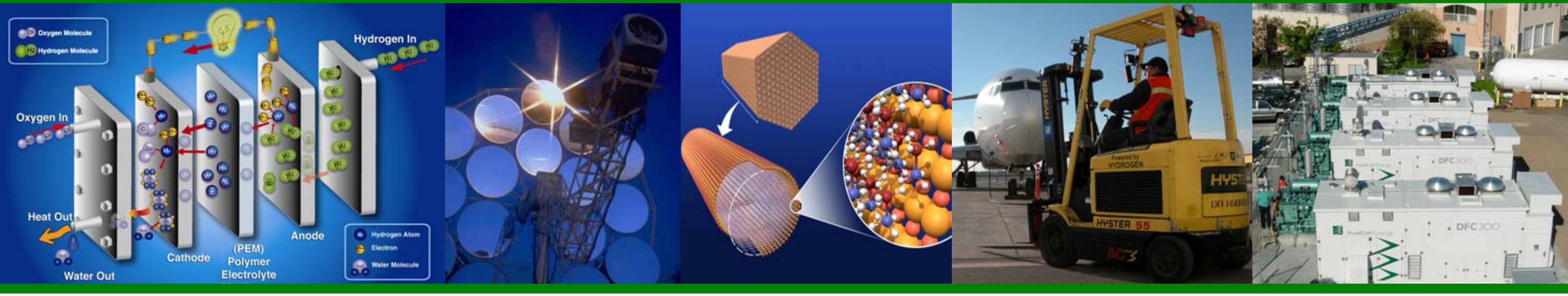
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Fuel Cell Technologies Program

Sunita Satyapal

Acting Program Manager

and Team Leads:

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Dimitrios Papageorgopoulos, Pete Devlin*, Christy Cooper**

*On detail

September 24, 2009

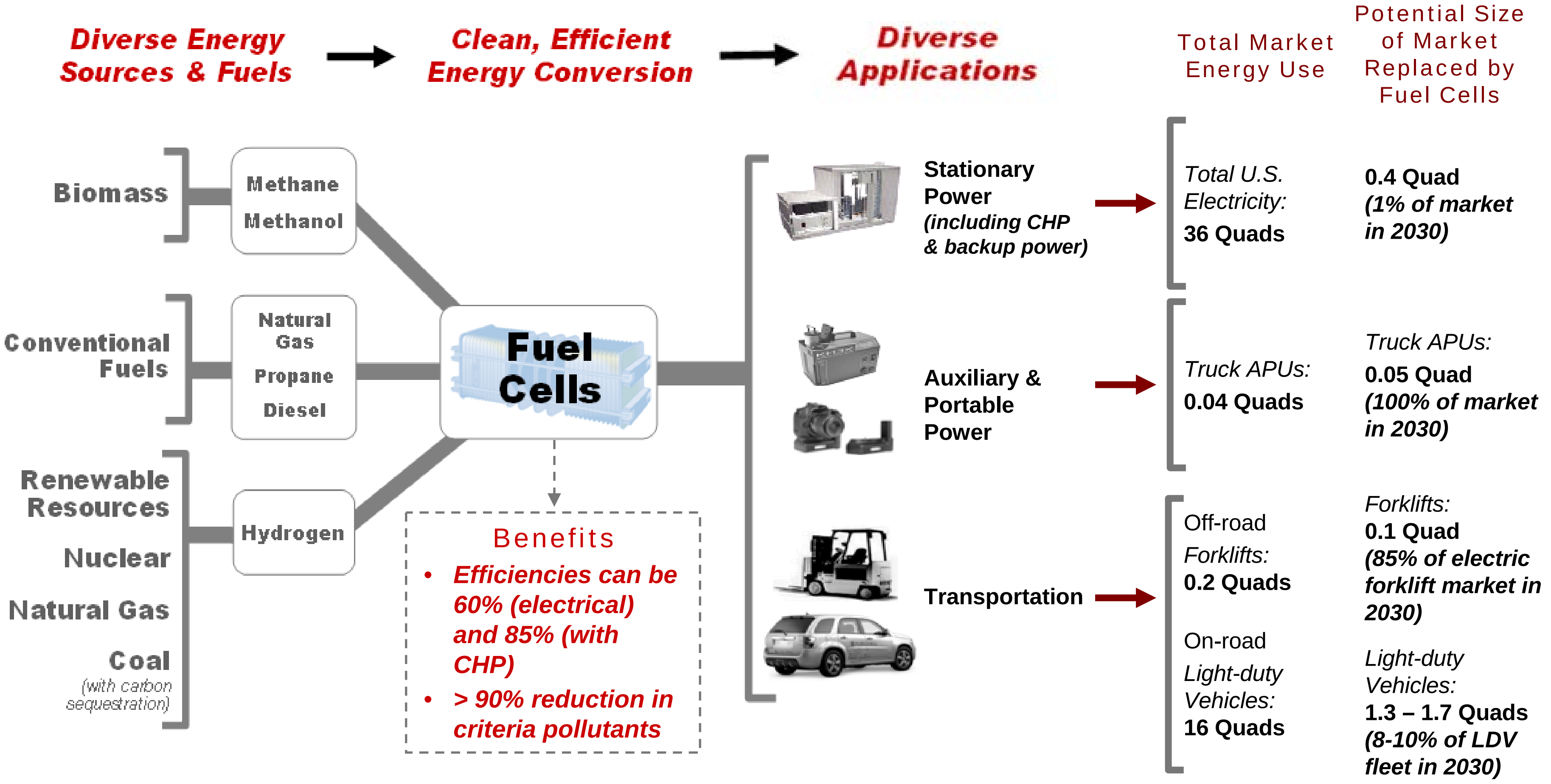
Fuel Cells: Addressing Energy Challenges

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.***



Diverse Energy Sources & Fuels → **Clean, Efficient Energy Conversion** → **Diverse Applications**

Biomass: Methane, Methanol

Conventional Fuels: Natural Gas, Propane, Diesel

Renewable Resources, **Nuclear**, **Natural Gas**, **Coal** (with carbon sequestration): Hydrogen

Fuel Cells

Benefits

- ***Efficiencies can be 60% (electrical) and 85% (with CHP)***
- ***> 90% reduction in criteria pollutants***

Diverse Applications	Total Market Energy Use	Potential Size of Market Replaced by Fuel Cells
Stationary Power ***(including CHP & backup power)***	*Total U.S. Electricity:* **36 Quads**	**0.4 Quad** ***(1% of market in 2030)***
Auxiliary & Portable Power	*Truck APUs:* **0.04 Quads**	*Truck APUs:* **0.05 Quad** ***(100% of market in 2030)***
Transportation	Off-road *Forklifts:* **0.2 Quads** On-road *Light-duty Vehicles:* **16 Quads**	*Forklifts:* **0.1 Quad** ***(85% of electric forklift market in 2030)*** *Light-duty Vehicles:* **1.3 – 1.7 Quads** ***(8-10% of LDV fleet in 2030)***

Program Goals and Barriers

The Program's overarching goal is to enable the widespread commercialization of hydrogen and fuel cell technologies.

Technology Barriers

Fuel Cell Cost & Durability

	Status:	Targets:
Stationary Systems:	~$3,500/kW	$750/kW
	20,000 hr	40,000-hr durability
Vehicles:	$61/kW	$30/kW
	2,000 hr	5,000-hr durability

Cost of H_2 Production & Delivery

(cost is untaxed and delivered)

	Status:	Targets:
Production:	$3 - $12/gge	$2 – 3/gge
Delivery:	$2.30 – 3.30/gge	<$1/gge

gge = gallon gasoline equivalent

Capacity & Cost of H_2 Storage

(>300 mile range)	Status:	Targets:
Volumetric	15 – 50 g/L	70 g/L
Gravimetric	3.0 – 6.5 wt%	7.5 wt%
Cost	$15 – 23/kWh	$2/kWh

Technology Validation:

Technologies must be demonstrated under real-world conditions.

E.g., 140 vehicles & 20 stations demonstrated with GM, Ford, Daimler/ Chrysler, Hyundai

- *2.2 million miles, 90,000 kg dispensed; 53-58% efficiency; up to 254 mile range demonstrated.*

Economic & Institutional Barriers

Safety, Codes & Standards Development

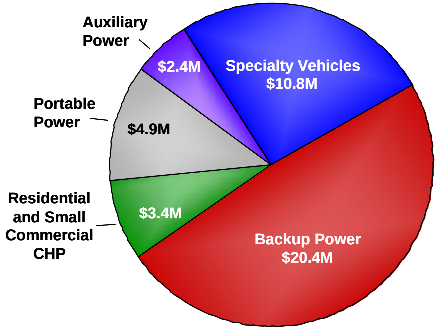
Domestic Manufacturing & Supplier Base

Public Awareness & Acceptance

Investment in Delivery Infrastructure

COMPANY	AWARD
Anheuser-Busch	$1.1 M
Delphi Automotive	$2.4 M
FedEx	$1.3 M
GENCO	$6.1 M
Jadoo Power	$1.8 M
MTI MicroFuel Cells	$2.4 M
Nuvera Fuel Cells	$1.1 M
Plug Power	$3.4 M
Plug Power	$2.7 M
PolyFuel	$2.5 M
ReliOn (inc. AT&T)	$8.6 M
Sprint Comm.	$7.3 M
Sysco of Houston	$1.2 M

Market Transformation

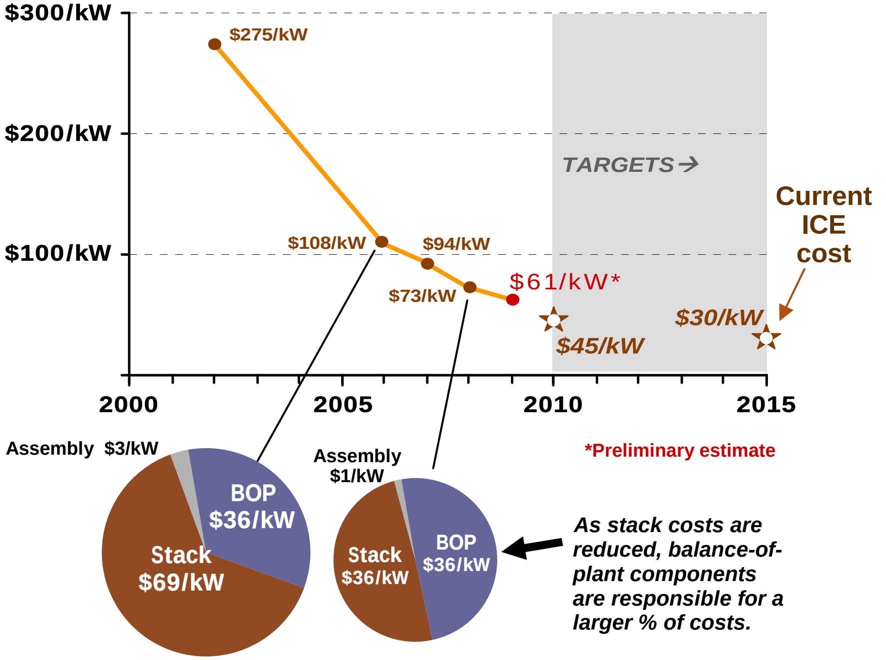


Recovery Act enables up to 1,000 fuel cell systems for early markets ($42M)

NOTE: All costs are projected to high-volume manufacturing and production.

Major Technology Pathways: Status of Fuel Cells

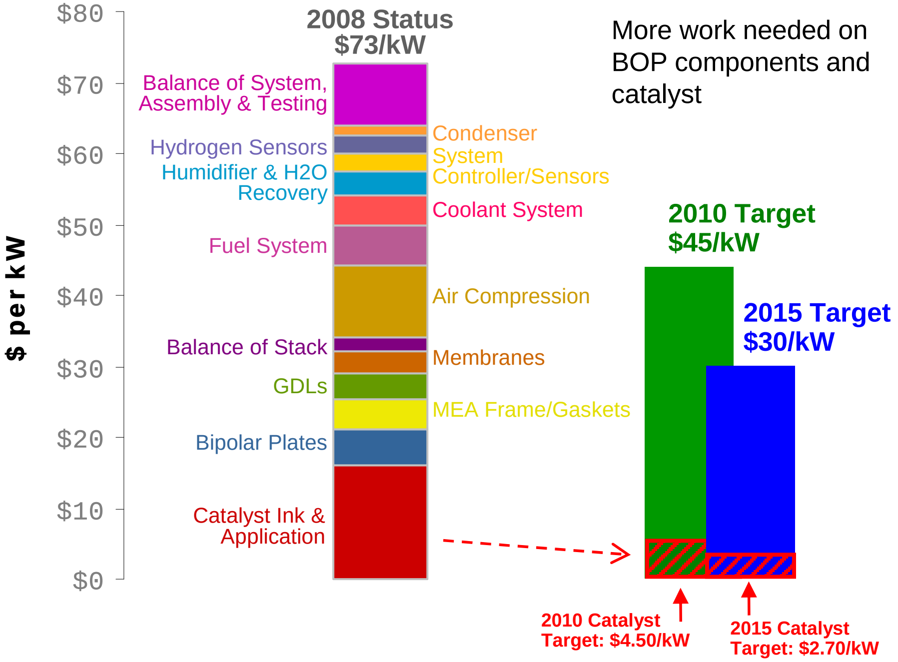
We've reduced the cost of fuel cells by more than 75% since 2002.



*Preliminary estimate

As stack costs are reduced, balance-of-plant components are responsible for a larger % of costs.

Breakdown of 2008 Cost Estimate



More work needed on BOP components and catalyst

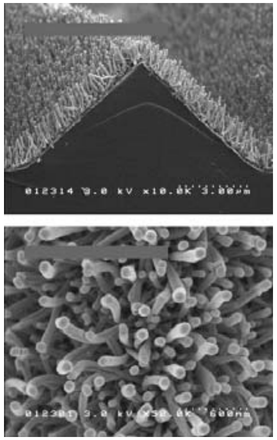
From 2007 to 2008, key cost reductions were made by:

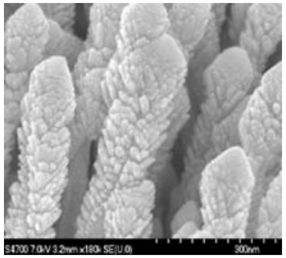
- ***Reducing platinum group metal content from 0.6 to 0.35 g/kW***
- ***Increasing power density from 583 to 715 mW/cm^2***

→ These advances resulted in a $12.40/kW cost reduction.

→

Key Improvements enabled by using novel organic crystalline whisker catalyst supports and Pt-alloy whiskerettes
~ 5 billion whiskers/cm^2
Whiskers are ~ 25 X 50 X 1000 nm





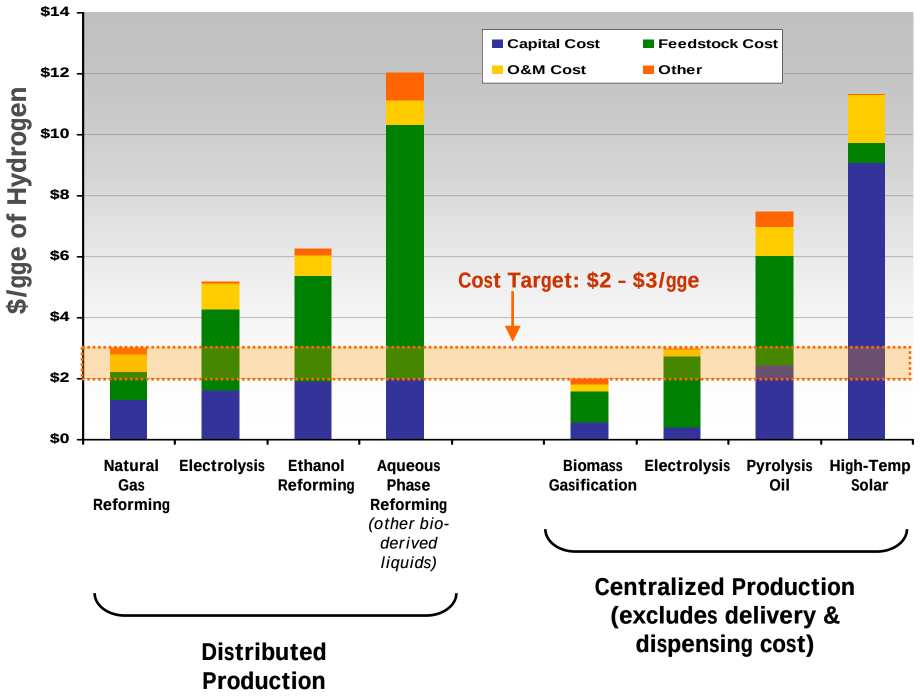
Whiskerettes: 6 nm x 20 nm

- *2008 cost projection validated by an independent panel, which found $60 – 80/kW to be a "valid estimate"*
- *Cost estimates are based on projection to high-volume manufacturing (500,000 units/year); 80 kW PEM fuel cell. Breakdown by DTI, Inc.*

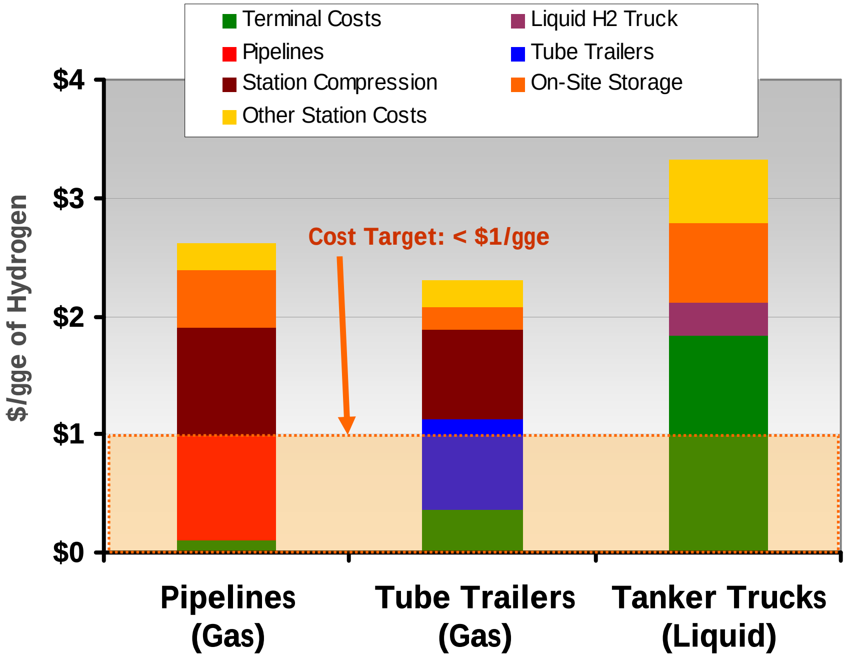
Major Technology Pathways: Status of Hydrogen Production & Delivery Technologies

Currently there are ~9M tons of H_2 produced in the U.S. each year and ~1200 miles of pipelines.

Modeled High-volume Cost of Major Hydrogen Production Pathways



Modeled High-volume Cost of Major Hydrogen Delivery Pathways



Key Assumptions:

- Distributed pathways: 500 units/year and station capacity of 1500 kg/day
- Central Biomass: ~150,000 kg/day, 90% operating capacity
- Central Electrolysis: ~ 50,000 kg/day, 98% operating capacity, $0.045/kWh, $50M depreciable capital cost
- Pyrolysis oil: 1,500 kg/day, mixture of pyrolysis oil and methanol cost ~$0.34/kg mixture
- Solar thermochemical: 100,000 kg/day, 70% operating capacity (uses thermal and chemical storage to overcome diurnal limitations to get to 70%)

Current Low-volume Costs (e.g., 10 kg/day, single-station): > $30/gge →

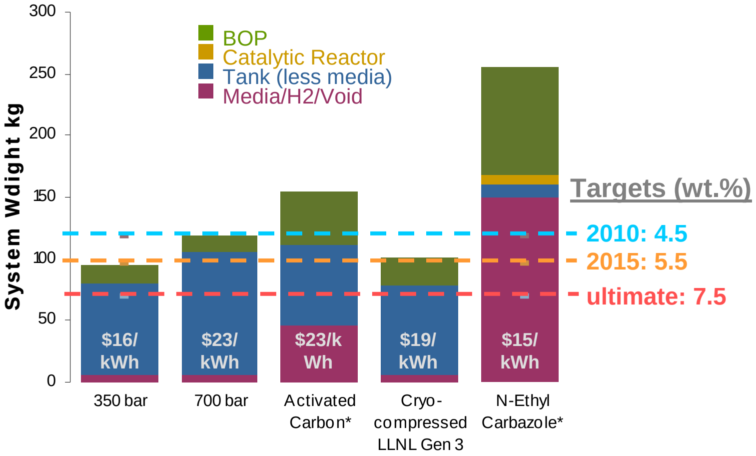
Key Assumptions:

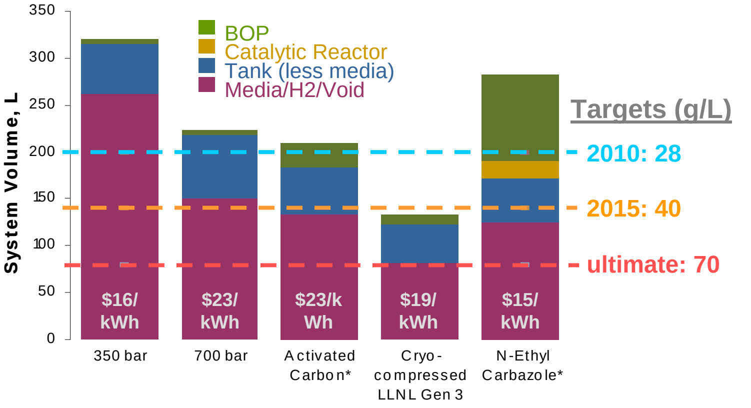
- Scenarios assume current technology with potential 2030 market penetration of 25%
- H_2 is delivered 62 miles, from production plant to Los Angeles
- Stations dispense 1000 kg/day at 350 bar

New concept under development: Tri-generation - produces heat, power and H_2 (if required) using high T fuel cell. Can potentially reduce cost to ~ $5/gge & help address infrastructure.

Major Technology Pathways: Status of H_2 Storage Technologies

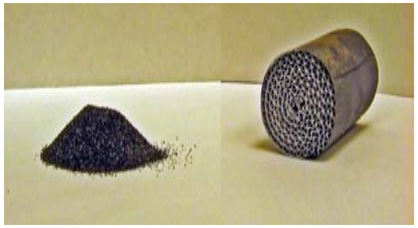
High pressure tanks can already enable > 400 mile range on some vehicles. Costs must be reduced from \$16-\$23/kWh to \$2-\$4/kWh. But higher capacity is required for full range of light duty vehicle platforms.



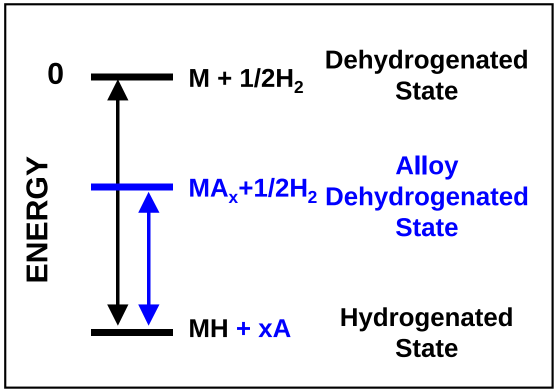


Notes for bar graphs:
Assumptions: High pressure tanks are carbon fiber
5.6 kg chosen to meet ~350 mile driving range (gasoline tank equivalent ~50 L)
**Selected examples based on modeling of materials*

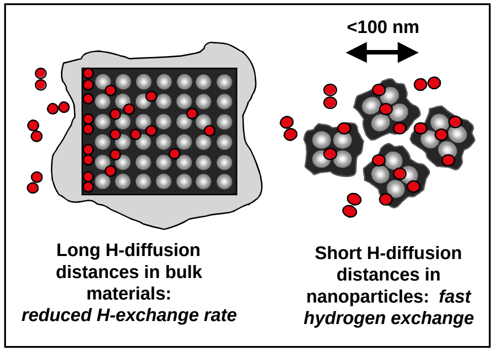
Goal is to replace high-P tanks with solid-state storage. →
Status: 2- 5 wt% & 20-50 g/L vs. goal of 7.5 wt% (=2.5 kWh/kg, 9 MJ/kg) and 70 g/L (=2.3 kWh/L, 8.3 MJ/L)



Strategies include advanced metal hydrides, sorbents and chemical hydrides. Focus is to tailor materials to optimize thermodynamics and kinetics



Intermediate dehydrogenated state enables lower thermodynamics. For example, desorption enthalpies for $LiBH_4$ and MgH_2 are lowered from 67 and 75 kJ/mol H_2 respectively to 40.5 kJ/mol H_2 when coupled to form MgB_2.



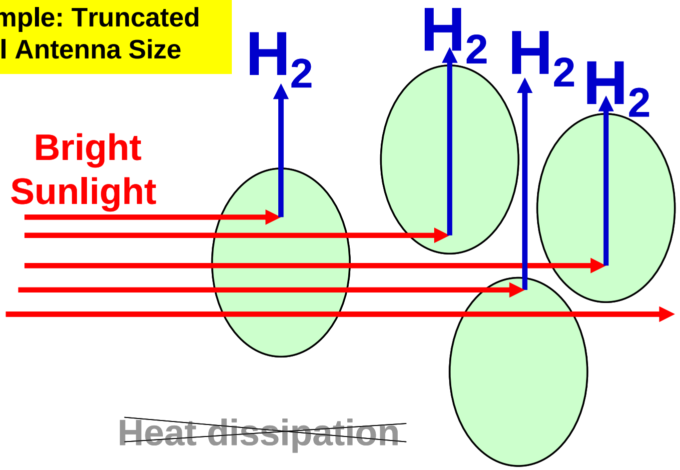
Nanostructured scaffolds enabled 60X increase in H_2 kinetics- approaching targets but T> 300 C

Potential Game-Changing Breakthroughs — *Examples*

H_2 Production: ***Highly Efficient Production using Microalgae***

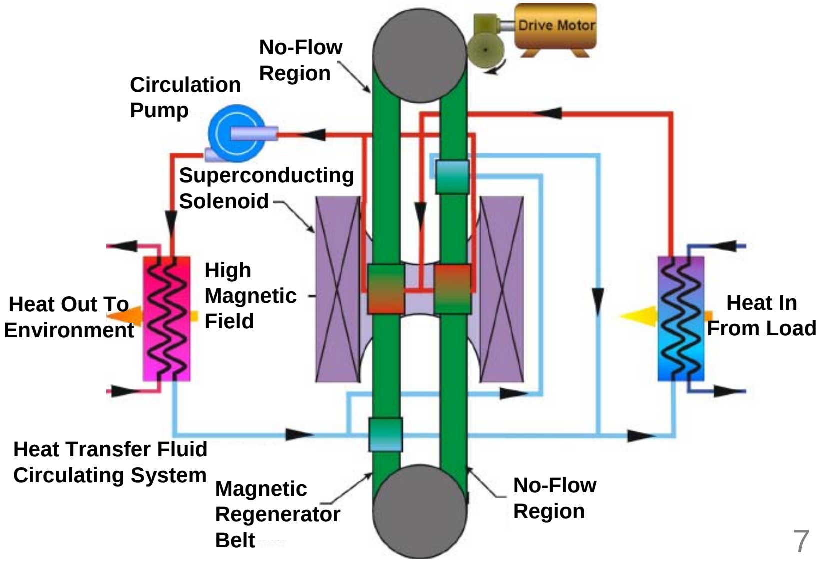
- UC Berkeley cloned the previously reported Tla2 gene, which:
  - Enables a 15% solar-to-chemical energy conversion efficiency in microalgae.
  - Brings the effort midway from the 3% solar-to-chemical energy conversion efficiency in wild type microalgae, to the 30% theoretical maximum of photosynthesis.
  - Can also apply to bio-fuel production.
  - Requires more genetic engineering and cost reduction.

Example: Truncated Chl Antenna Size



H_2 Delivery: ***Low-Cost, Highly Efficient Hydrogen Delivery***

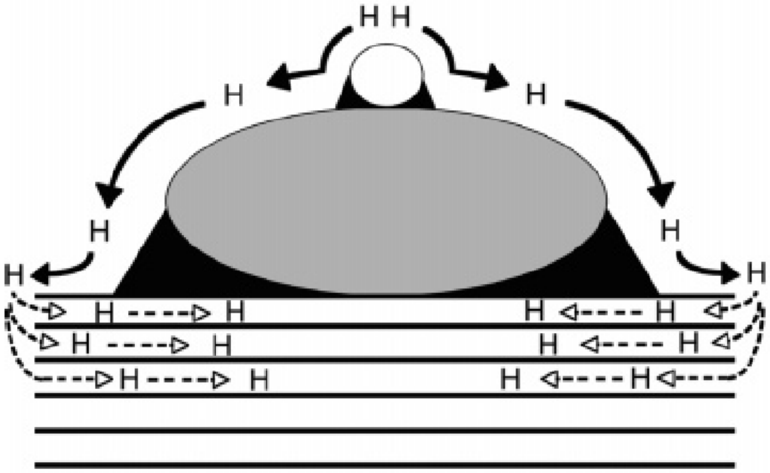
- Active magnetic regenerative liquefaction (AMRL), coupled with cryogenic pumps.
  - AMRL demagnetization step can be 95% efficient, compared to a 20% – 80% efficient expansion step in mechanical refrigeration, reducing liquefaction energy from 12 kWh to 8 kWh.
  - Cryogenic pumps reduce forecourt operation and maintenance costs by 50 – 70% compared to chillers and compressors.
  - Requires further reductions in cost and energy penalty.



Potential Game-Changing Breakthroughs — *Examples*

H_2 Storage: ***Materials for Storage at Low Pressures & Near Room Temperature***

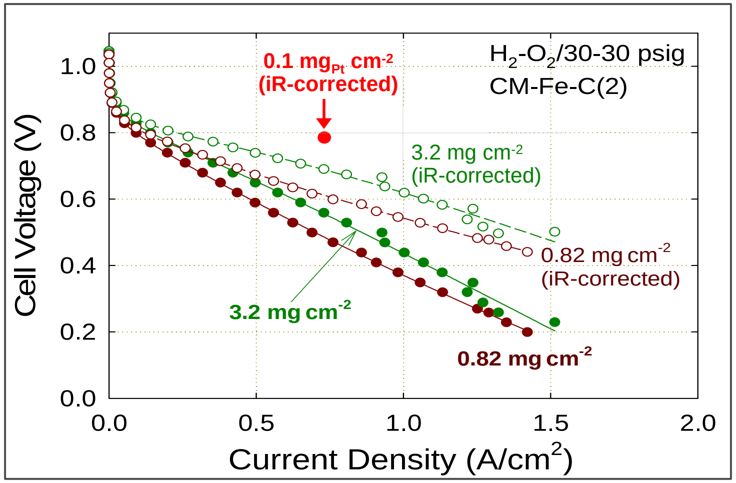
- Engineered high capacity storage materials, using surface and materials modifications:
  - Improved uptake rates by 5X and increased capacity by 20% (up to 3 wt% at near-ambient temperatures) for adsorption spillover materials.
  - Increased uptake/release kinetics in engineered nanostructured materials by 60X.
  - Require further optimization of structures and thermodynamics for high capacity storage and uptake/release of H_2 near room temperature.



Fuel Cells: ***No Major Breakthrough Needed ...***

Ultra-low and Non–Platinum Group Metal Catalysts will Further Reduce Cost

- LANL has increased non-Platinum Group Metal (PGM) catalyst activity by 62x with cyanamide-iron-based catalyst.
  - Demonstrated volumetric activity with the potential to exceed both 2010 and 2015 targets for non-PGM catalyst activity.
  - Non-PGM catalysts would eliminate Pt from the cathode, which is currently 10% – 20% of the estimated fuel cell cost.
  - Requires durability improvements.
  - Must be demonstrated under more realistic operating conditions.



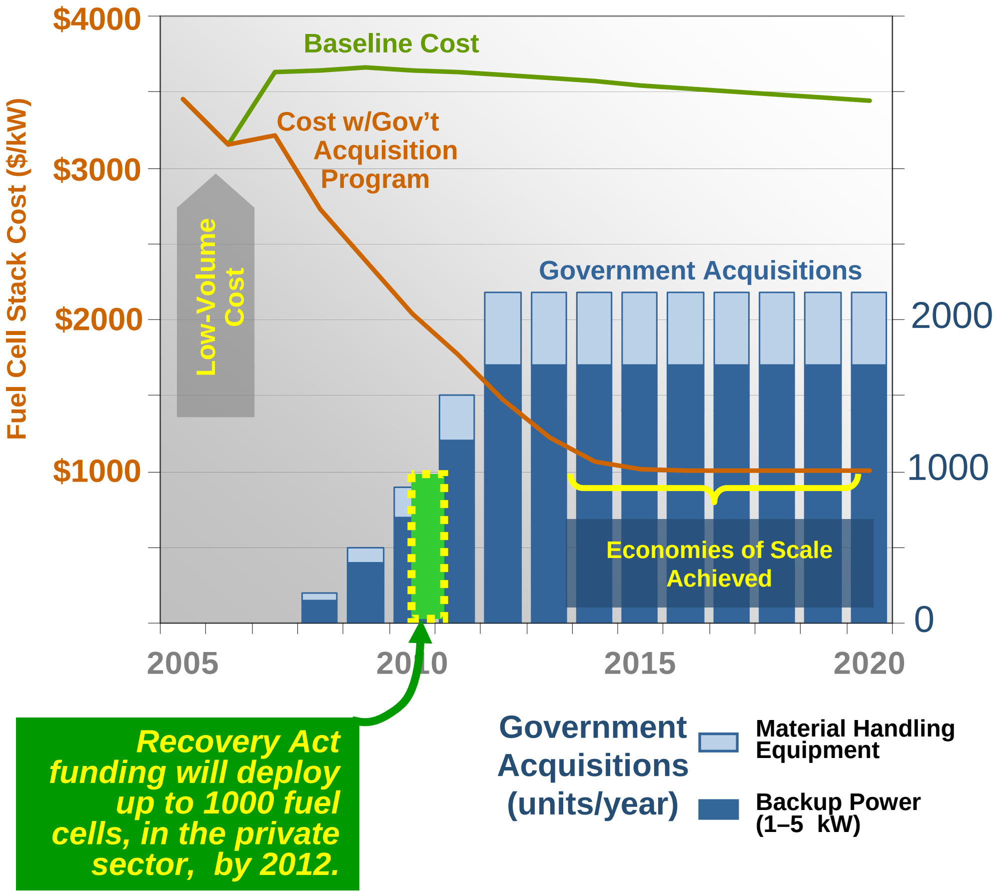
Market Transformation activities seek to overcome barriers to commercialization

	BARRIERS
Market/Industry	Lack of domestic supply base and high volume manufacturing. Estimated backlog > 100 MW
	Low-volume capital cost is >2-3x of targets
	Policies — e.g., many early adopters not eligible for $3,000/kW tax credit
Delivery Infrastructure	Significant investment needed—~$55B gov't funding required over 15 years for ~5.5M vehicles ($~10B for stations)*
Codes and Standards	Complicated permitting process. 44,000 jurisdictions
	H_2-specific codes needed; only 60% of component standards specified in NFPA codes and standards are complete
	Need for domestic and international consistency
Education	>7,000 teachers trained; online tools average 300-500 visits/month, but negative public perception and safety concerns remain.

*2008 National Academies Study, *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen*

ADDRESSING BARRIERS—Example:

A government acquisition program could have a significant impact on fuel cell stack costs

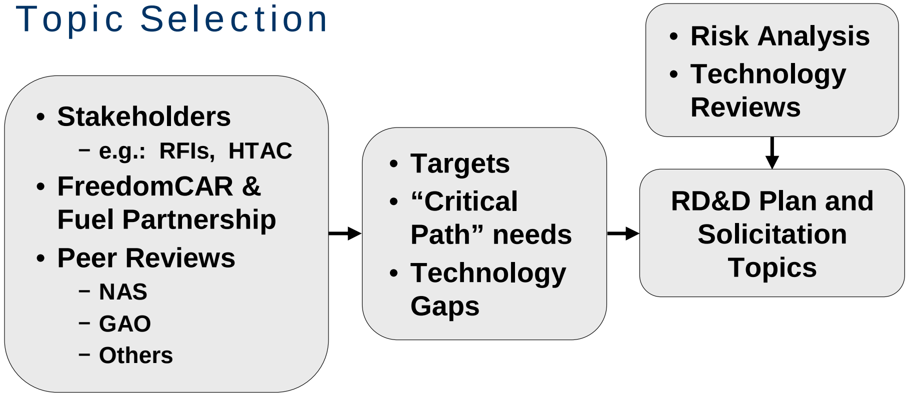


Recovery Act funding will deploy up to 1000 fuel cells, in the private sector, by 2012.

Source: David Greene, ORNL; K.G. Duleep, Energy and Environmental Analysis, Inc., *Bootstrapping a Sustainable North American PEM Fuel Cell Industry: Could a Federal Acquisition Program Make a Difference?*, 2008.

Methodology – Includes competitive review processes, peer reviews & risk analyses

Topic Selection



- **Stakeholders**
  - **e.g.: RFIs, HTAC**
- **FreedomCAR & Fuel Partnership**
- **Peer Reviews**
  - **NAS**
  - **GAO**
  - **Others**

- **Targets**
- **"Critical Path" needs**
- **Technology Gaps**

- **Risk Analysis**
- **Technology Reviews**

RD&D Plan and Solicitation Topics

Project & Program Review Processes

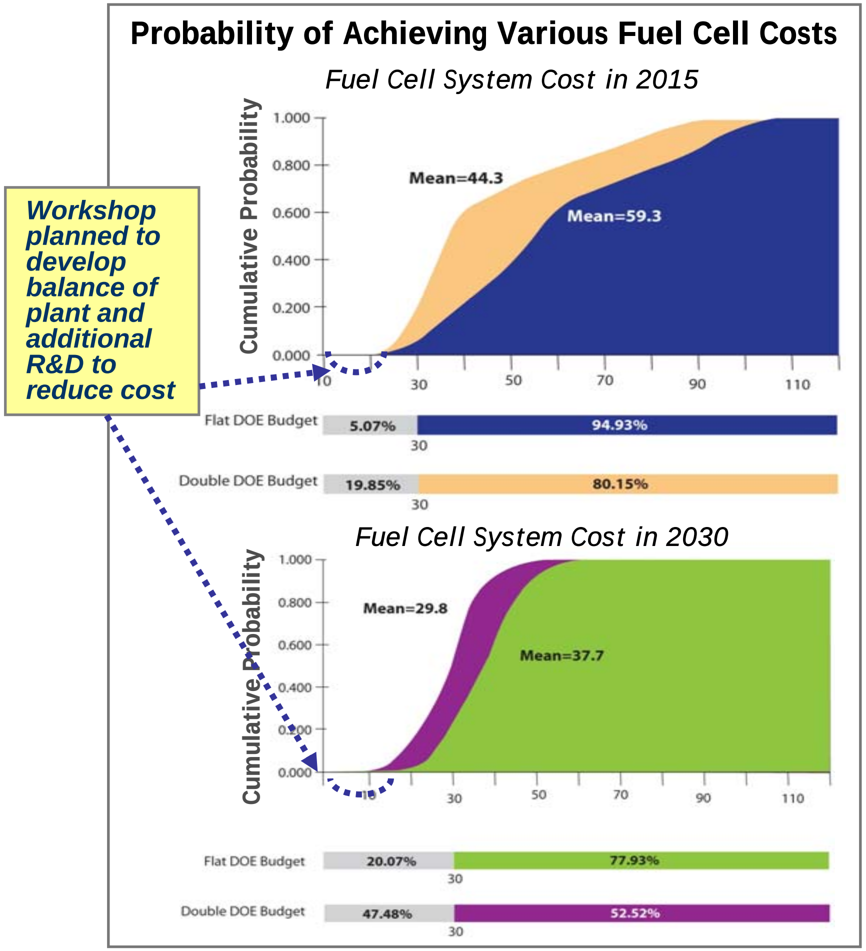
- **Annual Merit Review & Peer Evaluation meetings (EE, NE, FE, SC)**
- **FreedomCAR & Fuel Partnership Tech Team reviews (monthly)**
- **Other peer reviews- National Academies, GAO, etc.**
- **DOE quarterly reviews and progress reports**

Project Number	Project Title *PI Name & Organization*	Final Score	Continue	Discontinue	Other	Summary Comment
123	Fluoroalkyl-Phosphonic-Acid-Based Proton Conductors *Xxx University*	2.7		X		Progress was made in molecular dynamics modeling of model compounds, but the membranes synthesized failed in testing and did not meet the conductivity targets. The project will not be continued.

Reviewer comments for projects posted online annually. Projects discontinued/ work scope altered based on performance & likelihood of meeting goals.

Example: Risk Analysis with independent expert input helps Program estimate probabilities of achieving targets under different budget and schedule scenarios.

Probability →	10%	50%	90%
2015	$27	$44	$76
2030	$19	$30	$39



Probability of Achieving Various Fuel Cell Costs

Fuel Cell System Cost in 2015

Fuel Cell System Cost in 2030

Workshop planned to develop balance of plant and additional R&D to reduce cost

Collaborations

Federal Agencies

- DOC
- DOD
- DOEd
- 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 the Hydrogen Economy –
  16 countries
  30 projects

EERE Fuel Cell Technologies Program

- ***Applied RD&D***
- ***Efforts to Overcome Non-Technical Barriers***
- ***Internal Collaboration with FE, NE, BES***

Industry Partnerships & Stakeholder Assn's.

- FreedomCAR and Fuel Partnership
- National Hydrogen Association
- U. S. Fuel Cell Council
- 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

NREL ($23M)
P&D, S, FC, A, SC&S, TV

ANL ($15M)
A, FC, P&D

LANL ($15M)
S, FC, SC&S

SNL ($8M)
P&D, S, SC&S

PNNL ($7M)
P&D, S, FC, A

BNL ($3M)
S, FC

LLNL ($4M)
P&D, S

ORNL ($6M)
P&D, S, FC, A

SRNL ($4M)
S, P&D

LBNL ($4M)
FC, A

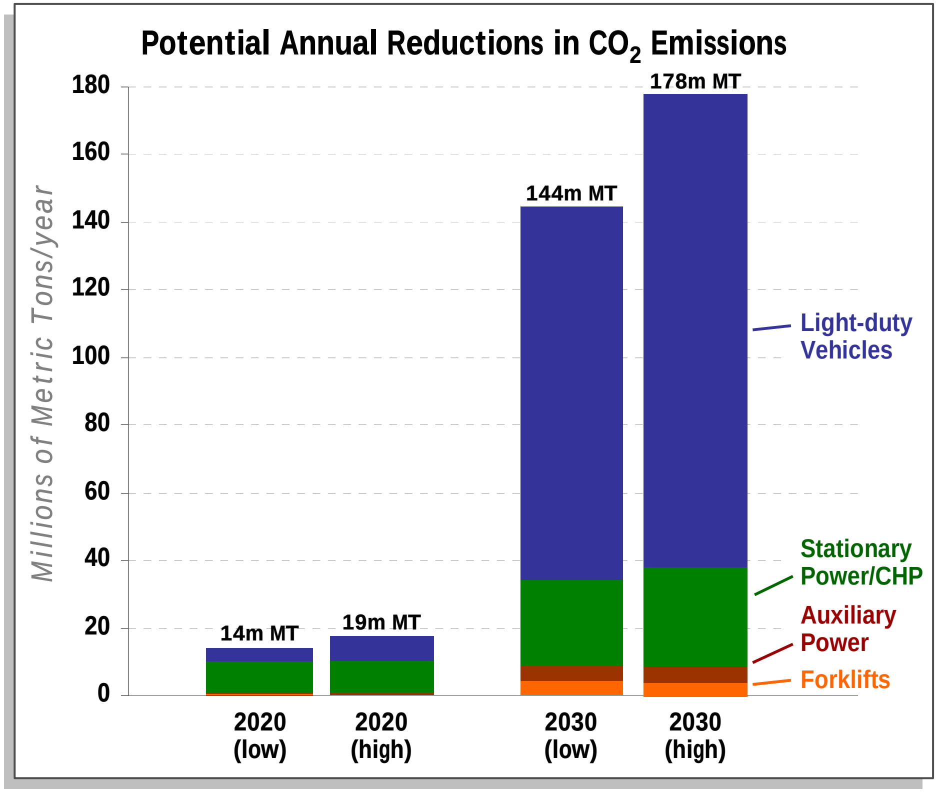
Other Labs

- JPL
- NIST
- NETL
- INL

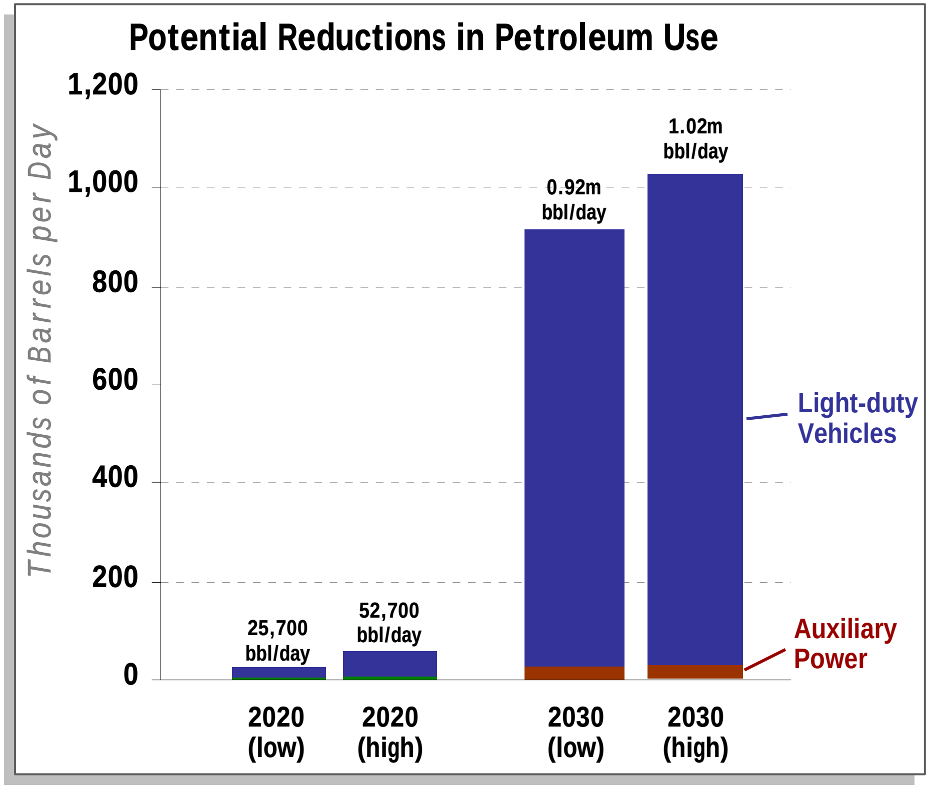
P&D = Production & Delivery; S = Storage; FC = Fuel Cells; A = Analysis; SC&S = Safety, Codes & Standards; TV = Technology Validation

Estimated Potential Impacts — *for Reducing GHG Emissions & Petroleum Use*

As the Program continues to broaden its portfolio beyond automotive applications, market penetration and benefits analyses for diverse applications will be developed and refined.



Potential Annual Reductions in CO_2 Emissions



Potential Reductions in Petroleum Use

Assumptions

Forklifts: 2020 Market Share = 12% or 36,000 units; 2030 Market Share = 85% or 300,000 units

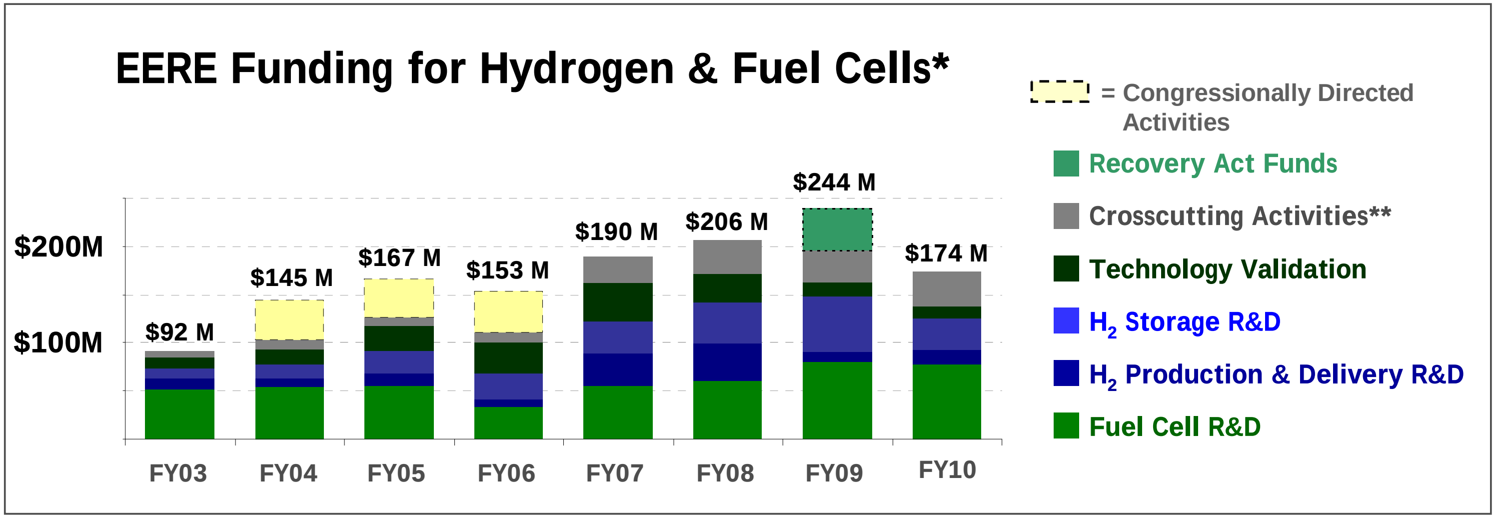
Auxiliary Power: 2020 Market Share = 10% of long-haul trucks; 2030 Market Share = 100% of long-haul trucks

Stationary Power/CHP: 2020 Market Share = 0.4% of U.S. Electricity; 2030 Market Share = 0.8 – 1% of U.S. Electricity

Light-duty Vehicles: 2020 Market Share = 0.7 – 1.5 million vehicles; 2030 Market Share = 25 – 30 million vehicles. (Light-duty vehicle assumptions are derived from a scenario in the 2008 National Academies report, *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen.)*

Budget

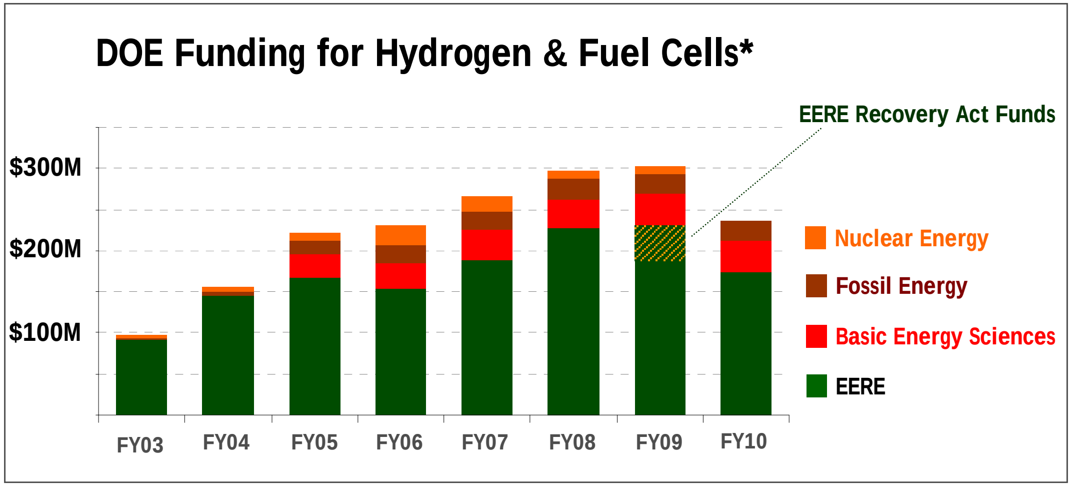
Program activities are an integrated, comprehensive effort addressing the full range of technical, institutional, and economic barriers.



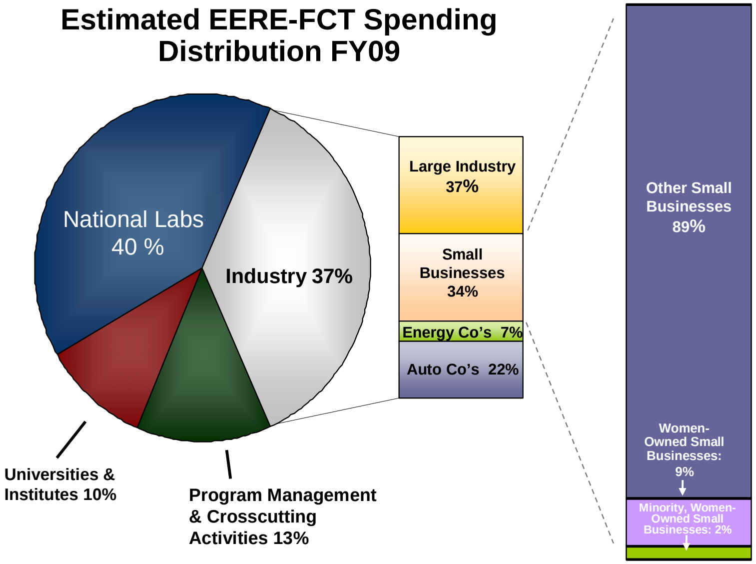
EERE Funding for Hydrogen & Fuel Cells*

* Budget numbers have been updated to include FY 2010 appropriations.

**Crosscutting activities include Safety, Codes & Standards, Education, Systems Analysis, Manufacturing R&D, and Market Transformation.



DOE Funding for Hydrogen & Fuel Cells*



Estimated EERE-FCT Spending Distribution FY09