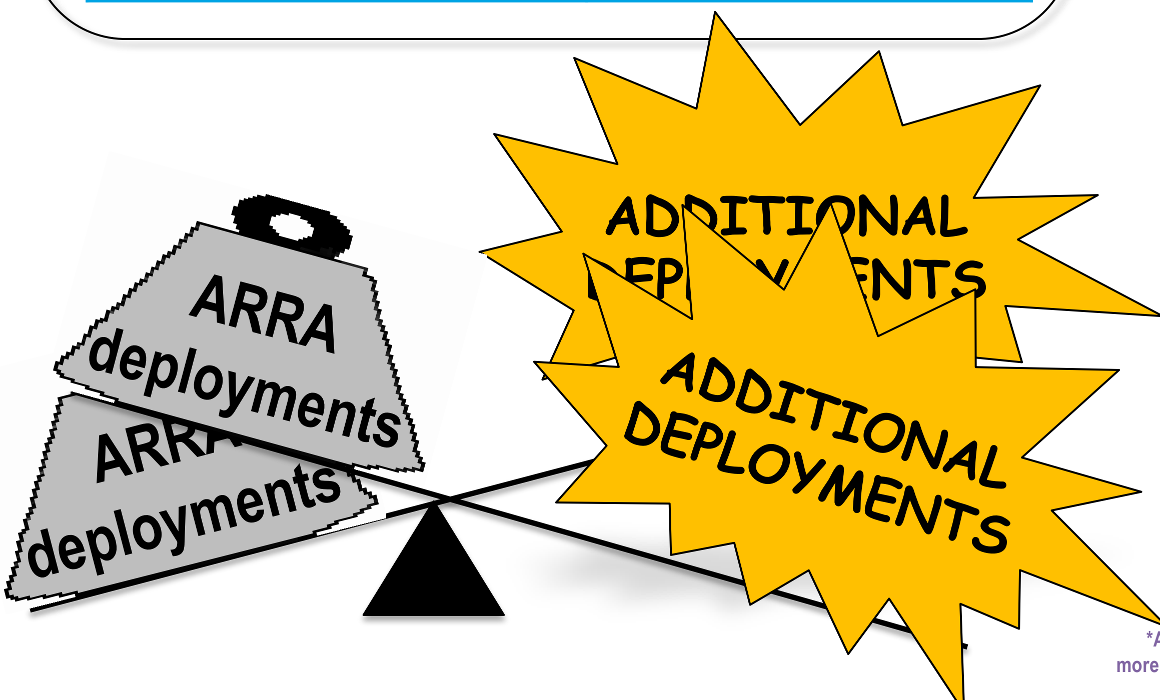
- *Project will be implemented by Army ERDC-CERL.*
- *LOGANEnergy will install fuel cells from four manufacturers: ReliOn, Altergy, Idatech and Hydrogenics.*
- *NREL will collect data.*

Accomplishments

Data Collection Snapshot (NREL)

ARRA Material Handling Equipment Data	As of 12/31/2010
Hydrogen Dispensed	> 18,500 kg
Hydrogen Fills	> 38,800
Hours Accumulated	> 307,400 hrs
Durability	~3,000 hrs*
Reliability	75% w/MTBF > 100 hrs

Additional fuel cell lift truck deployments taking place based on ARRA experience and lessons learned!



MORE THAN 500 ADDITIONAL FUEL CELL FORKLIFTS PLANNED

E.g., Sysco, H-E-B Grocery, BMW

*Average projected hours to 10% voltage drop of all the fleets with a max fleet project of more than 9,500 hours. 25% of systems have more than 2,300 operation hours and one fleet averages more than 2,6000 operation hours.

Example – The Case for Fuel Cell Forklifts

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

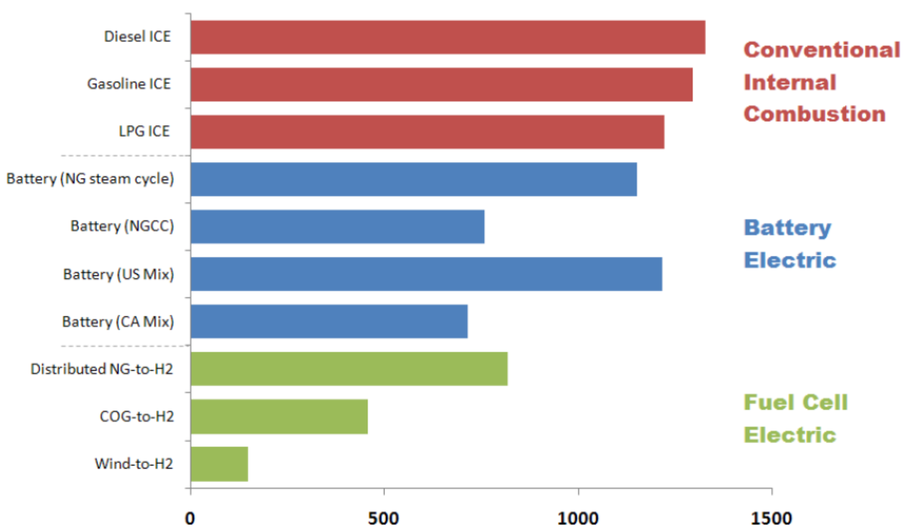
Fuel cell forklifts offer several advantages compared to conventional fork lift technology

Preliminary Analysis

Compared to conventional forklifts, fuel cell forklifts have:

- 1.5 X lower maintenance cost
- 8 X lower refueling/recharging labor cost
- 2 X lower net present value of total system cost

Fuel Cycle GHG Emissions for Forklifts
(g/kWh at the fork)

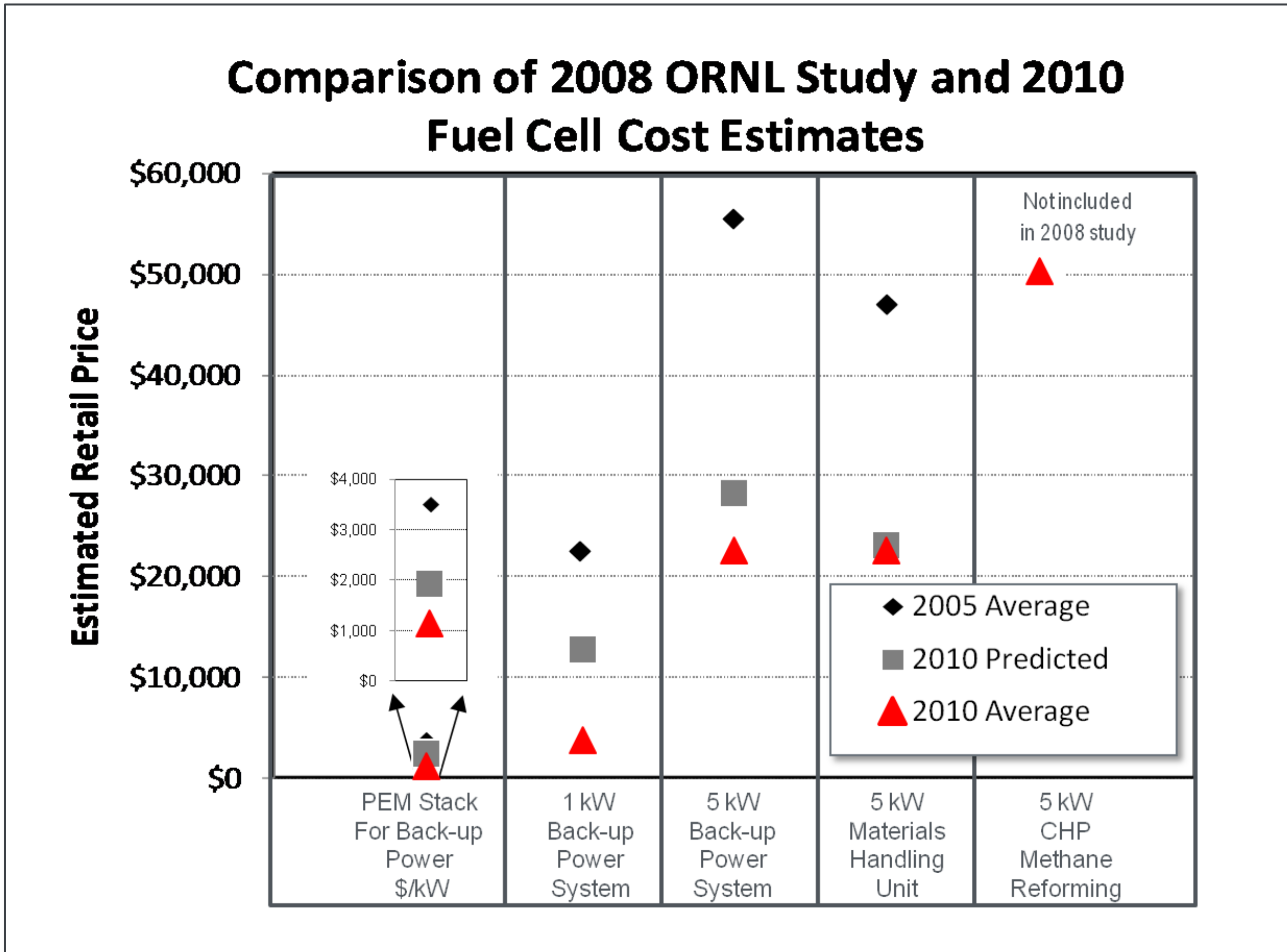


Preliminary Analysis: Comparison of PEM Fuel Cell- and Battery-Powered Forklifts

Time for Refueling/ Changing Batteries	4-8 min/day	45-60 min/day (for battery change-outs) 8 hours (for battery recharging & cooling)
Labor Cost of Refueling/Recharging	$1,100/year	$8,750/year
NPV of Capital Costs	$12,600 ($18,000 w/o incentives)	$14,000
NPV of O&M Costs (including fuel)	$52,000	$128,000

Published Fact Sheets & Case Studies

Deployments of fuel cells in early markets have reduced costs substantially.



- ***50% or greater reduction in costs***
- ***2008 model generally underestimated cost reductions***


Oak Ridge National Laboratory

ORNL/TM-2011/101

Status and Outlook for the U.S. Non-Automotive Fuel Cell Industry: Impacts of Government Policies and Assessment of Future Opportunities

May 2011

Prepared by:
David L. Greene
Oak Ridge National Laboratory
K.G. Duleep
ICF International
Girish Upreti
University of Tennessee

2005 and 2010 averages based on estimates supplied by OEMs. 2010 predicted assumed government procurements of 2,175 units per year, total for all market segments. Predictions assumed a progress ratio of 0.9 and scale elasticity of -0.2.

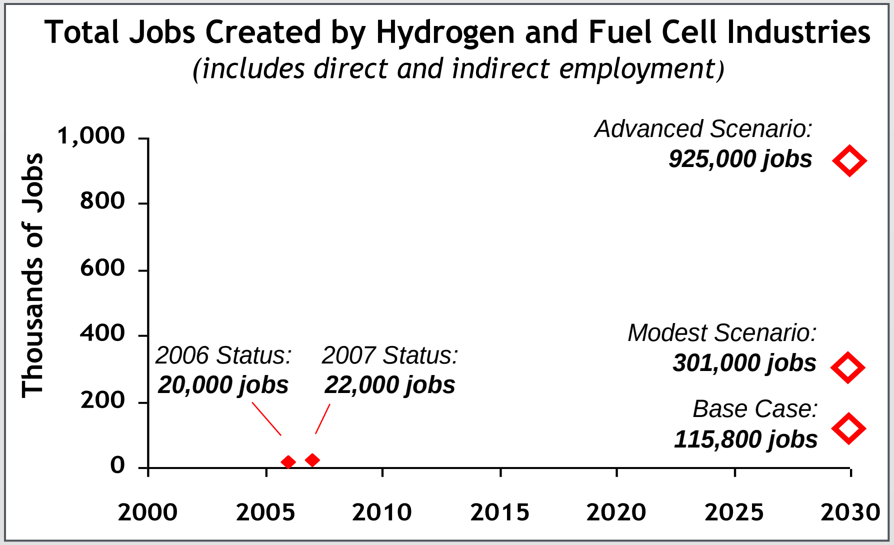
Fuel Cells - *The Economic Potential*

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

The fuel cell and hydrogen industries could generate substantial revenues and job growth.

Renewable Energy Industry Study*

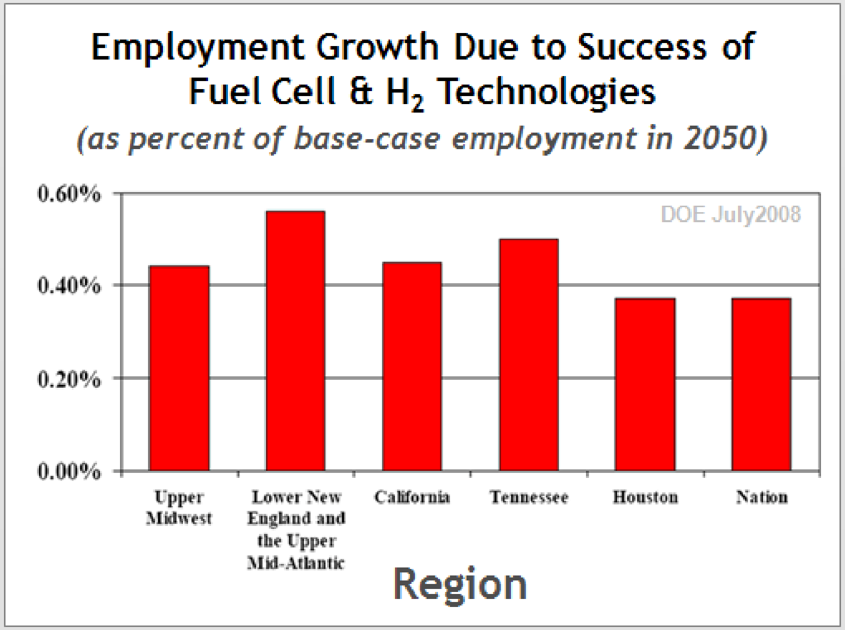
- **Fuel cells are the third-fastest growing renewable energy industry** (after biomass & solar).
- Potential U.S. employment from fuel cell and hydrogen industries of **up to 925,000 jobs** (by 2030).
- Potential gross revenues up to **$81 Billion/year** (by 2030).



***Study Conducted by the American Solar Energy Society**
www.ases.org/images/stories/ASES/pdfs/CO_Jobs_Final_Report_December2008.pdf

DOE Employment Study

- Projects net increase of **360,000 – 675,000** jobs.
- Job gains would be distributed across up to 41 industries.
- Workforce skills would be mainly in the vehicle manufacturing and service sectors.



www.hydrogen.energy.gov/pdfs/epact1820_employment_study.pdf

Employment Impacts of Early Markets

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

Developed user-friendly tool to calculate economic impacts

REQUIRED USER INPUT FIELDS	
Select State or Region	NE
Type of Fuel Cell	PEMFC
Application	Stationary - Backup
Average Size of Manufactured Fuel Cell	5
Fuel Cells Manufactured by Year	2000
Annual Fuel Cell Production (kW/year)	10,000
Time Frame (years)	5

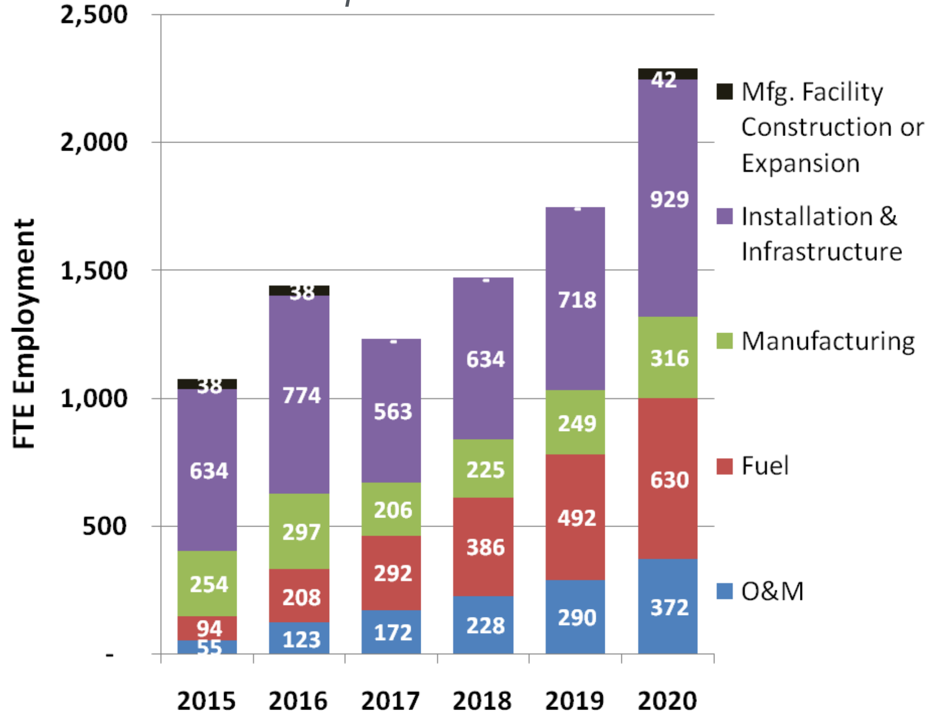
OPTIONAL USER INPUT FIELDS	
Existing Fuel Cell Production Capacity (kW/year)	0
Additional Manufacturing Capacity to be Constructed (kW/year)	10,000
Sales Price ($/kW)	$2,000
Production Cost ($/kW, initial)	$1,301
Progress Ratio	0.97
Production Volume for Initial C...	10,000
Scale Elasticity	-0.2
Full ...	25,000
Annu...	2%
Averag... ...e Frame ($/kW)	$1,098
Installation Cost ($/kW)	TBD
Operations & Maintenance Cost ($/kW, annual)	TBD

Will be available for beta testing (2011)

Argonne National Lab/RCF

Preliminary Analysis

Gross National Impact of PEMFCs in Forklifts

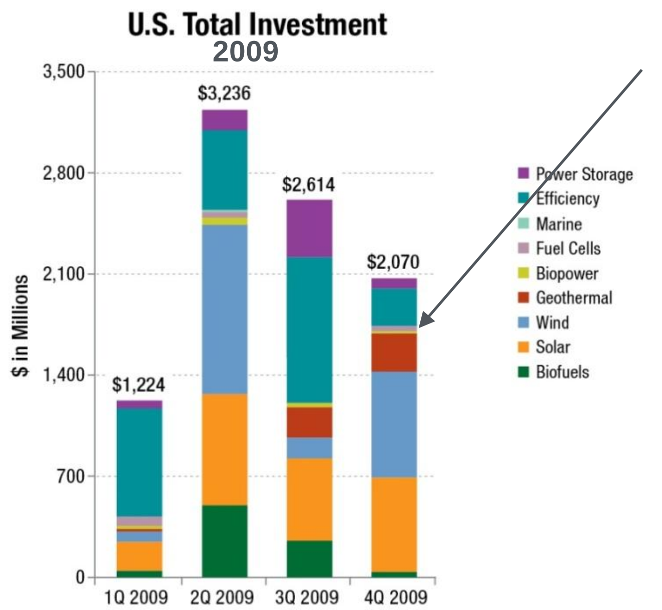


Includes *short-term jobs* (construction/ expansion of mfg capacity, installation & infrastructure) & *on-going jobs* (manufacturing, O&M and fuel production & delivery)

Technology/Market Assumptions:

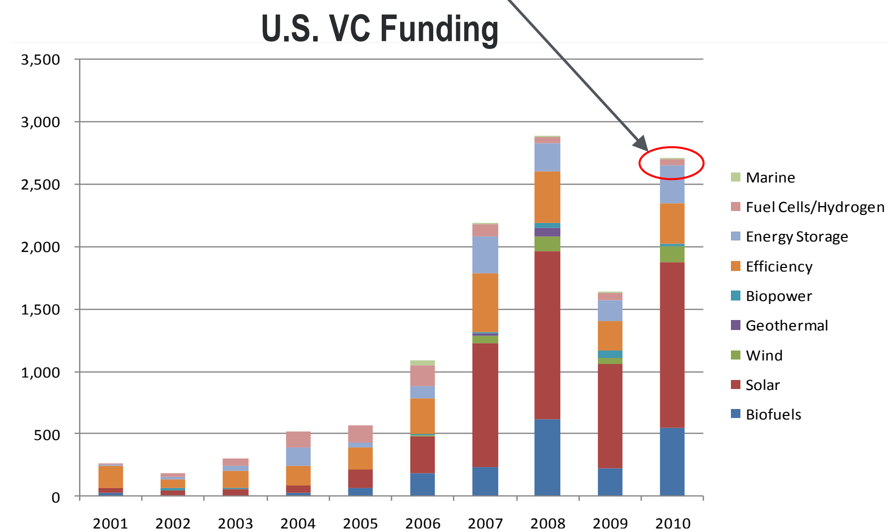
- $1,300/kW initial mfg cost (*Battelle*), $4,200/kW retail price.
- Shipments reach 3,300 annually by 2020 *(Greene et. al.)* out of ~100,000.
- 15,000 FC forklifts in operation by 2020 (<2 percent of Class 1-3 forklifts).
- Average of 60 fuel cells/site, 250 site installations by 2020.
- Tax credit expires in 2016.

Federal budget in fuel cells complements industry



Source: Bloomberg New Energy Finance; completed and disclosed deals only; includes VC/PE, public market activity, asset financing, and acquisition transactions.

Funding is critical to the emerging fuel cell industry



Source: Bloomberg New Energy Finance, as of June 8th, 2011. Completed and disclosed deals only.

Fuel cell industry is less established than other clean energy industries—DOE funds have significant impact on emerging industries such as fuel cells.

* Source: www.cleanedge.com/reports/pdf/Trends2009.pdf

EERE H_2 & Fuel Cells Budgets

Funding *($ in thousands)*		
Key Activity	**FY 2011 Appropriation ($ thousands)**	**FY 2012 Request ($ thousands)**
Fuel Cell Systems R&D	**43,000**	**45,450**
Hydrogen Fuel R&D	**33,000**	**35,000**
Technology Validation	**9,000**	**8,000**
Safety, Codes & Standards	**7,000**	**7,000**
Systems Analysis	**3,000**	**3,000**
Manufacturing R&D	**3,000**	**2,000**
Total	**98,000**	**100,450**

Budget is approximately $100 million per year

Future Plans - Summary

- **Continue to promote and strengthen R&D activities**
  - **Hydrogen, fuel cells, safety, codes and standards, etc.**
- **Conduct strategic, selective demonstrations of innovative technologies**
  - **Technology validation – solicitation planned**
- **Continue to conduct key analysis to guide RD&D and path forward**
  - **Life cycle cost; economic & environmental analyses, etc.**
- **Leverage activities to maximize impact**
  - **U.S. and global partnerships**

Acknowledgements

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

Federal Agencies

- DOC
- DOD
- DOE
- DOT
- EPA
- GSA
- DOI
- DHS
- NASA
- NSF
- USDA
- USPS

– *Interagency coordination through staff-level Interagency Working Group (meets monthly)*
– *Assistant Secretary-level Interagency Task Force mandated by EPACT 2005.*

Universities

~ 50 projects with 40 universities

International

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

External Input

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

DOE Hydrogen & Fuel Cells Program

Industry Partnerships & Stakeholder Assn's.

- Tech Teams (USCAR, energy companies- U.S. DRIVE)
- Fuel Cell and Hydrogen Energy Association (FCHEA)
- Hydrogen Utility Group
- ~ 65 projects with 50 companies

State & Regional Partnerships

- California Fuel Cell Partnership
- California Stationary Fuel Cell Collaborative
- SC H_2 & Fuel Cell Alliance
- Upper Midwest Hydrogen Initiative
- Ohio Fuel Coalition
- Connecticut Center for Advanced Technology

National Laboratories

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

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

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

Thank you

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Additional Information

EERE Budget: *FY09 – FY12*

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Funding *($ in thousands)*				
Activity	**FY 2009**	**FY 2010**	***FY 2011 Appropriation***	***FY 2012 Request***
Biomass and Biorefinery Systems	214,245	216,225	182,695	340,500
Building Technologies	138,113	219,046	210,500	470,700
Federal Energy Management Program	22,000	32,000	30,402	33,072
Geothermal Technology	43,322	43,120	38,003	101,535
Hydrogen Technology	164,638	0	0	0
Hydrogen and Fuel Cell Technologies	0	170,297	98,000	100,450
Water Power	39,082	48,669	30,000	38,500
Industrial Technologies	88,196	94,270	108,241	319,784
Solar Energy	172,414	243,396	263,500	457,000
Vehicle Technologies	267,143	304,223	300,000	588,003
Weatherization & Intergovernmental Activities	516,000**	270,000	231,300	393,798
Wind Energy	54,370	79,011	80,000	126,859
Facilities & Infrastructure	76,000	19,000	51,000	26,407
Strategic Programs	18,157	45,000	32,000	53,204
Program Direction	127,620	140,000	170,000	176,605
Congressionally Directed Activities	228,803	292,135	0	0
RE-ENERGYSE	0	0	0	0
Adjustments	-13,238	0	-30,000	-26,364
Total	**$2,156,865**	**2,216,392**	**1,795,641**	**3,200,053**

* SBIR/STTR funding transferred in FY 2009 was $19,327,840 for the SBIR program and $2,347,160 for the STTR program.
** Includes $250.0 million in emergency funding for the Weatherization Assistance Grants program provided by P.L. 111-6, "The Continuing Appropriations Resolution, 2009."

Portable Power Targets

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		Portable Power Applications, Under 2W[1]		Portable Power Applications, 10-50 W[1]		Portable Power Applications, 100-250 W[1]	
	Units	**2011 Status**	**2015 Target**	**2011 Status**	**2015 Target**	**2011 Status**	**2015 Target**
Specific Power[2]	W/kg	5	10	15	45	25	50
Power Density[2]	W/L	7	13	20	55	30	70
Specific Energy[2,3]	Wh/kg	110	230	150	650	250	640
Energy Density[2,3]	Wh/L	150	300	200	800	300	900
Cost[4]	$/system	150	70	15	7	15	5
Durability[5,6]	hours	1500	5000	1500	5000	2000	5000
Mean Time Between Failures[6,7]	hours	500	5000	500	5000	500	5000

Assumptions and supporting information can be found here: http://hydrogendoedev.nrel.gov/pdfs/11009_portable_fuel_cell_targets.pdf.

APU Targets

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Revised FCT fuel cell APU targets published in 2010

	Units	Status	2013	2015	2020
Electrical efficiency at rated power[1]	%	25	30	35	40
Power density	W/L	17	30	35	40
Specific power	W/kg	20	35	40	45
Factory cost, stack plus required BOP[2]	$/kW	750 [3]	700	600	500
Factory cost, system[4]	$/kW	2000	1400	1200	1000
Transient response (10 to 90% rated power)	min	5	4	3	2
Start-up time from: 20 °C Standby conditions[5]	Min	 50 50	 45 20	 45 10	 30 5
Degradation with cycling[6]	%/1000 h	2.6	2	1.3	1
Operating lifetime6,[7]	h	3000	10,000	15,000	20,000
System availability	%	97	97.5	98	99

Assumptions and supporting information can be found here: http://hydrogendoedev.nrel.gov/pdfs/11009_portable_fuel_cell_targets.pdf.

APU targets were developed using:
- **Comparison with incumbent technology (diesel ICE APUs)**
- **An RFI process to obtain input from stakeholders**
- **Direct discussion with developers**

Example: 2020 power density target

Stakeholder recommendations: 20 – 55 W/L

Incumbent technology: 11 – 33 (mean 20) W/L

Final DOE 2020 target: 40 W/L – within range suggested by stakeholders and superior to incumbent technology

Micro-CHP Targets

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Targets developed with input from stakeholders and the research community
Cost and durability are the major challenges

Preliminary Technical Targets: 1 – 10 kW_e Residential Combined Heat and Power Fuel Cells Operating on Natural Gas[1]

	Units	Status	2020 FCT Targets
Electrical energy efficiency at rated power[2]	%	34	45
CHP energy efficiency at rated power[3]	%	80	90
Cost[4]	$ / kW_e	750	500
Transient response time (from 10 - 90% rated power)	min	5	2
Start-up time from 20°C ambient temperature	min	60	20
System availability	%	97	99
Operating lifetime[5]	hours	6,000	60,000
Degradation with cycling	% / hours	<2/1000	0.3/1000

Assumptions and supporting information can be found here: http://hydrogendoedev.nrel.gov/pdfs/11009_portable_fuel_cell_targets.pdf.

2010 Independent Assessment of CHP Fuel Cell Status & Targets

- **Confident that by 2015, LT-PEM & HT-PEM can achieve 40,000 hr**
- **45% electrical efficiency (2020 target) for 1-10kW systems is feasible for HT-PEM, LT-PEM depends on improved catalysts & higher operating temps**
- **SOFT systems are likely to achieve DOE tarets for electricla and CHP efficiences. 90% CHP efficiency is likely to be attainable by SOFC systems.**
- **Confident that by 2020, LT-PEM & HT-PEM can achieve $450-$750/kW, while SOFC can achieve $1000-2000/kW**

Targets & Status for Automotive fuel Cells

Challenge	Requirement (target)	Status in Lab	DOE Demo status Vehicles + Stations
Fuel Cell Cost & Durability	**Cost:** \$30/kW, **Durability:** 5,000 hr (150,000 mi)	**Cost:** \$51/kW *(at 500,000 units/year)* **Durability:** Projected average > 4,000 hr (max > 5,000 hr)	2,500 hrs (75,000 mi)
Hydrogen Production & Delivery Cost	\$2 – \$4/gge *(gge = gallon gasoline equivalent; 1 gge H_2 = 1 kg H_2)*	High-volume projections: Achieved \$3/gge (distributed natural gas to H_2) Renewables and other low carbon pathways range from ~\$5/gge to >\$10/gge.	Low-volume H_2 cost >\$10/gge
Hydrogen Storage	1.8 kWh/kg (6.5 MJ/kg) 1.3 kWh/L (4.7 MJ/L)	**Storage System Status:** 350 bar: 1.8 kWh/kg, 0.6 kWh/L 700 bar: 1.7 kWh/kg, 0.9 kWh/L	Up to ~250 mile range (430 miles verified on Toyota FCEV)