FUEL CELL TECHNOLOGIES PROGRAM

Transportation Research Board

International Transport Energy Subcommittee Meeting

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

Hydrogen and Fuel Cell Overview

Washington DC

1/23/2012

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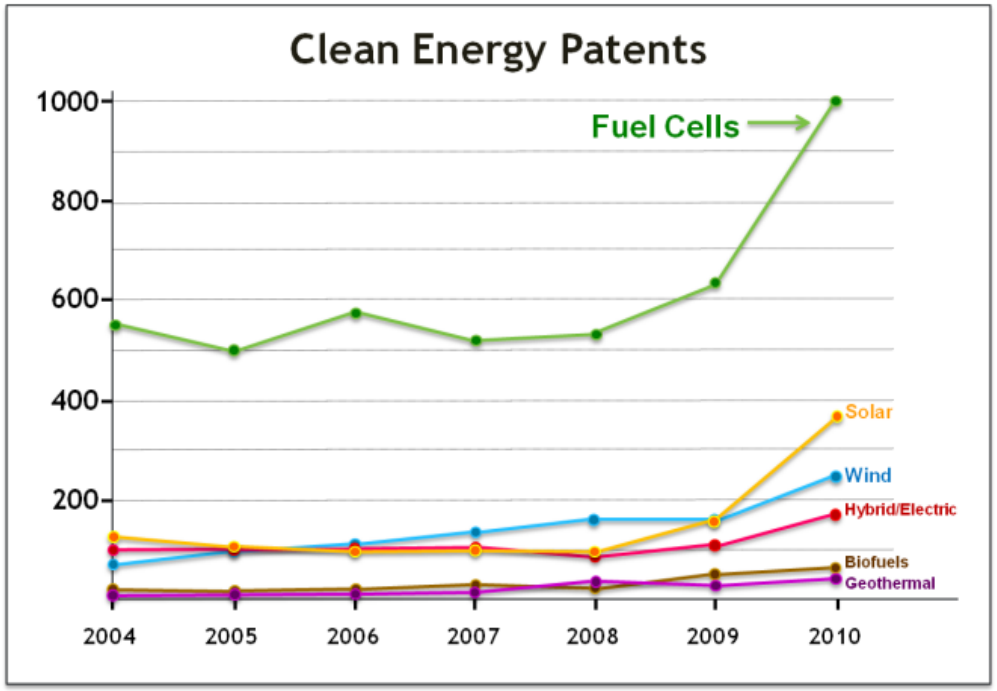
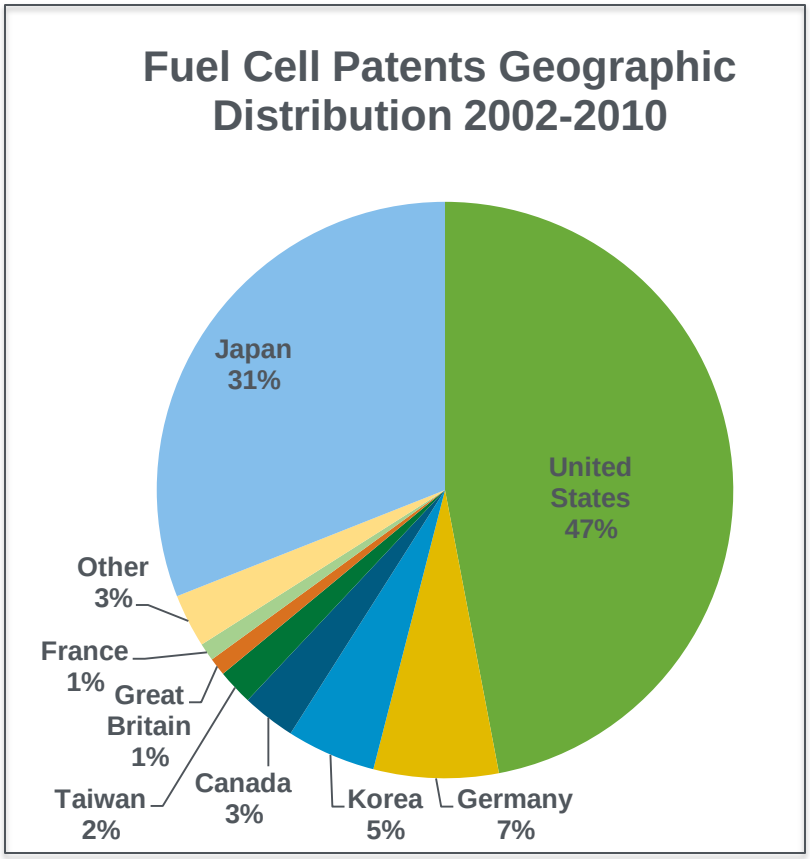
U.S. Department of Energy

Fuel Cell Technologies Program

Program Manager

Overview
Fuel Cells – An Emerging Industry





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

Clean Energy Patent Growth Index[1] shows that fuel cell patents lead in the clean energy field with nearly 1,000 fuel cell patents issued worldwide in 2010.

- 3x more than the second place holder, solar, which has just ~360 patents.
- Number of fuel cell patents grew > 57% in 2010.

[1} 2010 Year in Review from http://cepgi.typepad.com/heslin_rothenberg_farley_/

Worldwide Investment & Interest Are *Strong and Growing*

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

Activity by Key Global Players

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

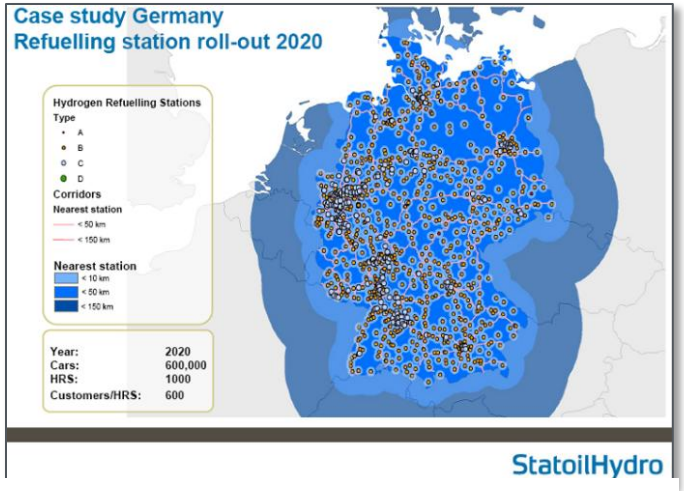
Japan: ~$1.0 Billion in funding ('08 – '12); plans for 2 million FCEVs and 1000 H2 stations by 2025; 100 stations by 2015; 15,000 residential fuel cells deployed

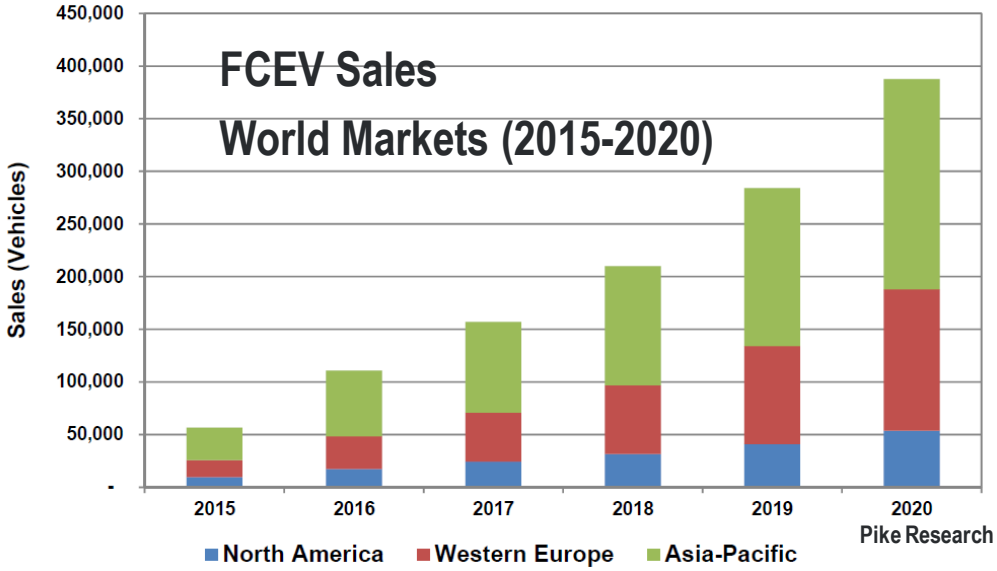
European Union: >$1.2 Billion in funding ('08–'13)

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

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

Germany and Japan have formed industry led consortia to enable 1,000 stations (each)





Worldwide Commitment to FCEVs

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The world's leading automakers have committed to develop FCEVs. Germany and Japan have announced plans to expand the hydrogen infrastructure.

Major Auto Manufacturers' Activities and Plans for FCEVs

Toyota
- 2010-2013: U.S. demo fleet of 100 vehicles
- 2015: Target for large-scale commercialization
- "FCHV-adv" has achieved 431-mile range and 68 mpgge

Honda
- Clarity FCX named "World Green Car of the Year"; EPA certified 72mpgge; leasing up to 200 vehicles
- 2015: Target for large-scale commercialization

Daimler
- Small-series production of FCEVs began in 2009
- Plans for tens of thousands of FCEVs per year in 2015 – 2017 and hundreds of thousands a few years after
- In partnership with Linde to develop fueling stations.
- ***Recently moved up commercialization plans to 2014***

General Motors
- 115 vehicles in demonstration fleet
- 2012: Technology readiness goal for FC powertrain
- 2015: Target for commercialization

Hyundai-Kia
- 2012-2013: 2000 FCEVs/year
- 2015: 10,000 FCEVs/year
- "Borrego" FCEV has achieved >340-mile range.

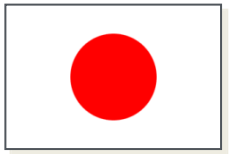
Volkswagen
- Expanded demo fleet to 24 FCEVs in CA
- Recently reconfirmed commitment to FCEVs

SAIC (China)
- Partnering with GM to build 10 fuel cell vehicles in 2010

Ford
- Alan Mulally, CEO, sees 2015 as the date that fuel cell cars will go on sale.

BMW
- BMW and GM plan to collaborate on the development of fuel cell technology

H_2Mobility will evaluate the commercialization of H_2 infrastructure and FCEVs
- **Public-private partnership between NOW and 10 industry stakeholders (OEM, oil, gas)**
- **FCEV commercialization by 2015.**



13 companies (OEMS, energy & infrastructure providers) and Ministry of Transport announce plan to commercialize FCEVs by 2015
- **100 HRS in 4 metropolitan areas and connecting highways planned, 1,000 HRS in 2020, and 5,000 HRS in 2030.**

UKH_2Mobility will evaluate anticipated FCEV roll-out in 2014/2015
- **13 industry partners and 3 UK government departments.**
- **Government investment of £400 million to support development, demonstration, and deployment.**

"Green Car Roadmap" for advanced powertrains
- **Plans for 168 HRS and 100,000 FCEVS by 2020**
- **Incentives for FCEVs to be defined but should be comparable to EVs (rebates, tax exemptions, and bonus/malus)**

Progress – Fuel Cells

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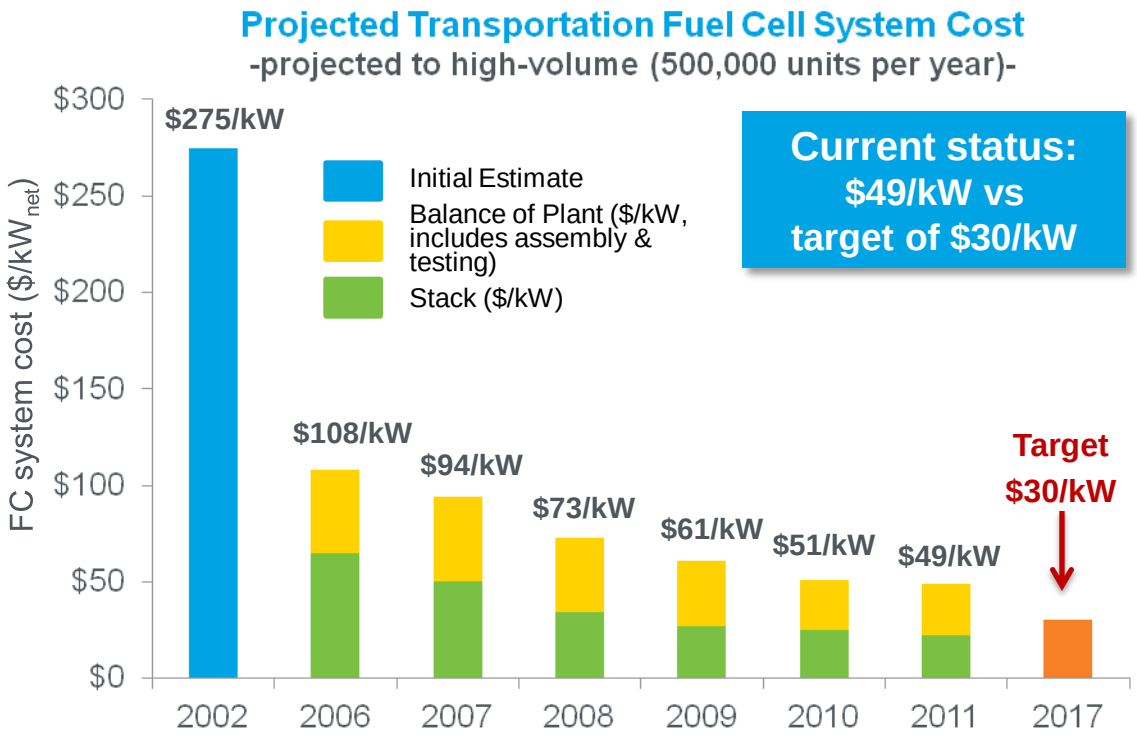
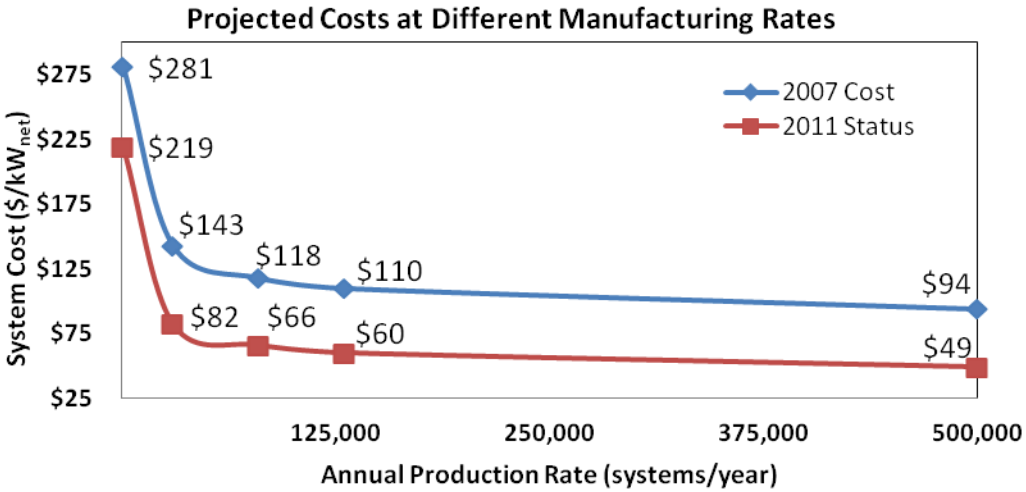
Projected high-volume cost of fuel cells has been reduced to $49/kW (2011)*

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





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

Progress—Hydrogen Production and Delivery

Significant progress has been made toward achieving hydrogen cost goals—*the cost at which hydrogen fuel cell electric vehicles are projected to become competitive on a cost-per-mile basis with competing vehicles (gasoline hybrid-electric vehicles) in 2020.*

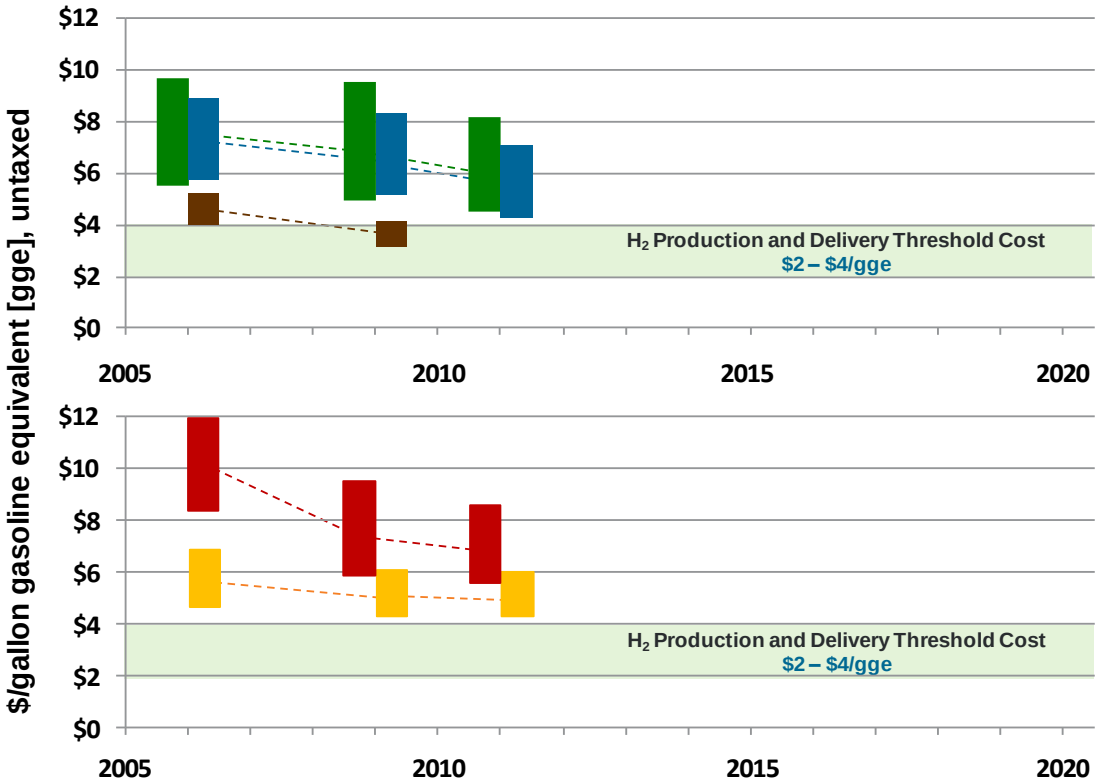
Projected High-Volume Cost of Hydrogen[i] —Status

Distributed Production (near-term)

- **Electrolysis**
  Feedstock variability: $0.03 – $0.08 per kWh
- **Bio-Derived Liquids**
  Feedstock variability: $1 – $3 per gallon ethanol
- **Natural Gas Reforming[ii]**
  Feedstock variability: $4 – $10 per MMBtu

Central Production (longer-term)

- **Electrolysis**
  Feedstock variability: $0.03 – $0.08 per kWh
- **Biomass Gasification**
  Feedstock variability: $40 – $120 per dry short ton



Notes:

(i) *Costs shown include all delivery and dispensing costs, but do not include taxes. A cost of $1.80 for forecourt compression, storage, and dispensing is included for distributed technologies, and $2.60 is included as the total cost of delivery (including transportation, compression, storage, and dispensing) for centralized technologies. All delivery costs are based on the Hydrogen Pathways Technical Report (NREL, 2009). Projections of distributed costs assume station capacities of 1,500 kg/day, with 500 stations built per year. Projections of centralized production costs assume capacities of ≥50,000 kg/day. Cost ranges for each pathway are shown in 2007 dollars, based on high-volume projections from H2A analyses, reflecting variability in major feedstock pricing and a bounded range for capital cost estimates.*

(ii) *DOE funding of natural gas reforming projects was completed in 2009 due to achievement of the threshold cost, based on projections to high-volume production. Incremental improvements will continue to be made by industry.*

Progress – Technology Validation

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DOE-industry demonstrations are validating technologies in integrated systems.

DOE National Learning Demonstration Real-world Validation

Vehicles & Infrastructure

- 170 FCEVs and 25 hydrogen fueling stations
- Over 3.4 million miles traveled
- Over 146 thousand total vehicle hours driven
- 2,500 hours (nearly 75K miles) durability (with 10% degradation)
- 5 minute refueling time (4 kg of hydrogen)
- Vehicle Range: >250 miles
  (vehicle capable of up to 430 mi)

Ford | bp | DAIMLER | GM | Shell | HYUNDAI | KIA | Chevron

Technology Validation—Tri-Generation

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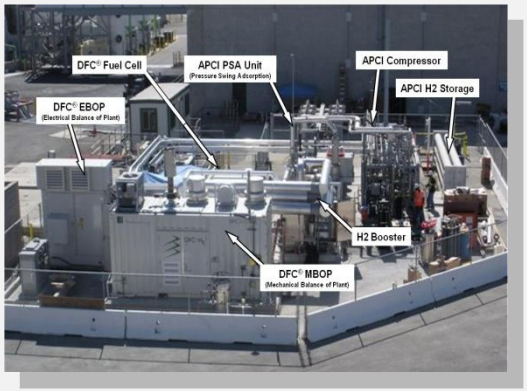
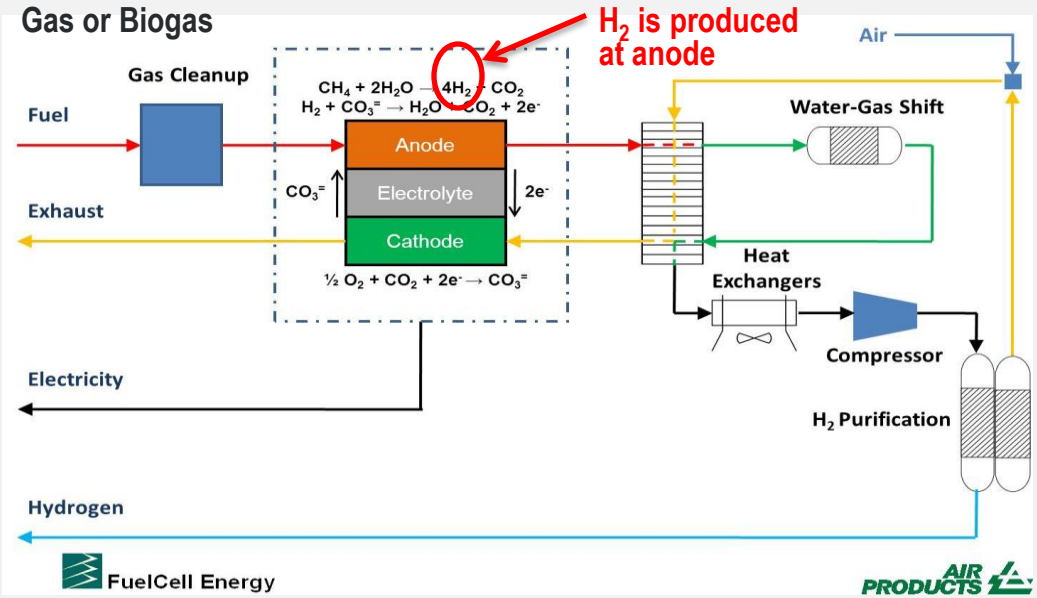
"Energy Department Applauds World's First Fuel Cell and Hydrogen Energy Station in Orange County" (Co-funded by DOE, CA and industry)

Demonstrated world's first Tri-generation station (CHHP with 54% efficiency)

-Anaerobic digestion of municipal wastewater-





Fountain Valley demonstration

- ~250 kW of electricity
- ~100 kg/day hydrogen capacity (350 and 700 bar), enough to fuel 25 to 50 vehicles.

Current Hydrogen Infrastructure

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Current Status

- Over **9 million metrics tons** of hydrogen produced per year
- Over **1,200 miles** of hydrogen pipelines (CA, TX, LA, IL, and IN)
- There are more than **50 fueling stations** in the U.S.

There have been **> 100,000 hydrogen refuelings** in the U.S. — including FCEVs, forklifts, and other applications.

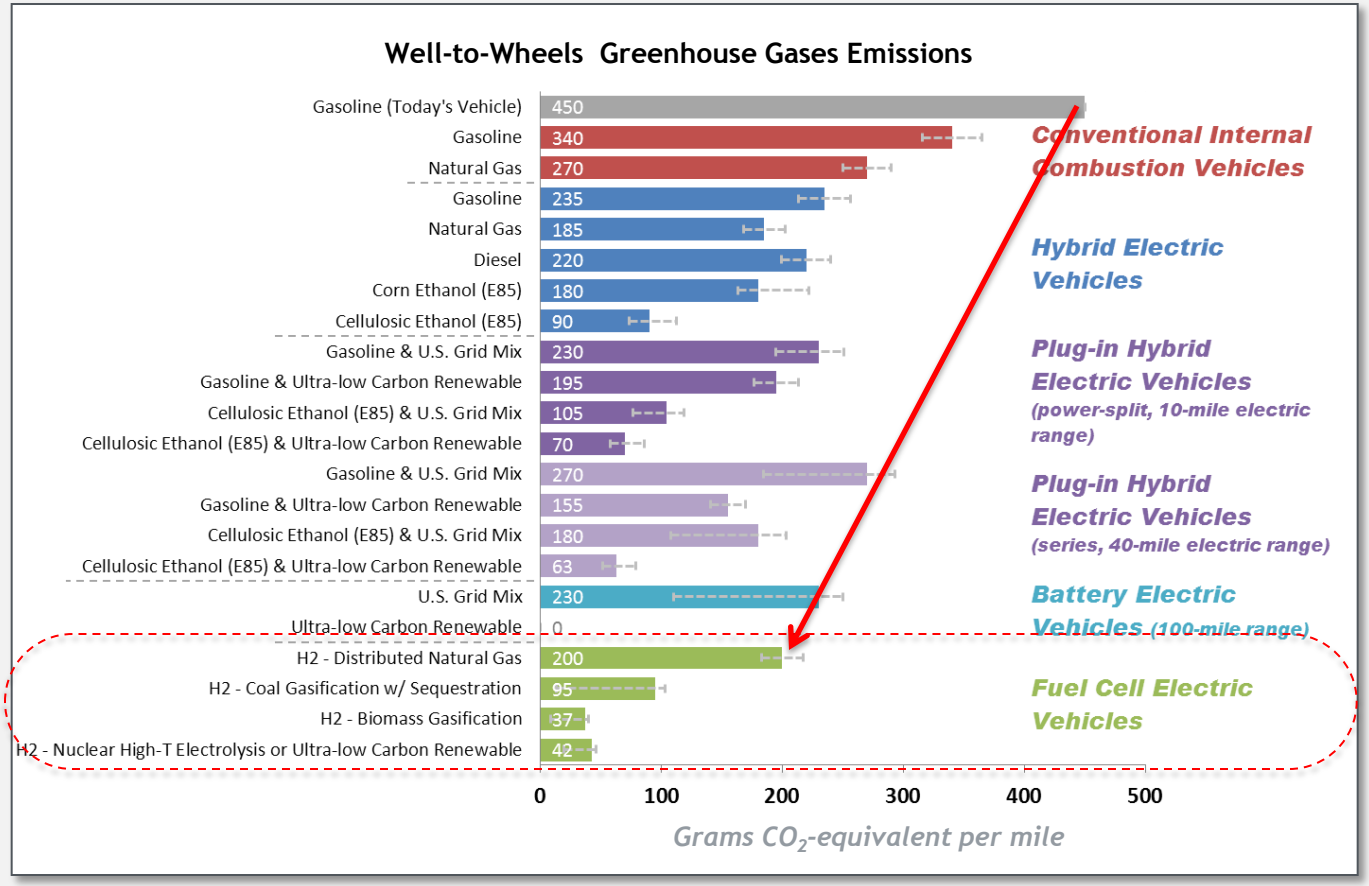
Existing Hydrogen Production Facilities

- ***Significant hydrogen supply infrastructure is already located near most major U.S. cities.***
- **Hydrogen can be delivered from central production facilities to fueling stations by liquid truck, tube trailer or new drop-tank system.**

Portfolio of vehicle technologies shows potential for carbon emissions reductions

Analysis periodically updated by DOE (Fuel Cell and Vehicles Programs) and Argonne National Lab as technologies progress

Environmental Analysis



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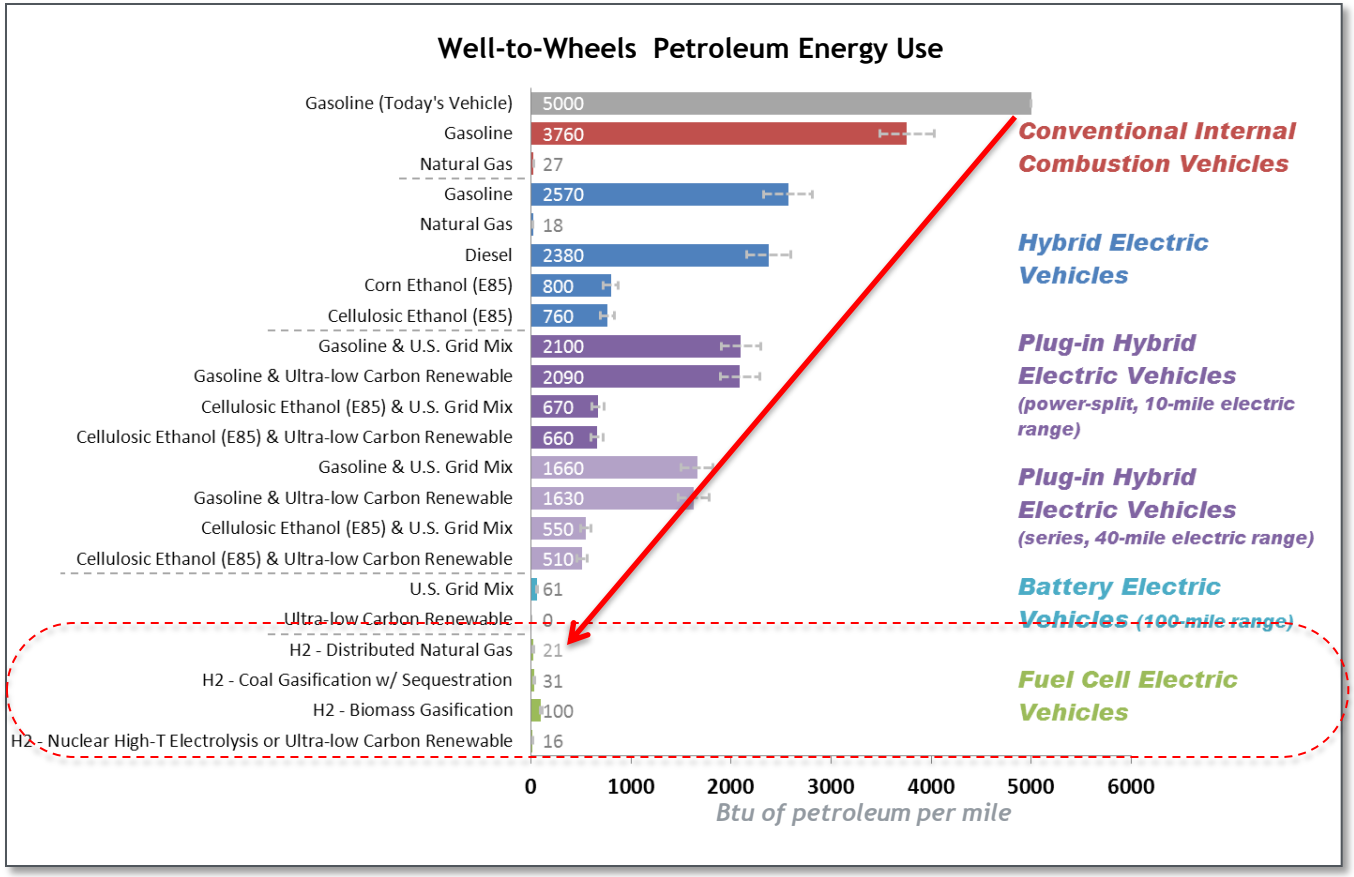
Analysis by Argonne National Lab, DOE Vehicle Technologies Program, and FCT Program shows benefits from a portfolio of options.



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%*

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

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

Long-term Impact with FCEVs

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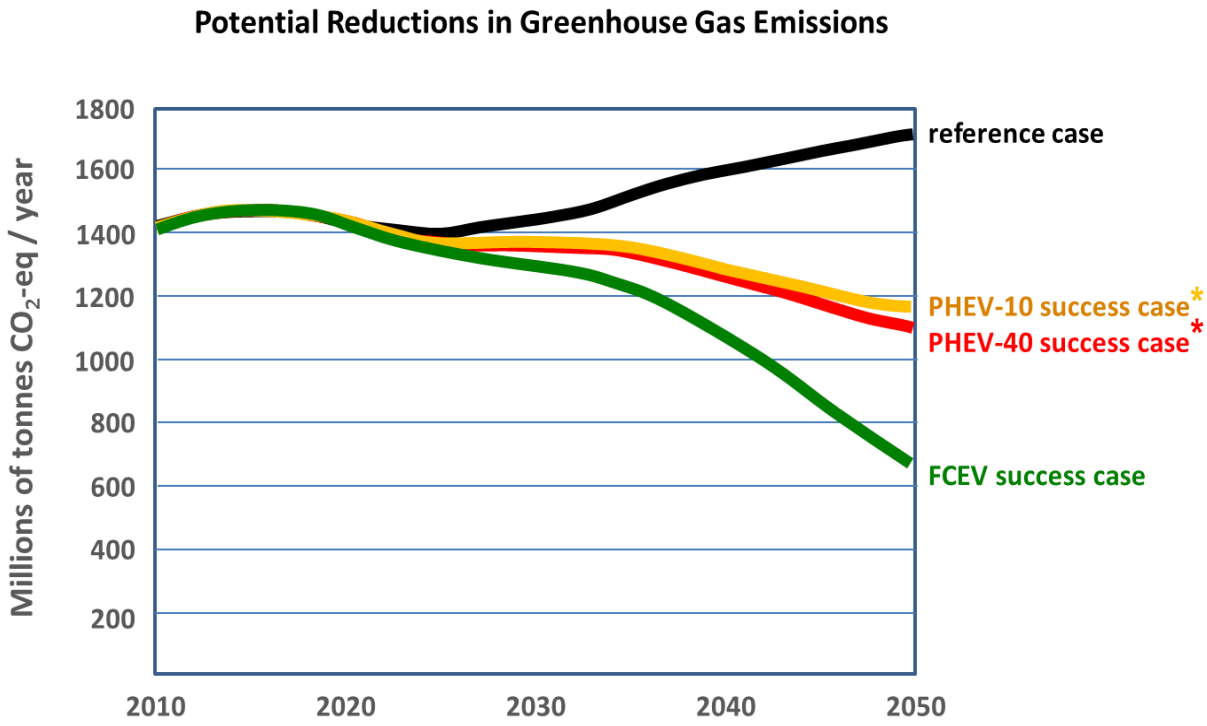
Analysis by National Academies shows that FCEVs would have significant impact in terms of GHG reduction.

Other Analyses/Benefits

- **McKinsey's study of European power-trains** highlights the need for BEVs, PHEVs, and FCEVs, ***with FCEVS being the best solution for longer trip sand mid- to large-size vehicles***—which account for 75% of LDV CO_2 emissions.
- **The IEA's "Blue Map" scenario** for GHG abatement, hydrogen use by LDVs in 2050 would be equivalent to nearly 4 million barrels per day of petroleum.



Adapted from NRC studies: ***Transitions to Alternative Transportation Technologies—a Focus on Hydrogen*** and ***Transitions to Alternative Transportation Technologies—Plug-In Hybrid Electric Vehicles***

*Assumes EIA projections for grid mix.

Vehicle Lifecycle Cost Analysis

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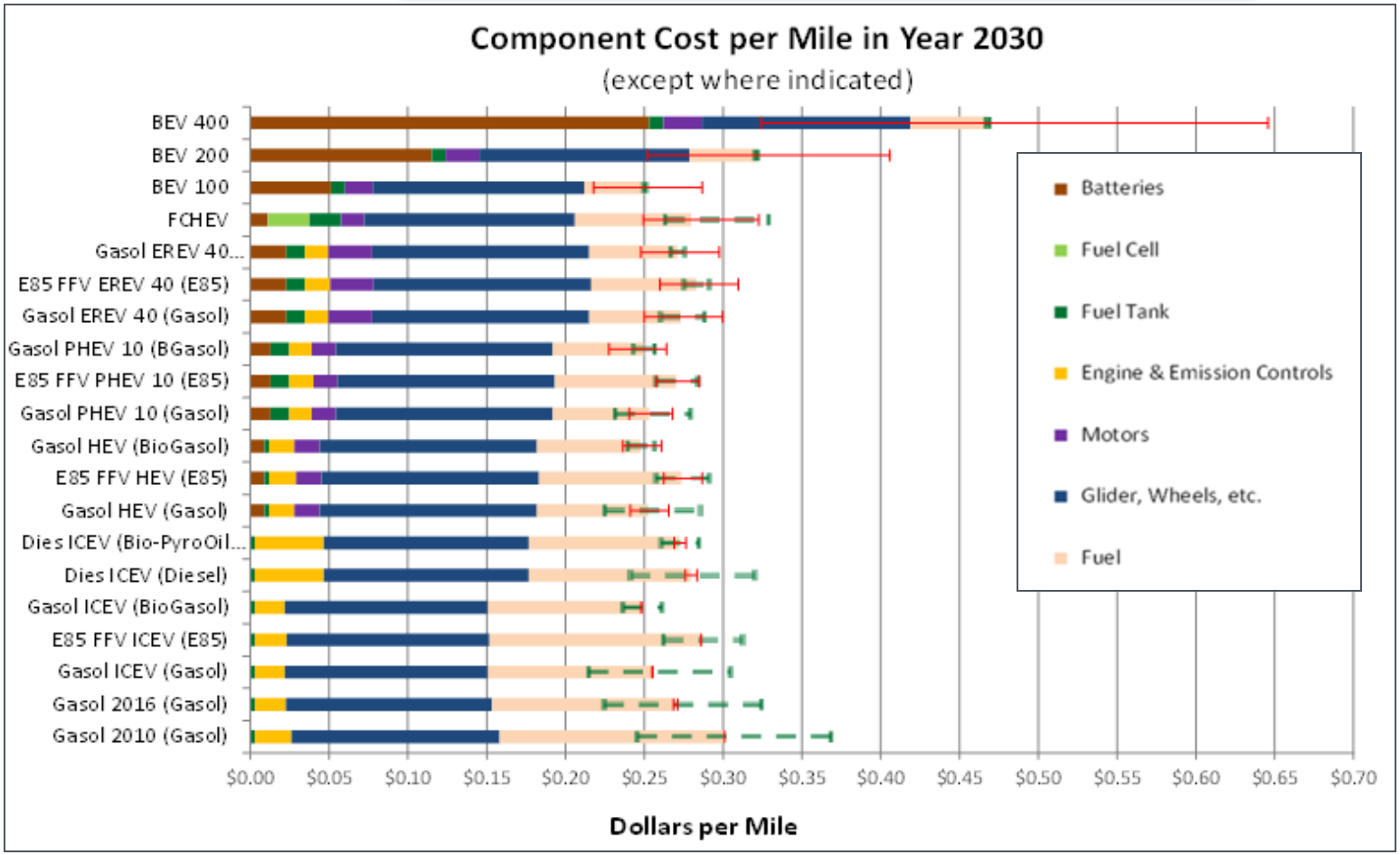
Preliminary DOE analysis (peer-review in process)



'Error bars' reflect range of assumptions:

Green: range of assumptions for fuel prices (EIA projections for fuels other than hydrogen; hydrogen range: $3.50 - $7.50 per kg)

Red: range of assumptions for technology success

See backup for range of assumptions.

Key Assumptions

	Fuel Cell HEV	BEV100 100-mile BEV	BEV200 200-mile BEV	BEV400 400-mile BEV
Battery Cost, $/kWh	$600, $800, $1000	$125, $220, $300		
Fuel Cell Cost, $/kW	$25, $30, $40	--	--	--
Fuel Cost in $/gge (¢/kWh)	$3.50, $4.50, $7.50	$3.44 (10.3¢/kWh); $3.54 (10.6¢/kWh); $3.61 (10.8¢/kWh)		

Hydrogen and Fuel Cell Initiatives at the State Level

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Several states—including California, Connecticut, Hawaii, Ohio, New York, and South Carolina—have major hydrogen and fuel cell programs underway.

California

FCEVs and Fuel Cell Buses

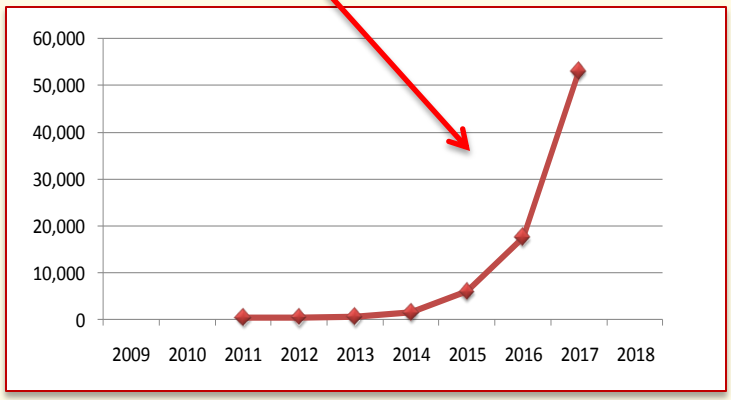
- **> 400 vehicles** in operation since 1999 — >160 currently operating
- **~3.9 million miles** driven
- **> 1 million passengers** on fuel cell buses

Investment in Hydrogen Stations

- **20 stations** — including planned/funded
- **~$34M invested** *(C.A.R.B. and C.E.C.)* — with ~$23M industry cost share
- **~$18M planned** for future solicitations

Industry's Plans for FCEV Sales in CA

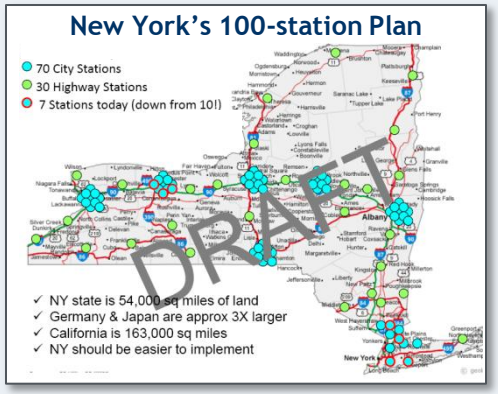
(based on 2010 survey of automakers)



New York

Plans 100 hydrogen stations (70 city, 30 highway) by 2020 to support minimum of 50,000 FCEVs — plan starts in 2015 with 1500 vehicles and 20 stations

- **Industry Investment:** Six auto companies plan total investment of nearly $3.0 Billion
- **State Investment:** NY plans to provide $50M to support infrastructure rollout and $165M to supplement federal subsidies for FCEVs



Hawaii

Agreement signed by 12 stakeholders—including GM, utilities, hydrogen providers, DOD, DOE—to establish hydrogen as a major part of the solution to Hawaii's energy challenges.

- **15 GM FCEVs** currently in demonstrations with military

- **Renewable hydrogen** (from geothermal and wind energy) will be used for buses
- Goals include **20-25 stations** on Oahu by 2015 to support annual sales of up to **5,000 FCEVs** in early years.

Summary

Progress continues in H_2 and FCEVs.
R&D still needed to address remaining challenges: H_2 production, delivery, storage as well as fuel cell cost and durability

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:** $49/kW *(at 500,000 units/year)* **Durability:** 3,700 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 >$10/gge to ~$5/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)

Thank you

For more information:
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www.hydrogen.energy.gov

http://www1.eere.energy.gov/hydrogenandfuelcells/

Additional Information

External Analysis of FCEV Cost vs. Time

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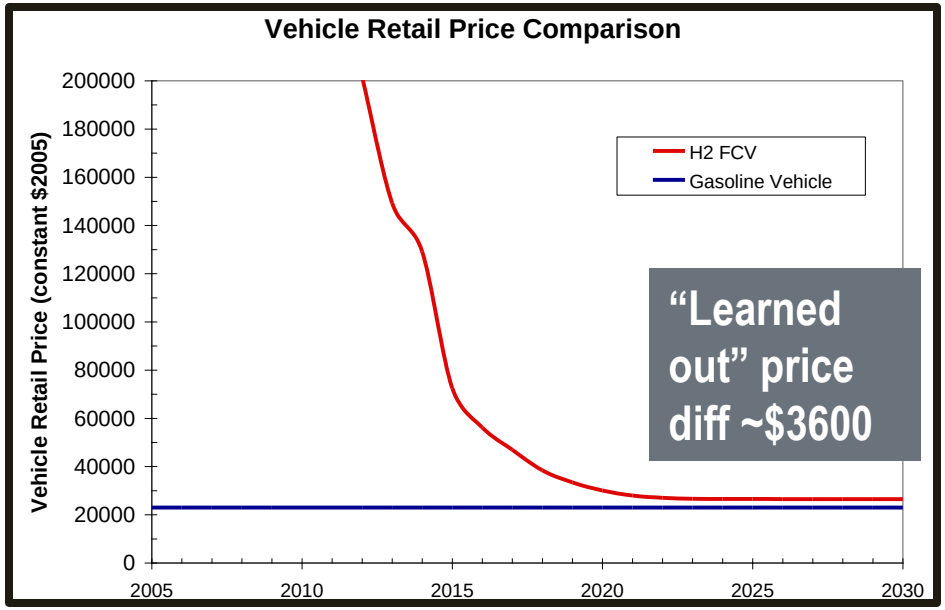

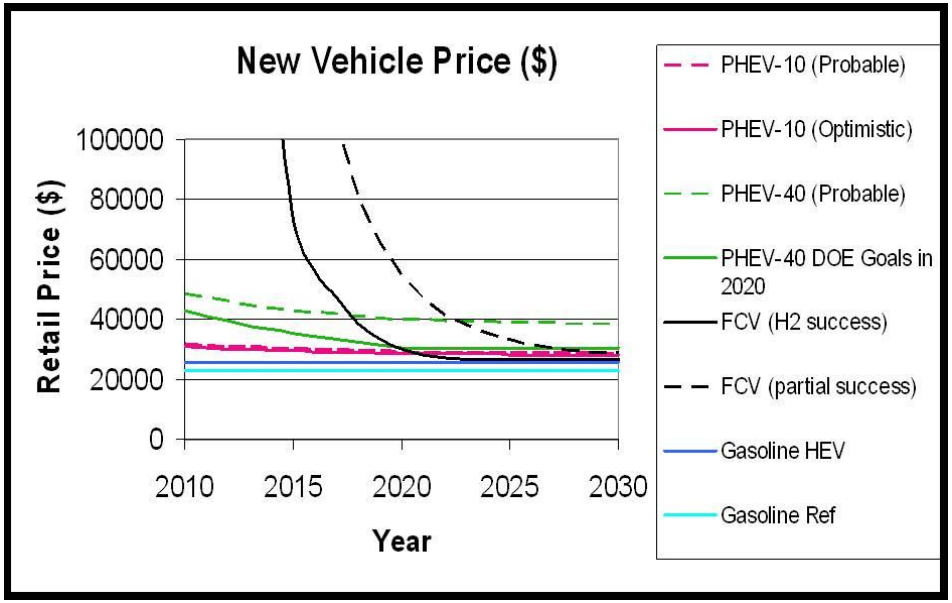

FCEV Vehicle Price curve based on model by Greene, Leiby and Bowman (2007). Price falls due to R&D improvements, cumulative experience and manufacturing scale-up (NRC, UC Davis studies)*

PHEVs start out at lower prices but learned out prices FCEV prices could be lower (NRC, UC Davis studies)*

	Current Gasoline ICEV	2035 Gasoline ICEV	2035 Gasoline HEV	2035 PHEV30	2035 BEV200	2035 FCEV
Car	$19,600	$21,600	$24,100	$27,500	$36,000	$26,900
Light Truck	$21,000	$23,400	$26,600	$31,700	$45,500	$30,800

FCEVs offer cost-competitive technology for cars and light trucks.

http://web.mit.edu/sloan-auto-lab/research/beforeh2/otr2035/
MIT. On The Road in 2035, July 2008

*Source: Prof. J. Ogden, UC Davis, *STEPS Program, presented at the Ford Research and Innovation Center, January 28, 2011*

Recent Argonne Studies on Manufacturing Cost Comparisons

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Technology improvements should lead to significant cost reductions and market penetration. Additional manufacturing cost for advanced powertrains includes a high uncertainty—suggests needs to pursue aggressive research and development.

	Additional manufacturing Cost ($) of Each Powertrain by 2045 compared to Reference 2010 Gasoline Conventional Engine for Compact Cars
Conventional ICE	584-1240
HEV	560-3091
PHEV10	1029-4086
PHEV40	2188-8402
BEV	1446-10649
Fuel Cell	-264-1812

External studies show FCEVs are competitive with other advanced powertrains.

Source: Analysis done for Vehicle Technologies Program by Argonne National Lab. (Light-Duty Vehicle Fuel Consumption Displacement Potential up to 2045, July 2011).

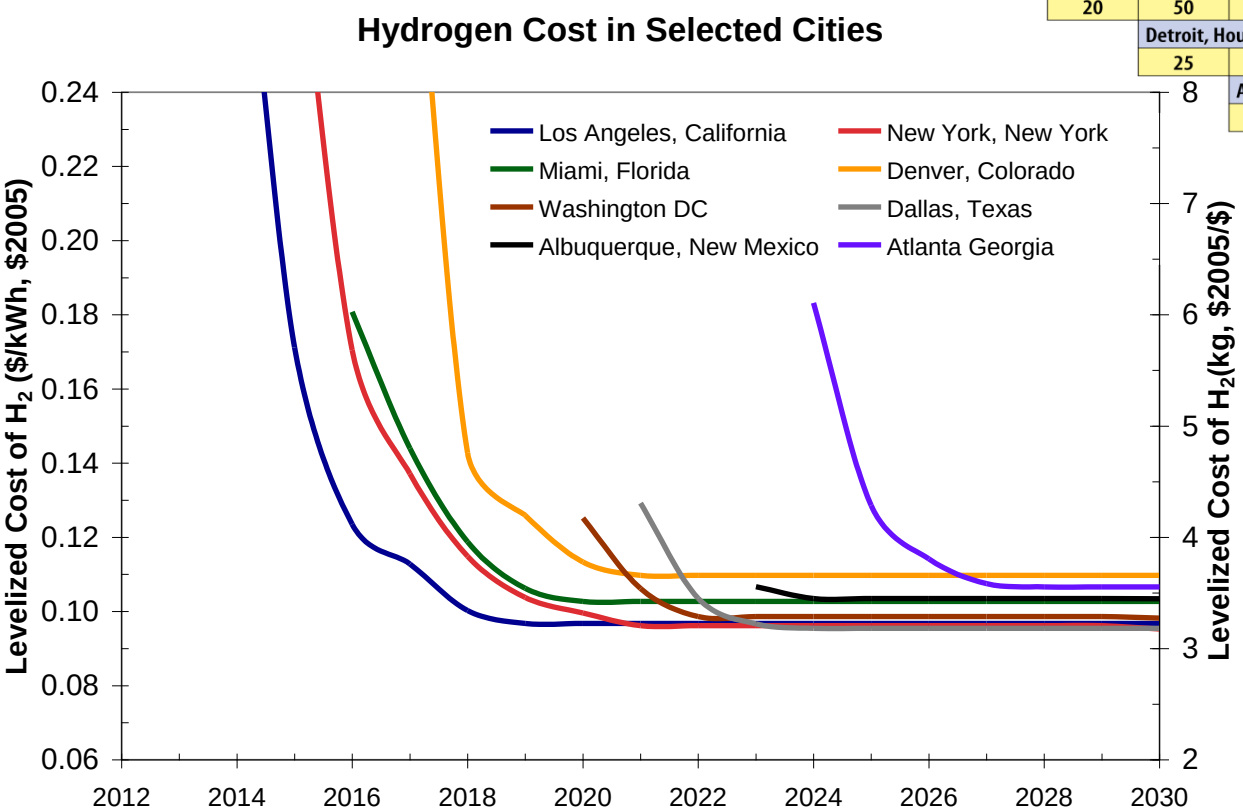
http://www.autonomie.net/pdfs/ANL%20-%20Executive%20Summary%20ANL-ESD-11-4%20-%20Potential%20of%20Technologies%20for%20Displacing%20Gasoline%20Consumption%20by%20Light-Duty%20Vehicles%20through%202045%20-%20Jun11.pdf

Hydrogen Cost

Early hydrogen costs high, but falls with increasing scale to $3-4/gge.

Clear path forward in reducing cost and hitting targets.

2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Los Angeles													
1	2	2	25	40	50	85	120	160	190	210	250	270	300
			New York, Chicago										
			25	40	50	85	120	150	175	185	225	240	270
				San Francisco, Washington/Baltimore									
				20	30	55	85	120	140	160	190	210	230
					Boston, Philadelphia, Dallas								
					20	50	85	120	145	165	195	210	220
						Detroit, Houston							
						25	50	80	120	140	160	190	210
							Atlanta, Minneapolis, Miami						
							40	75	100	115	130	160	180
								Cleveland, Phoenix, Seattle					
								45	70	90	120	150	170
									Denver, Pittsburgh, Portland, St. Louis, Cincinnati, Indianapolis, Kansas City				
									60	80	110	130	150
										Milwaukee, Charlotte, Orlando, Columbus, Salt Lake City			
										55	80	110	130
											Nashville, Buffalo, Raleigh		
											40	70	90
												Nationwide	
												260	540



Source: J. Ogden and C. Yang, "Build-up of a hydrogen infrastructure in the US," Chapter 15, in The Hydrogen Economy: Opportunities and Challenges, edited by Dr Michael Ball and Dr Martin Wietschel, Cambridge University Press, 2009, pp.454-482.

Challenges & Path Forward: Policy Analysis

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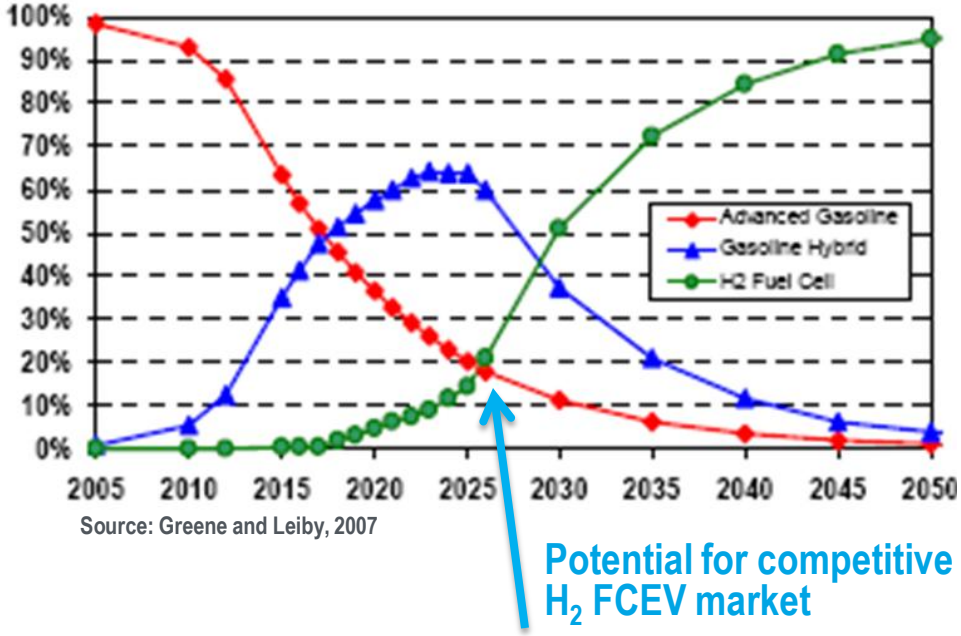
With targeted deployment policies during 2012 to 2025, FCEV market share could grow to 50% by 2030 and 90% by 2050, leading to sustainable and competitive market for FCEVs beyond 2025, without a continuing need for policy support.



Source: Greene and Leiby, 2007

Potential Policy Impacts

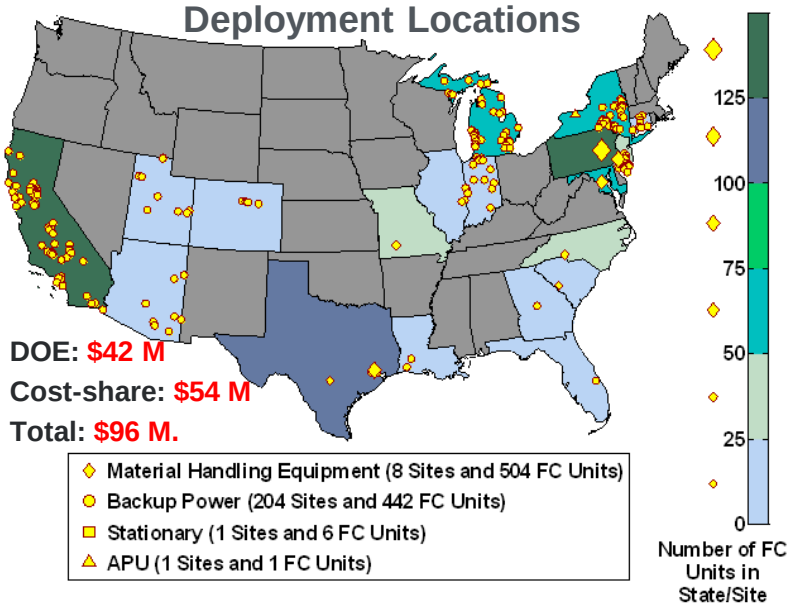
Policy Case	Time Period	Vehicle Policies		Fueling Infrastructure Policies	
		Fuel Cell Vehicle Cost Sharing	Fuel Cell Vehicle Tax Credits	Station Cost Sharing (for Distributed Hydrogen Production)	Hydrogen Fuel Subsidy (Production Tax Credit)
Case 1	2012 - 2017	50% of incremental FCV costs	None	$1.3 Million/Station	$0.50/kg
	2018 - 2021	50% of incremental FCV costs	None	$0.7 Million/Station	Decreases linearly From 2018 to $0.30/kg in 2025
	2022 - 2025	50% of incremental FCV costs	None	$0.3 Million/Station	$0.30/kg in 2025
Case 2	2012 - 2017	50% of total FCV costs	None	$1.3 Million/Station	$0.50/kg
	2018 - 2021	None	100% of incremental cost	$0.7 Million/Station	Decreases linearly From 2018 to $0.30/kg in 2025
	2022 - 2025	None	100% of incremental cost	$0.3 Million/Station	$0.30/kg in 2025
Case 3	2012 - 2017	50% of total FCV costs	None	$1.3 Million/Station	$0.50/kg
	2018 - 2021	None	100% of incremental cost plus $2,000/vehicle	$0.7 Million/Station	Decreases linearly From 2018 to $0.30/kg in 2025
	2022 - 2025	None	100% of incremental cost plus $2,000/vehicle	$0.3 Million/Station	$0.30/kg in 2025

Progress — *Spurring Early Markets with ARRA and Market Transformation Activities*

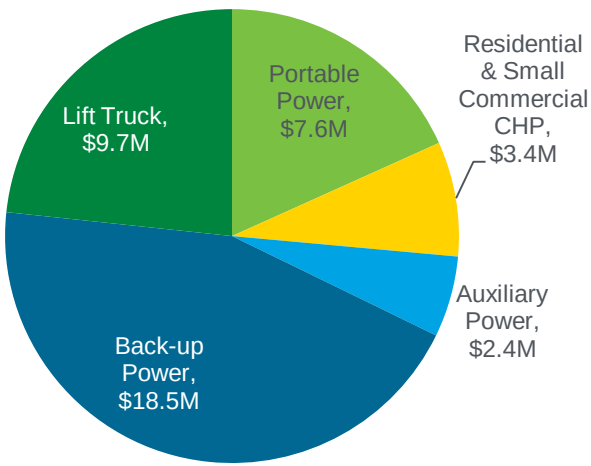
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Deployed more than 820 fuel cells to date for use in forklifts and backup power at several companies including Sprint, AT&T, FedEX, Kimberly Clark, and Whole Foods

Deployment Locations



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



ARRA Deployment Status – August 2011

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

NREL ARRA Data Collection Snapshot

ARRA Material Handling Equipment Data	As of 9/30/2011
Hydrogen Dispensed	>51,500 kg
Hydrogen Fills	>88,000
Hours Accumulated	>380,000 hrs

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

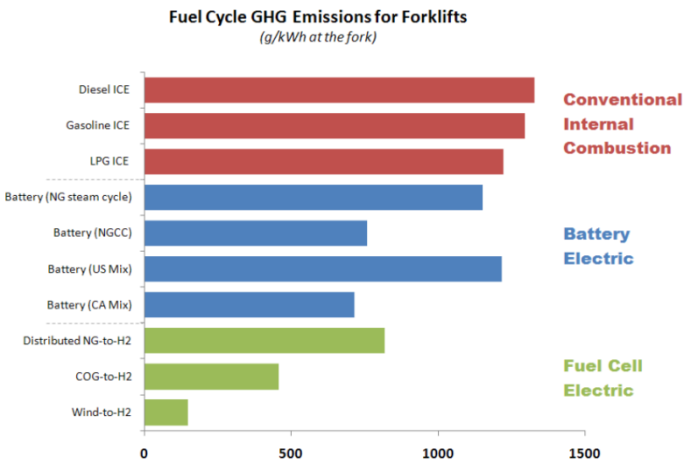
ARRA as Catalyst for Deployments

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

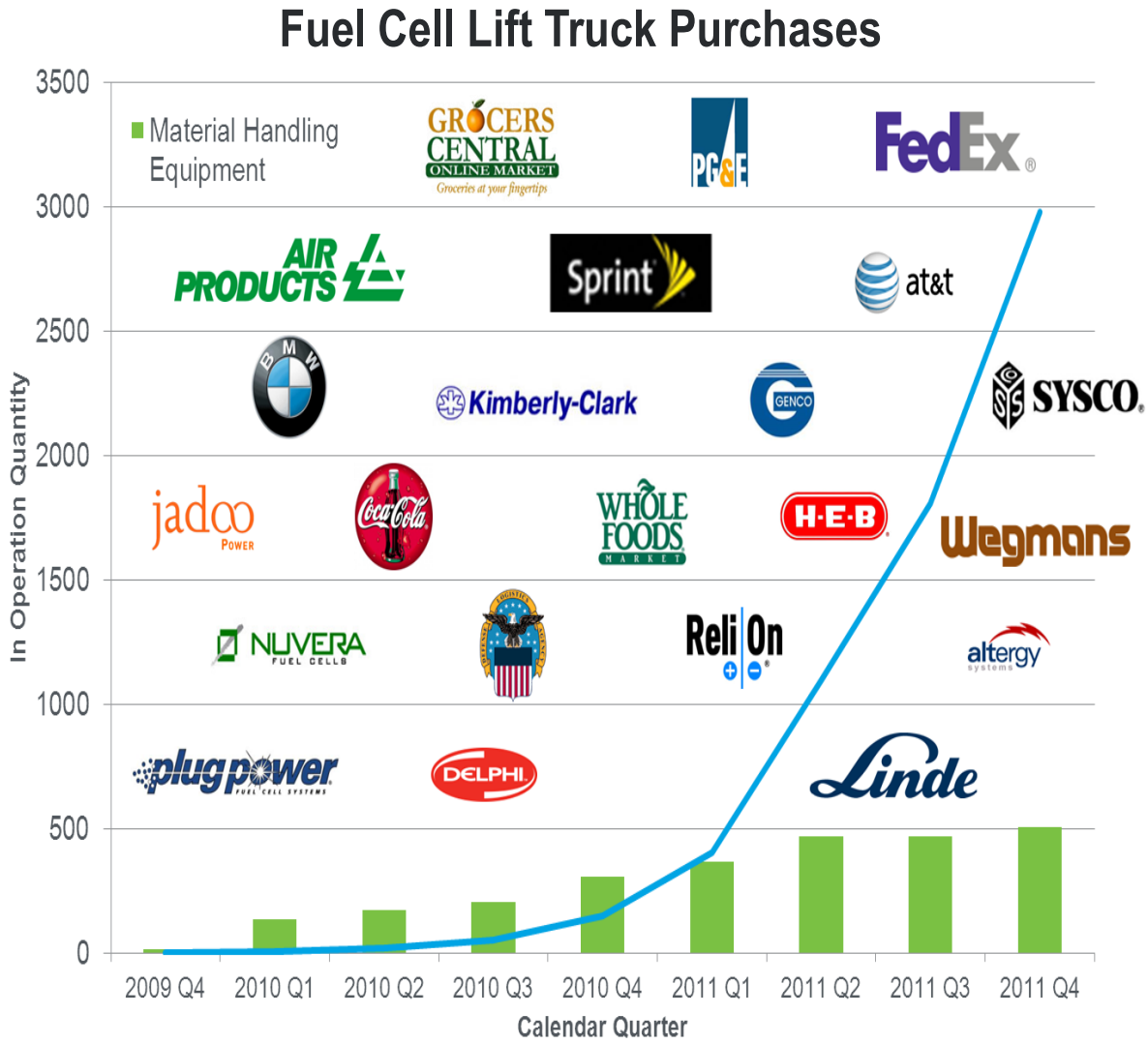
ARRA deployments of fuel cells for lift trucks (~400) led to industry purchases* of an estimated 3,000 additional fuel cell lift trucks with NO DOE funding

The Case for Forklifts*
Compared to conventional forklifts, fuel cell forklifts have:

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



**Preliminary Analysis*



* Including deployed and on order

Assessing the Impact of DOE Funding

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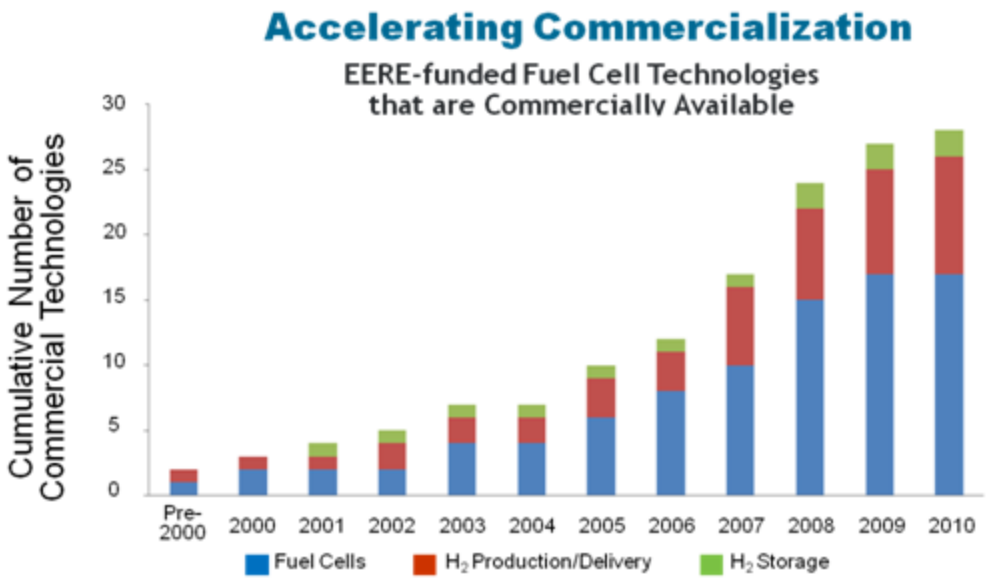
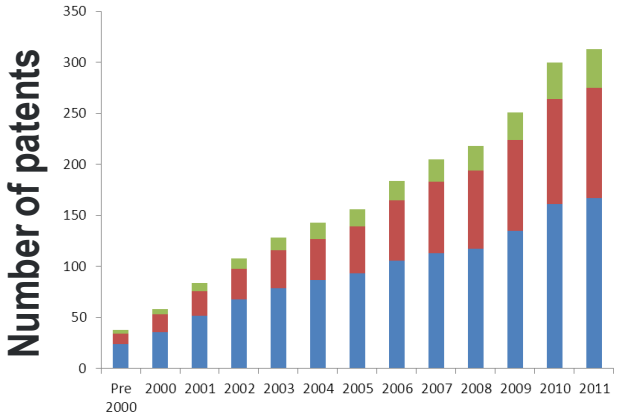
DOE funding led to 313 patents, ~30 commercial technologies and >60 emerging technologies

The Program is tracking impact: for example, ~$70M in DOE-funding has led to nearly $200M in industry investment and revenues.



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



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

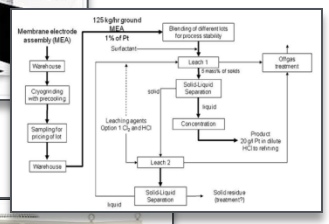
- *Includes technologies for hydrogen production and delivery, hydrogen storage, and fuel cells*

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

Examples

DuPont

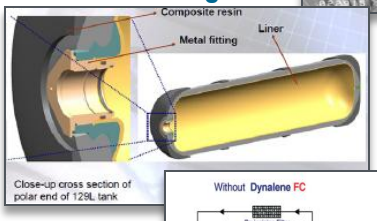
BASF Catalysts LLC



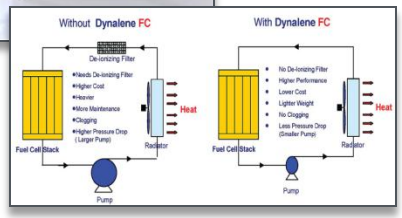
Proton Energy Systems

3M

Quantum Technologies



Dynalene, Inc.



The Role of Fuel Cells in Transportation

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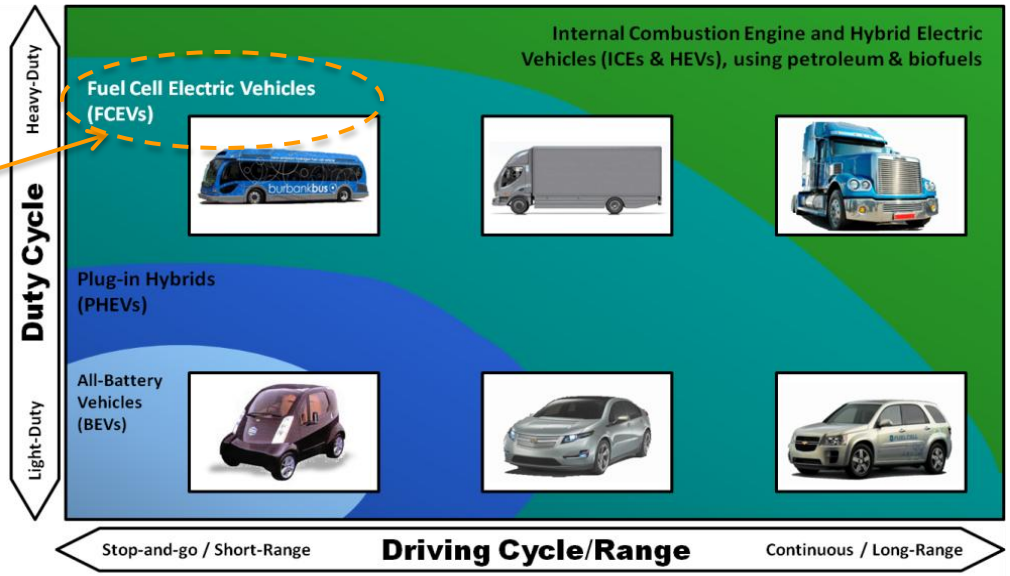
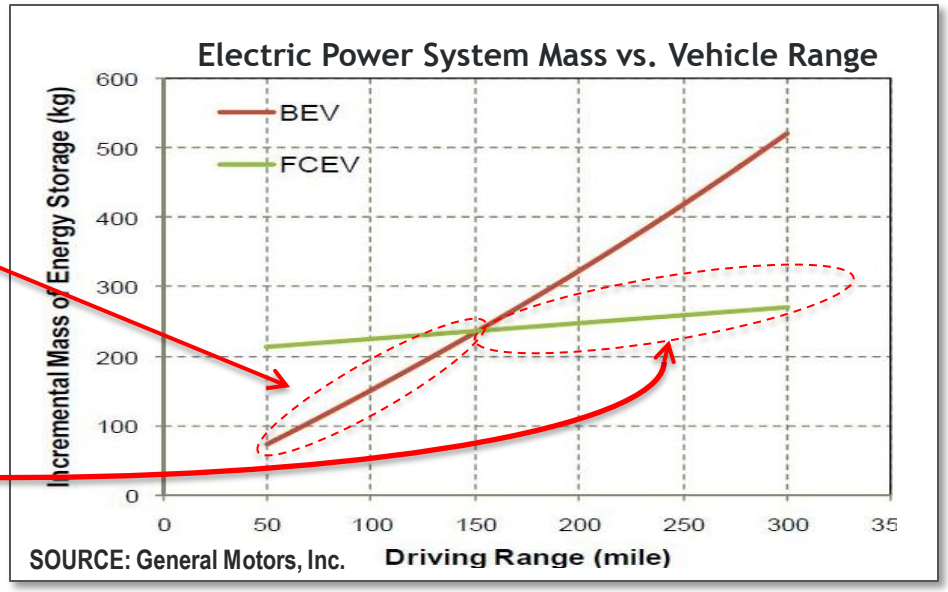
Transportation: A diverse portfolio is needed to meet the full range of driving cycles and duty cycles in the nation's vehicle fleet.

Fuel cells will play a central role — by enabling longer driving ranges and heavier duty cycles for certain vehicle types *(including **buses**, **light-duty cars & trucks**, **delivery vans**, and **short-haul trucks**)*



Advantages of Batteries and Fuel Cells:

- For shorter distances, batteries are more effective in terms of system mass
- ***Fuel cells will be essential for providing the driving ranges of today's vehicles***



Total Cost of Ownership Will Be Comparable Across Advanced Vehicle Types

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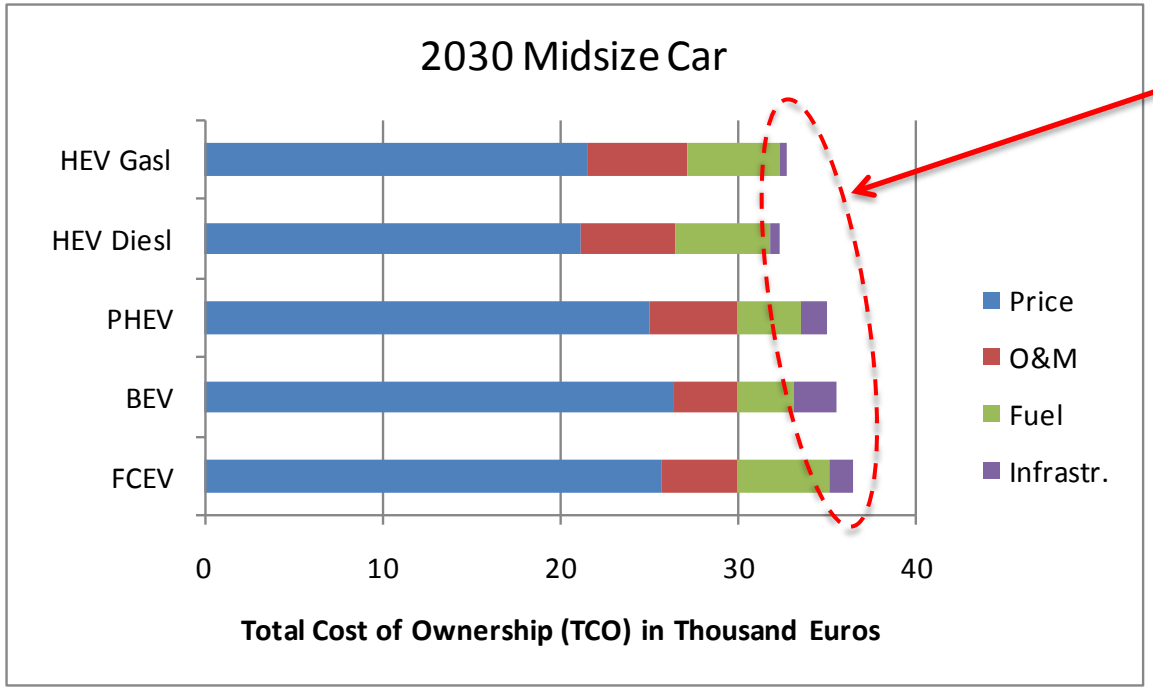
Study by McKinsey & Co. and automakers indicates that the costs of ownership of future light-duty vehicles will converge by 2030, with minimal infrastructure costs per vehicle.



Multiple studies show that incremental cost of refueling infrastructure is a minor part of the total cost of ownership of all advanced vehicle types, including FCEVs.

- *Charging infrastructure for electric vehicles ranges from €1,500 ($2,000) per vehicle for 100% home charging to €2,500 ($3,300) per vehicle for 50% home/50% public charging.*
- *McKinsey and its partners in this study (which included major car companies) assumed maximum BEV range to be 150 miles.*

Source: *EU Mobility study A Portfolio of Power-Trains for Europe: A Fact-Based Analysis*; analysis includes input from: major car companies, European oil & gas companies, industrial gas, and utility companies.

Widespread Support for FCEVs

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

Toyota*

- "Fuel cell Technology is viable and ready for the mass market" –Chris Hostetter, VP for Advanced Planning
- "People will be very surprised that we were able to achieve such an impressive cost reduction with our **2015** fuel cell vehicle" –Justin Ward, Advanced Powertrain Program Manager

GM*

"Fuel cell electric vehicles will be commercial by **2015/2016**" – Mark Adams, VP of Design

Daimler*

- "The product is ready for the market technically." High volume production will start in **2014**.
- "Hydrogen beats electric batteries" --Dieter Zetsche, CEO

BMW

BMW and GM plan to collaborate on the development of fuel cell technology

Hyundai*

- "EVs and hybrids are an intermediate step for fuel cell vehicles"
- "Our ultimate goal is to make fuel cell vehicles available by **2015**" –Steve Yang, President and CEO
- "Pilot-scale production of 1000 fuel cell cars a year will begin in **2012**" –Byung Ki Ahm, GM of FC Group

Honda*

- "The ultimate eco car is a fuel cell car" --Takanobu Ito, CEO
- Takanobu Ito fully expects Honda to offer a vehicle powered by hydrogen fuel cells by **2018**

VW

Expanded demo fleet to 24 FCEVs in CA. Recently confirmed commitment to FCEVs

Ford*

Alan Mulally, CEO, sees **2015** as the date that fuel cell cars will go on sale.

SAIC

Partnered with GM to build fuel cell vehicles

*Several major OEMs have signed an LOU anticipating widespread commercialization of FCEVs in 2015.Not shown: Nissan and Renault.