Challenges and Benefits of a Move Towards Hydrogen Fuel

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Hydrogen Program Manager

24 April 2006

AIChE 2006 Spring Meeting
Group: Topical C: Hydrogen (TC)
TC007 Hydrogen Topical Plenary

President Bush Announces Advanced Energy Initiative in 2006 State of the Union Address

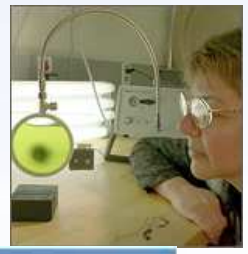
Promoting Technology Solutions for Clean Energy from Domestic Resources

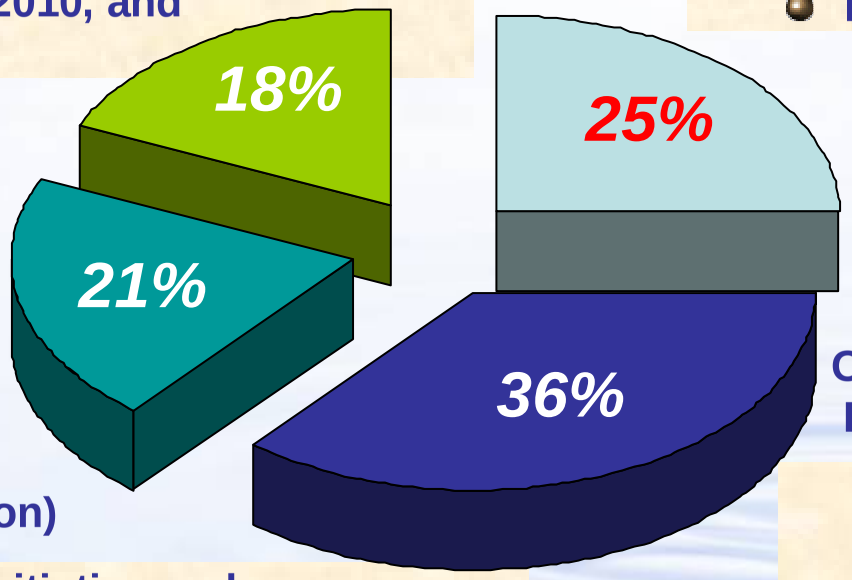
Office of Nuclear Energy, Science and Technology ($392 million)

- Global Nuclear Energy Partnership,
- Nuclear Hydrogen Initiative,
- Nuclear Power 2010, and
- Generation IV

Office of Science ($539 million)

- nuclear fusion,
- solar,
- biomass and
- hydrogen





Office of Energy Efficiency and Renewable Energy ($771 million)

- hydrogen technology,
- fuel cell technology,
- vehicle technology,
- biomass, solar, and wind

Office of Fossil Energy ($444 million)

- Coal Research Initiative and
- other power generation/stationary fuel cell

DOE FY 2007 budget requests $2.1 billion

($381 million increase over FY 2006)

Under President's Initiative, DOE has Robust Near-Term and Long-Term Technology Development Portfolio for Breaking Foreign Oil Dependence and Reducing GHG/Criteria Emissions

- Accelerate research in cutting-edge methods of producing "cellulosic ethanol" with the goal of making the use of such ethanol practical and competitive within 6 years.
- Step up research in better batteries for use in hybrid-electric vehicles (including "plug-in" hybrids).
- Accelerate the development of hydrogen fuel cells and affordable hydrogen-powered cars by providing $289 million – an increase of $53 million over FY06 –Consistent with $1.2B commitment from 2003 SOTU Address.

President participates in Energy Conservation & Efficiency Panel NREL, Golden, Colorado, February 21, 2006

"So tonight, I announce the Advanced Energy Initiative -- a 22-percent increase in clean-energy research..." — President George W. Bush on January 31, 2006

Hydrogen Production Strategy

Hydrogen Addresses the Root Cause of Energy Dependence and GHG & Criteria Emissions

Coal

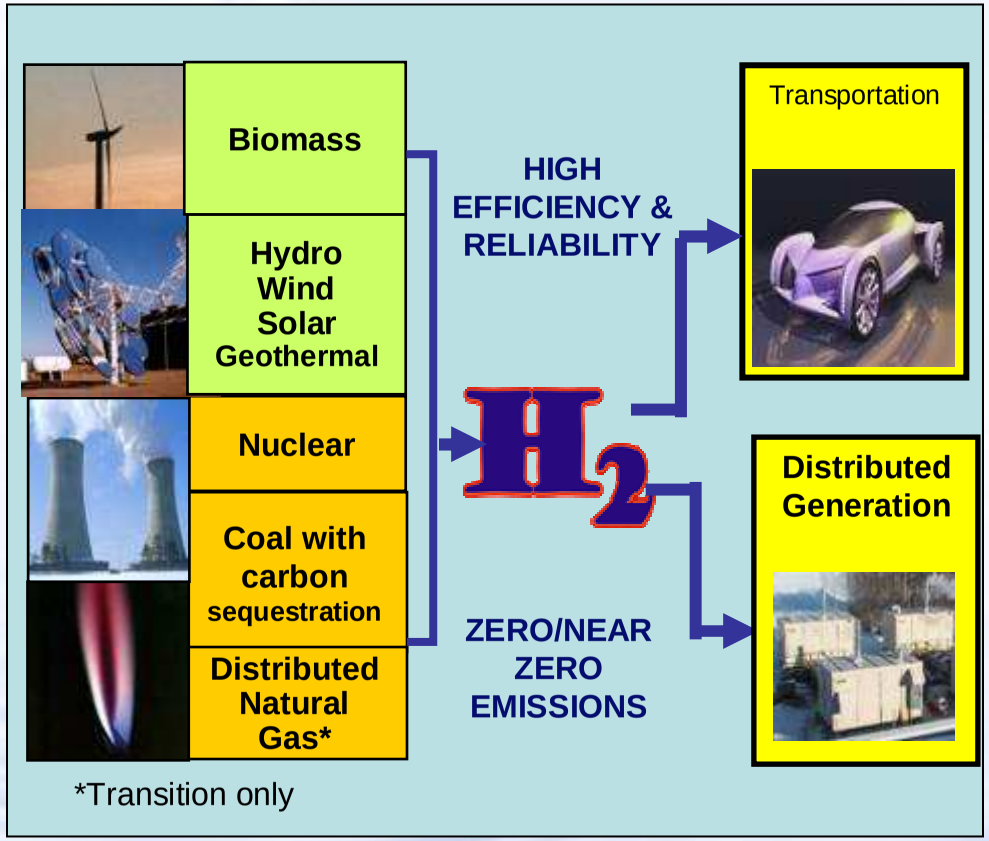
- Only with carbon capture & sequestration
- Gasification process produces hydrogen directly
- Electricity not produced as an intermediary

Distributed Natural Gas

- Transition strategy
- "Well-to-wheels" greenhouse gas emissions substantially less than gasoline hybrid-electric vehicle
- Not a long-term source for hydrogen (imports and demand in other sectors)

Nuclear/Renewable

- Electrolysis (one option)
- Electricity not necessarily produced as an intermediary, options being pursued include:
  - Gasification of biomass
  - Reforming of renewable liquids
  - Photoelectrochemical
  - Photobiological
  - Thermochemical (solar and nuclear)



Energy Policy Act of 2005
Title VIII - Hydrogen

EPAct 2005 (Public Law 109-58) "codifies" the President's Hydrogen Fuel Initiative. The national leaders are in agreement that a hydrogen economy can lead to energy and environmental security.

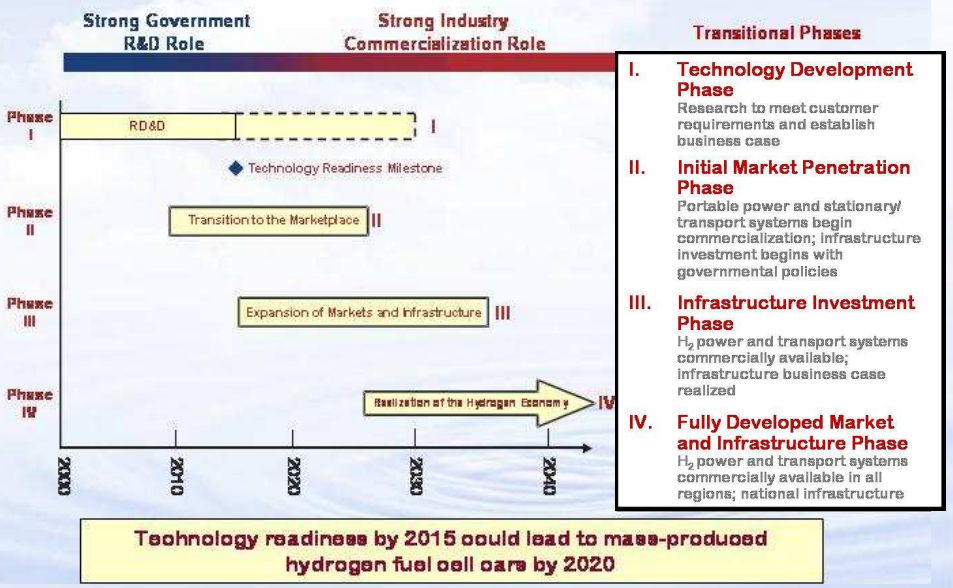
President Bush signs Energy Policy Act into law on August 8, 2005

Congress reinforces the timeline developed by DOE in support of the President's Hydrogen Fuel Initiative –

- **By 2015: Enable commitment by industry for fuel cell vehicles and hydrogen infrastructure**
- **By 2020: Enable consumers to purchase vehicles and make hydrogen available**

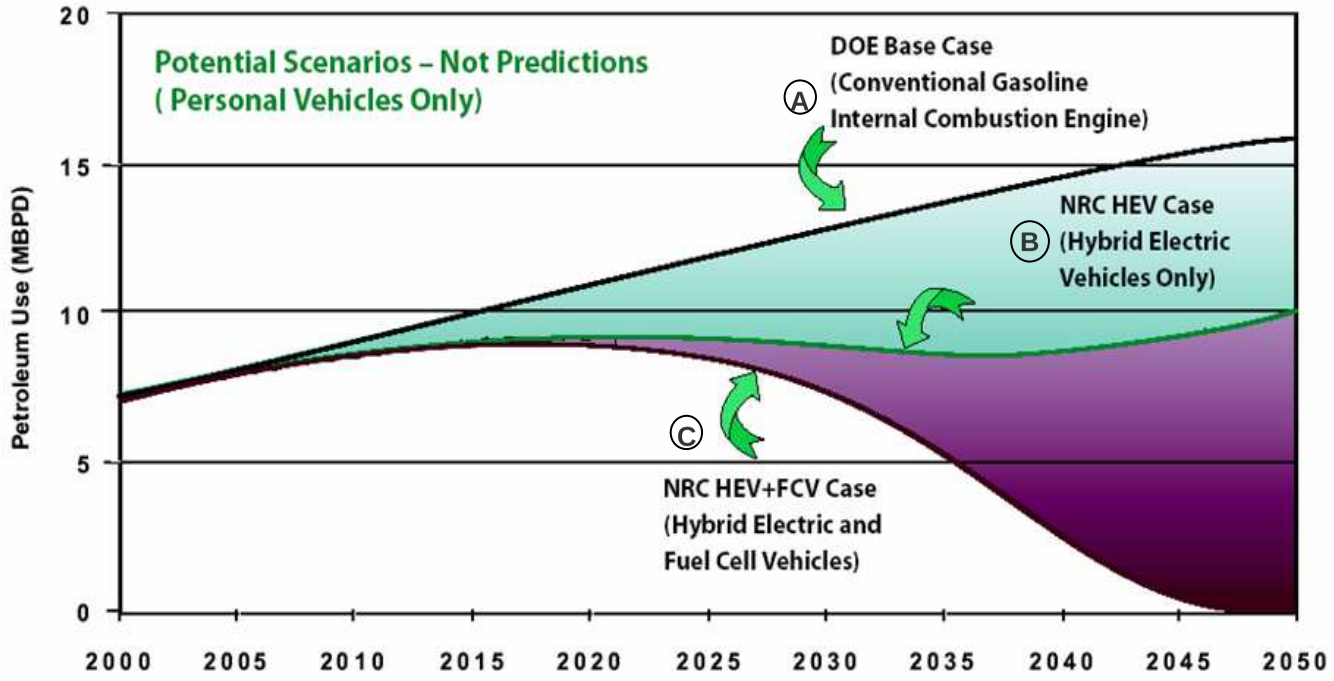
Congress makes the long-term commitment required for realization of the hydrogen economy by authorizing Title VIII of EPAct

Hydrogen Economy Timeline



National Academies' Study Supports President's Vision and Benefits

"A transition to hydrogen as a major fuel in the next 50 years could fundamentally transform the U.S. energy system, creating opportunities to increase energy security through the use of a variety of domestic energy sources for hydrogen production while reducing environmental impacts, including atmospheric CO_2 emissions and criteria pollutants… This committee believes that investigating and conducting RD&D activities to determine whether a hydrogen economy might be realized are important to the nation."



Shows:

- **Efficiency offsets oil growth**
- **Substitution can eliminate oil use**

Note: Cases B & C are from Figure 6-4 in NRC "The Hydrogen Economy" report

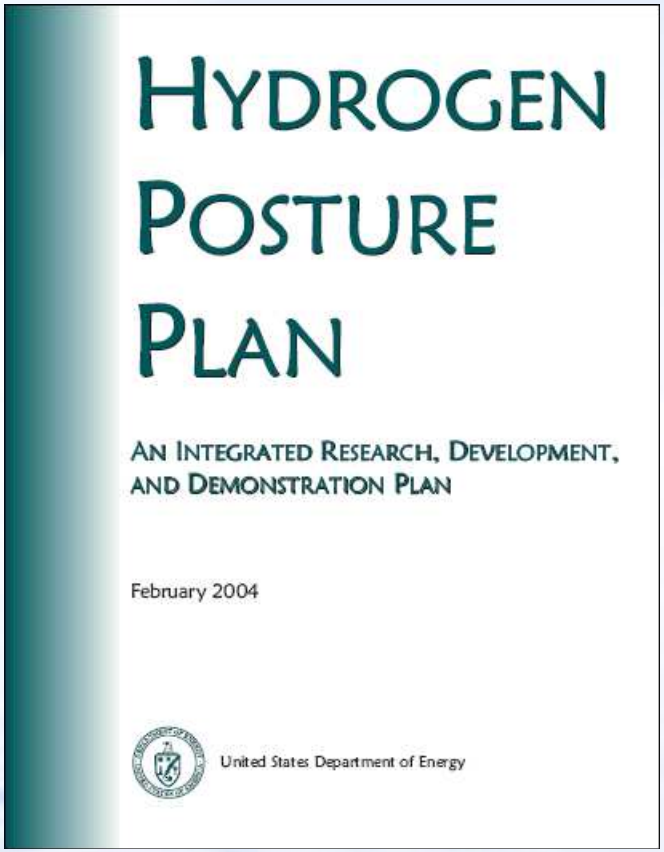
Posture Plan Describes the Research, Development & Demonstration Activities

Critical Path Technology Barriers:

- Hydrogen Storage (>300-mile range)
- Fuel Cell Cost ($30 per kW)
- Hydrogen Cost ($2.00 - 3.00 per gge)

Economic/Institutional Barriers:

- Codes and Standards (Safety, and Global Competitiveness)
- Hydrogen Delivery (Investment for new Distribution Infrastructure)
- Education

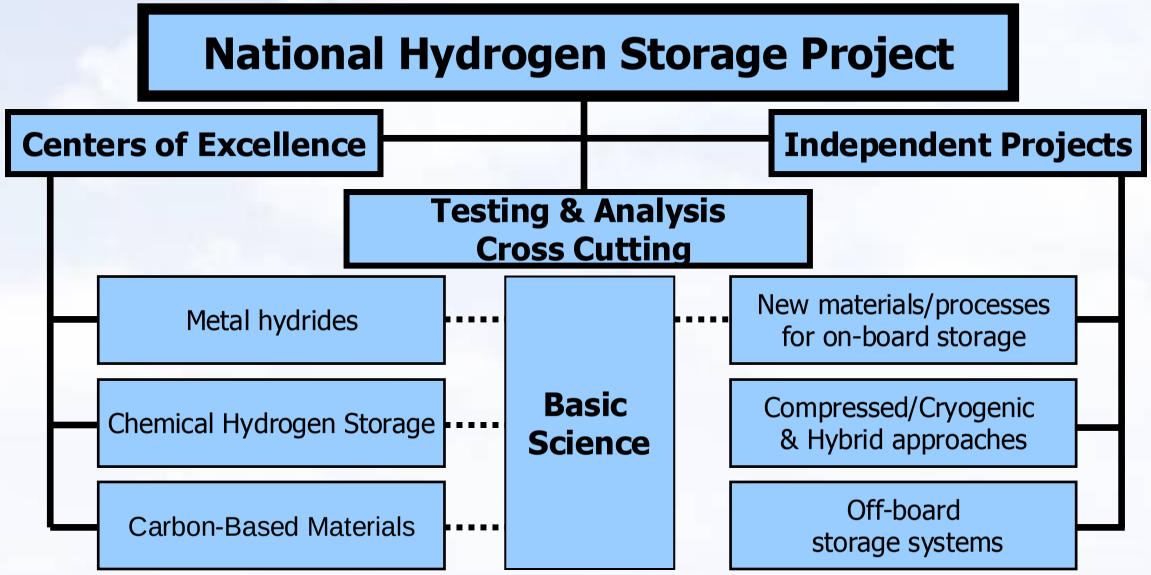


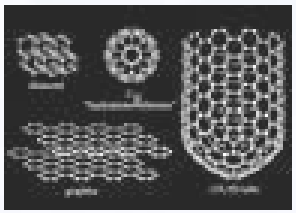
Posture Plan identifies major milestones related to each barrier in an integrated department schedule so that progress can be tracked.

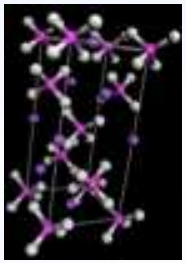
www.hydrogen.energy.gov/pdfs/hydrogen_posture_plan.pdf

Hydrogen Storage: The Grand Challenge

Focused on M*aterials-based* Technologies for >300 - Mile Range







~40 Universities, 15 Companies, 10 Federal Labs

High pressure tanks do not meet long term targets. Focus is on novel materials.

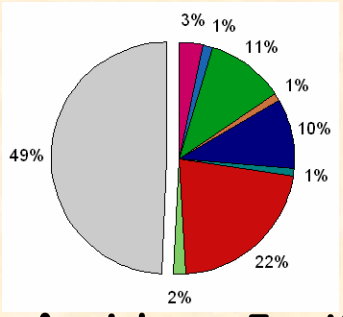
	Specific Energy	Energy Density	Cost
2015 Targets (2010)	3.0 kwh/kg (2.0)	2.7 kwh/L (1.5)	$2/kWh (4)
5,000 psi System*	1.9 kwh/kg	0.5 kwh/L	$15/kWh
10,000 psi System*	1.6 kwh/kg	0.8 kwh/L	$18/kWh

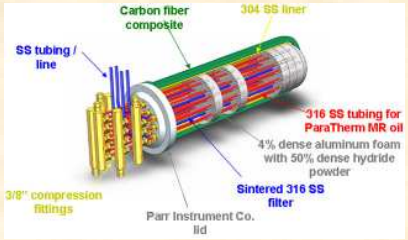
* Status of tank technology, 2005

Hydrogen Storage Update

Diverse Portfolio Starting to Show Promising Results

Prototype built (~50% is BOP)





Anton et. Al, UTRC

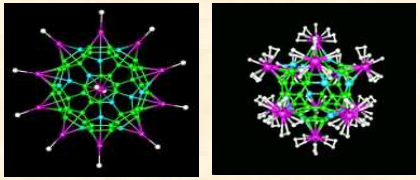
LiMg Amides ~5 wt%, 100 cycles

Sandia Livermore: Luo, Gross, et al

Destabilized hydrides & nanoscience

> 9 wt% shown $LiBH_4$ / MgH_2: *Vajo, et al, HRL*

Materials modeled for capacity:

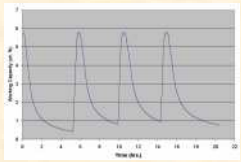


Potential for 8.8 wt%

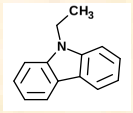
Zhao, Heben, Dillon, et al NREL

$C_{48}B_{12}[ScH]_{12} \rightleftharpoons C_{48}B_{12}[ScH(H_2)_5]_{12}$

Chemical hydrides developed, 5.5 to 7 wt% and 50-65 g/L

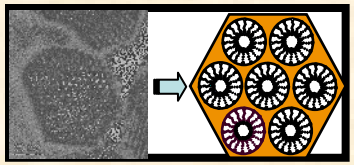


N-ethyl-carbazole



Cooper, Pez, Air Products

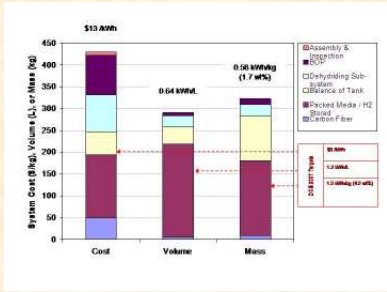
Mesoporous scaffolds with ammonia borane show >6 wt% (at < 80C & reduced byproducts)



Autrey, Gutowski, et al, PNNL

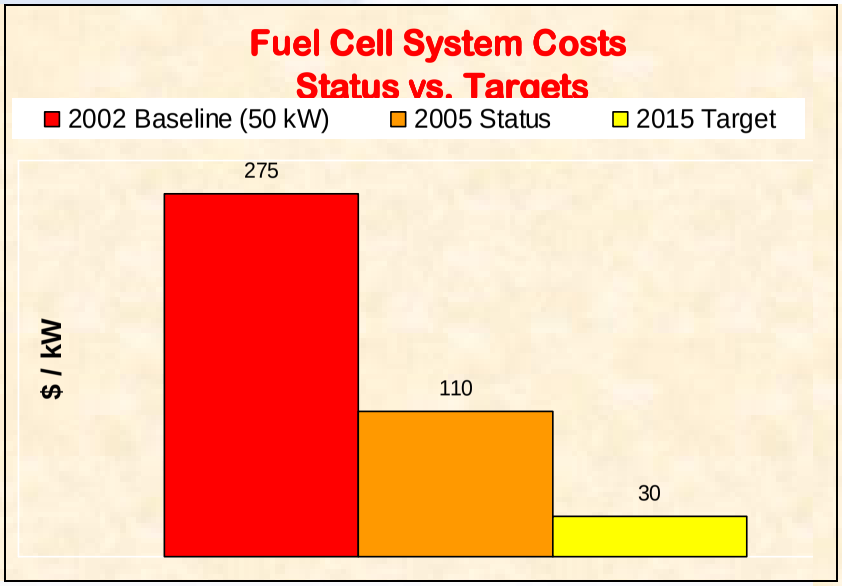
Storage Systems Analysis Working Group Established

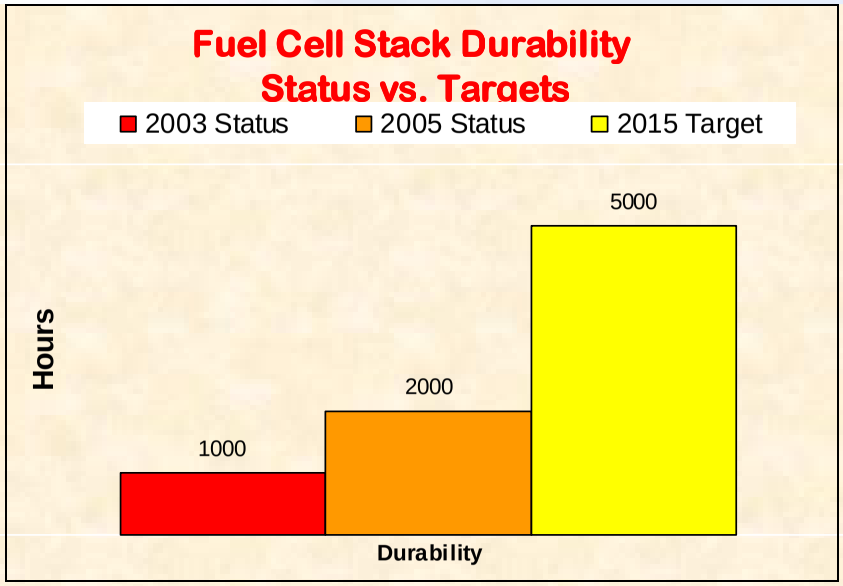
Materials > 7 wt% needed for 4.5 wt% system (2007 target)

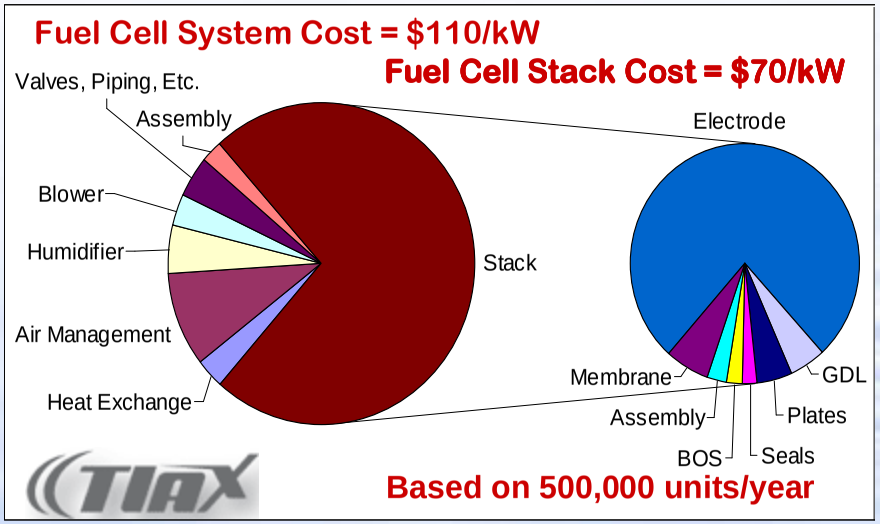


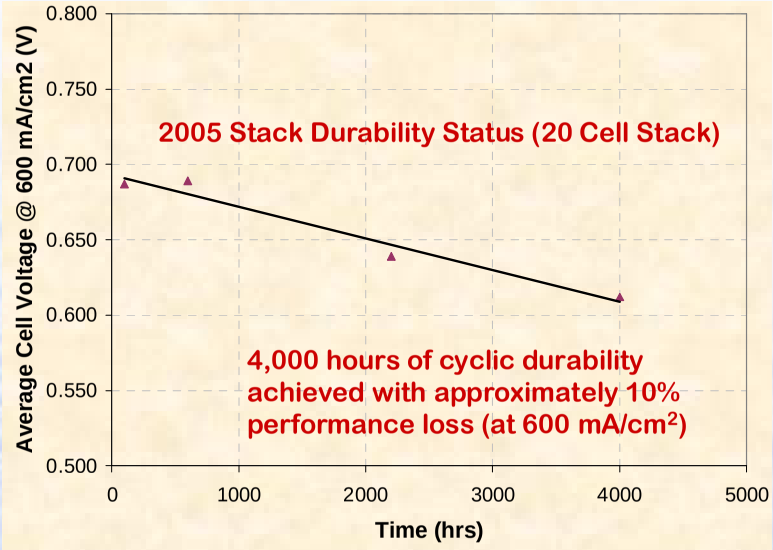
TIAX, ANL

Accomplishments: Reduced High Volume Fuel Cell Cost and Increased Durability



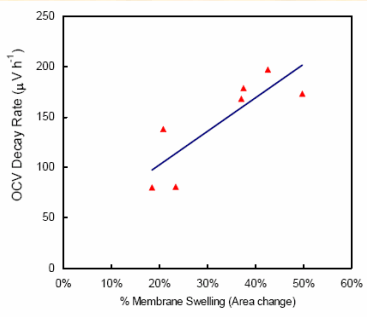






Fuel Cell Development Highlights

Durability improvements, MEA & PEMFC

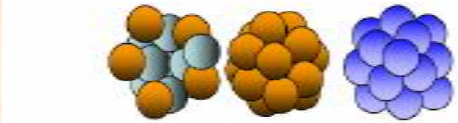


Data for 7 membrane types: reducing swelling percentage by reformulating the membrane, reduces degradation rate

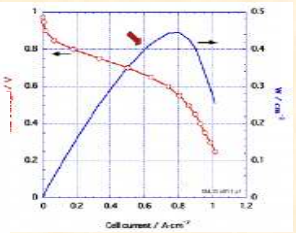
DuPont/ UTC

Higher FC catalyst activity with less Pt

Au + Ni co-deposit — **Synthesis** At 600°C Au segregates — Pt deposited by replacing Cu



$Ni + Au \rightarrow Au_{ML}/Ni \rightarrow Pt_{ML}/Au_{ML}/Ni$



BNL, MEA testing at LANL

4x Pt kinetic activity (RDE) & mass activity in FC consistent w/ <0.2mgPt/kW

Improved high current activity of non-Pt catalysts

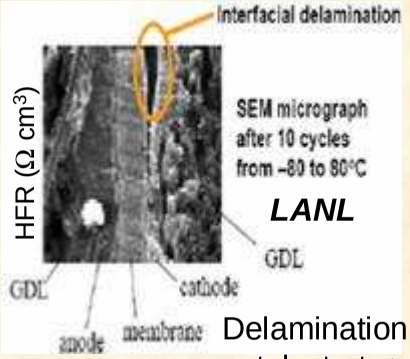
Density 2/3 that of state-of-art Pt

Pyropolymer CoTMPP

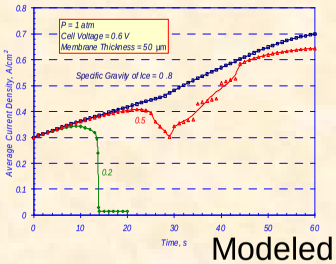
Poly $(CoN_4C_{36})_n$

LANL

Subfreezing effects & analysis



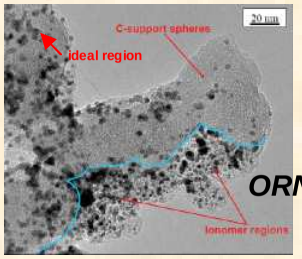
Delamination of cathode catalyst at <-40°C



ANL

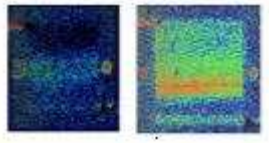
Modeled startup from subfreezing conditions (<30 s)

Improved characterization imaging



ORNL

TEM imaging of new & used FC components

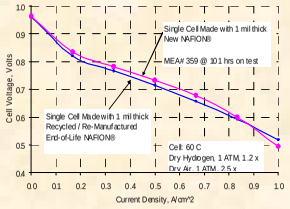


NIST, SNL, et al

Real-time imaging of H_2O in FC components during operation

Developed FC with remanufactured membrane

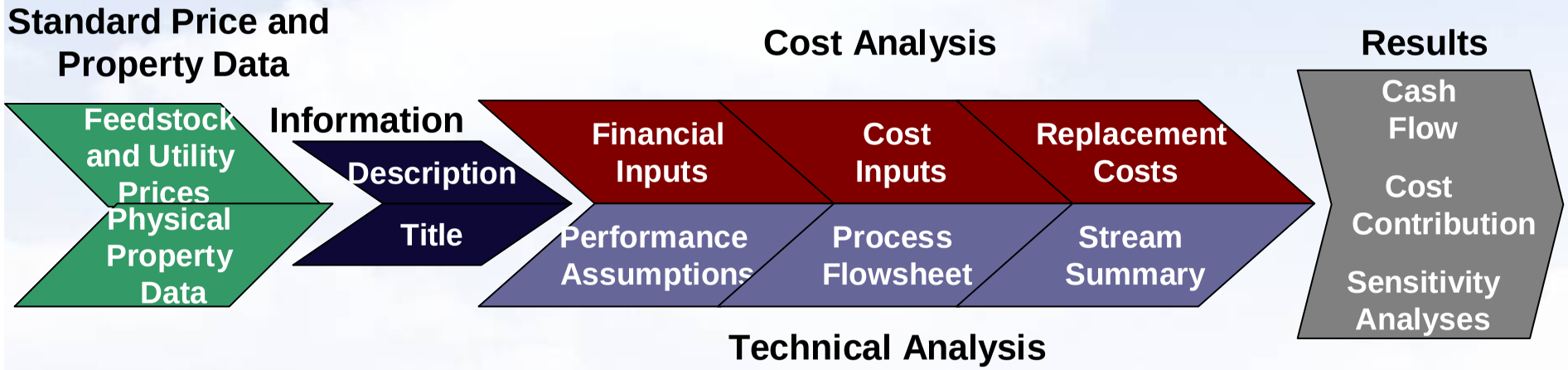
98% of Pt dissolves after holding at elevated temp & pressure



Ion Power, Engelhard

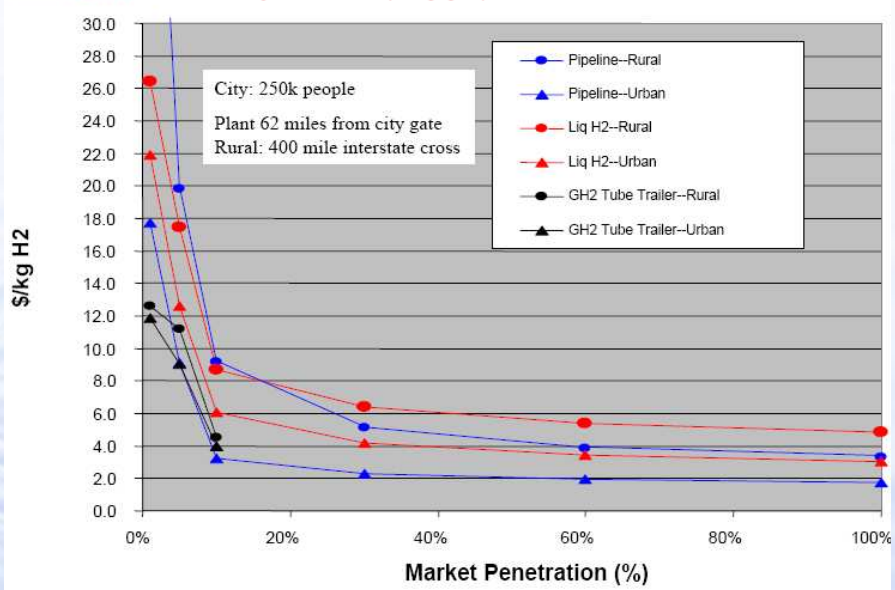
First operating FC w/ remanufactured membrane/downselect Pt separation procedures

Accomplishments: Analytical Tools Developed for Production/Delivery



http://hydrogen.pnl.gov/cocoon/morf/hydrogen

Delivery Costs ($/gge) vs. Market Penetration



Analysis of Distributed Hydrogen Production from Natural Gas Reforming

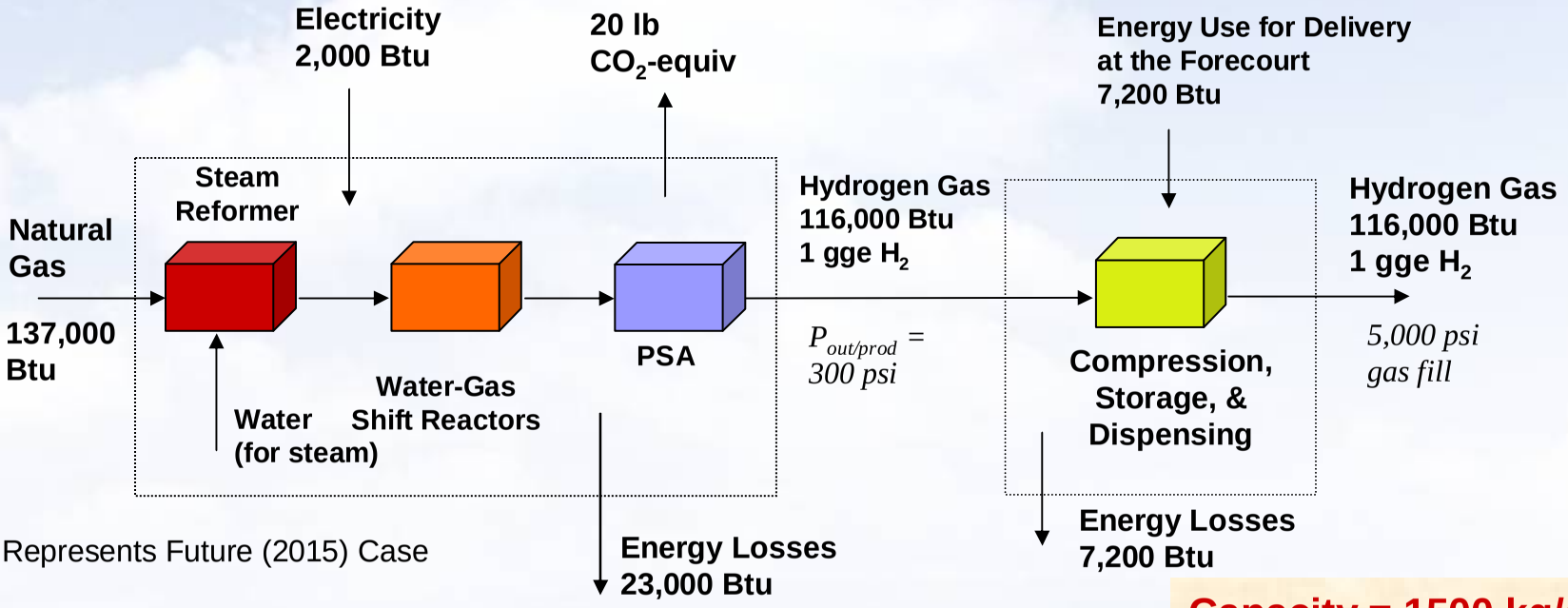


Figure Represents Future (2015) Case

Capacity = 1500 kg/day

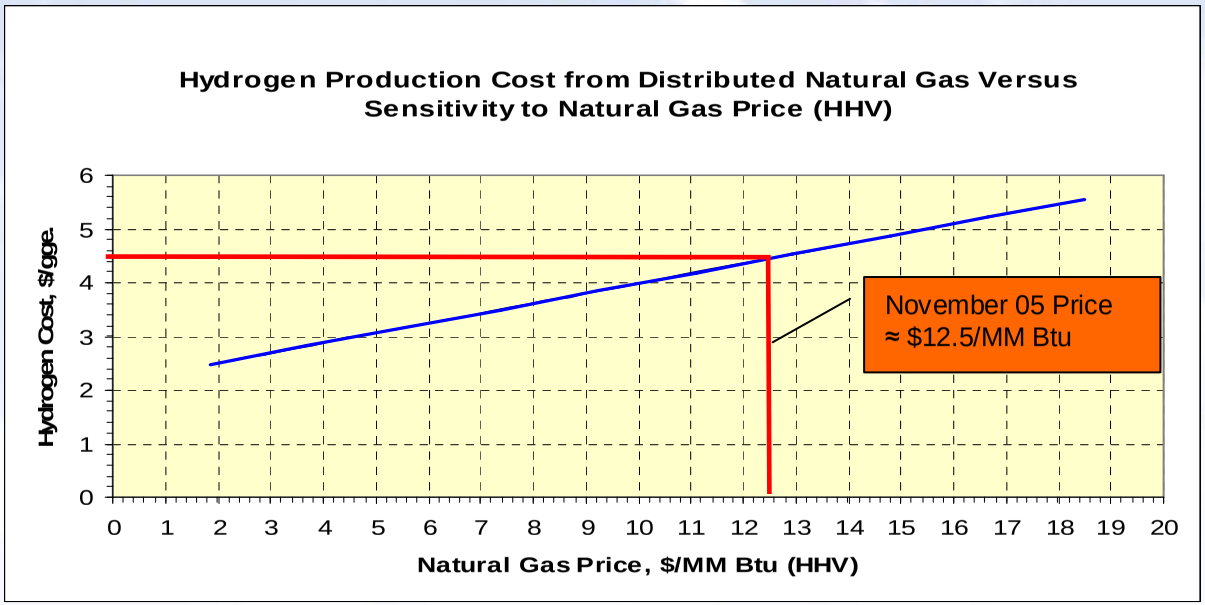
Well-to-Wheels Energy and Greenhouse Gas Emissions Data				
	Current (2005) Gasoline ICE Vehicle	Current (2005) Gasoline Hybrid Electric Vehicle	Current (2005) Distributed SMR - FCV	Future (2015) Distributed SMR - FCV
Well-to-Wheels Total Energy Use (Btu/mile)	5,900	4,200	3,700	2,800
Well-to-Wheels Petroleum Energy Use (Btu/mile)	5,300	3,800	40	40
Well-to-Wheels Greenhouse Gas Emissions (g/mile)	470	340	260	200
Cost of Hydrogen ($/gge, Delivered)			3.10	2.00

Source: NREL and H2A model
http://www.hydrogen.energy.gov/h2a_production.html

- Combines best available research
- Projected to 500 units/year
- Next step: Field Validation

Current (2005) Case: $5.24 Btu LHV feedstock; 70% capacity factor; 66% pathway efficiency
Future (2015) Case: $5.24 Btu LHV feedstock; 70% capacity factor; 79% pathway efficiency

Understanding the Effects of Feedstock Volatility

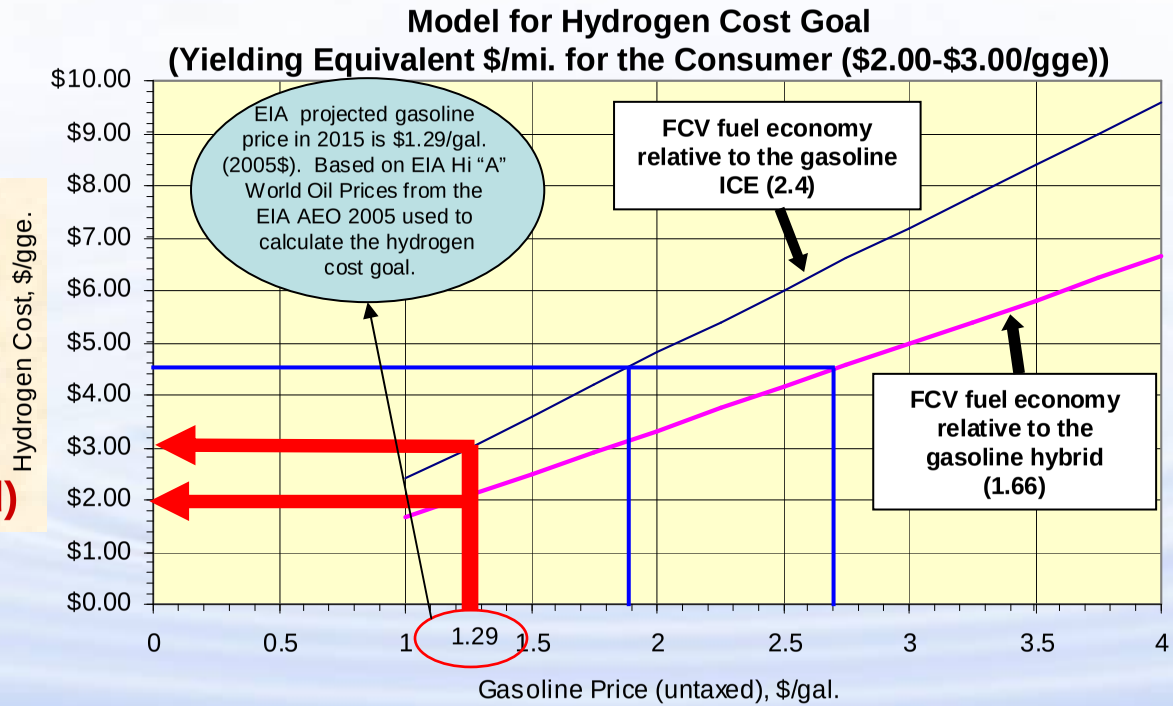


Hydrogen Costs based on:

- Combination of best available research
- Projected to 500 units/year
- Next Step: Field Validation

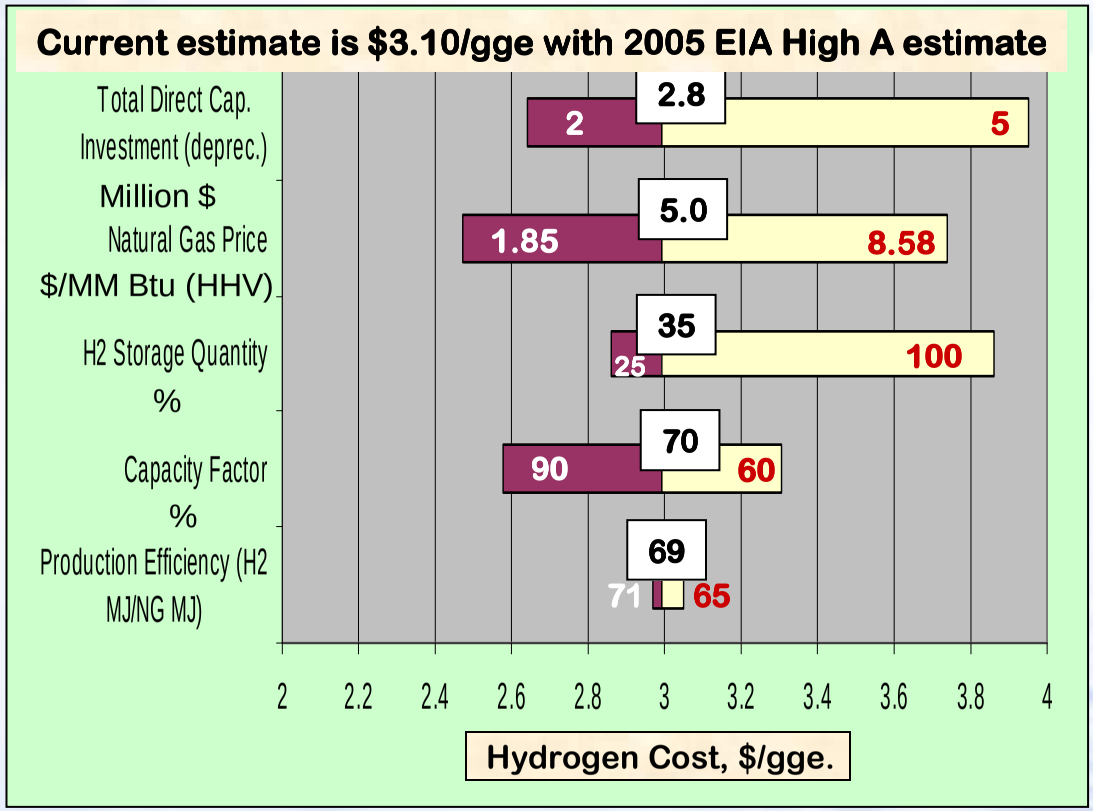
Hydrogen at $4.50/gge

- Competitive with conventional gasoline ICEVs at $1.90/gge (untaxed) and gasoline HEVs at $2.70/gge (untaxed)

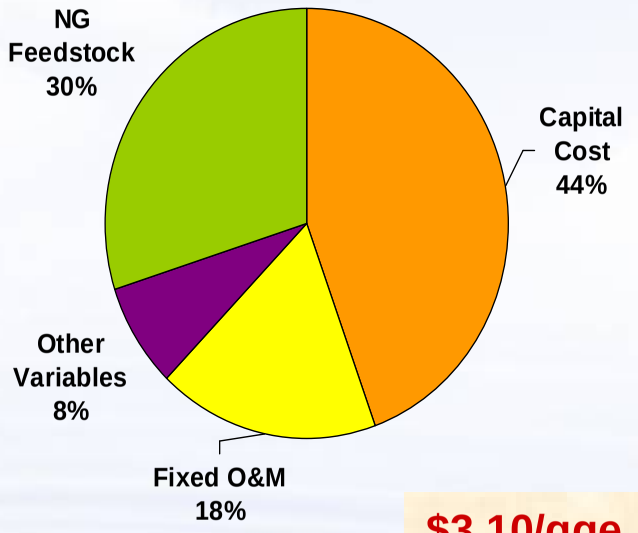


Sensitivity Analyses and Cost Breakdown

Sensitivity Analyses for Distributed Hydrogen Production from Natural Gas



Cost Breakdown of Hydrogen from Distributed Natural Gas



$3.10/gge

Hydrogen Costs based on:

- Combination of best available research
- Projected to 500 units/year
- Next Step: Field Validation

Centralized Hydrogen Production from Wind

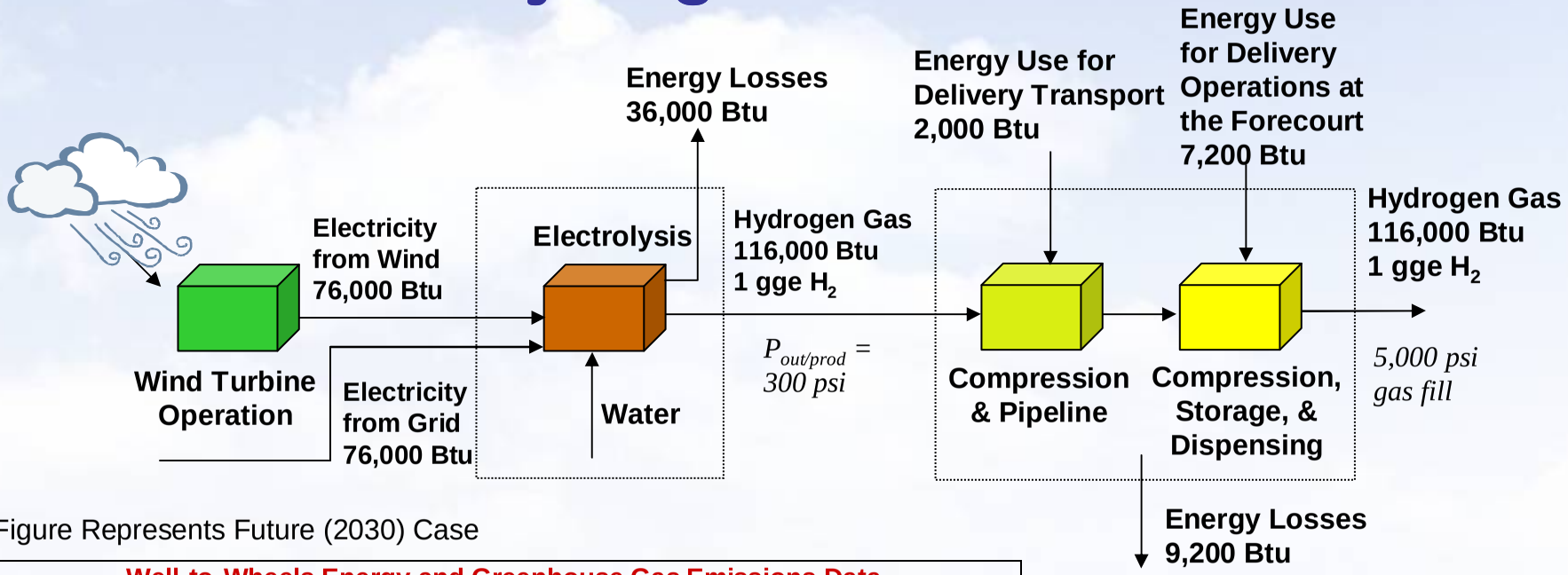


Figure Represents Future (2030) Case

Capacity = 1500 kg/day

Well-to-Wheels Energy and Greenhouse Gas Emissions Data				
	Current (2005) Gasoline ICE Vehicle	Current (2005) Gasoline Hybrid Electric Vehicle	Current (2005) Central Electrolysis Using Wind - FCV	Future (2030) Central Electrolysis Using Wind/Grid - FCV
Well-to-Wheels Total Energy Use (Btu/mile)	5,900	4,200	3,800	4,700
Well-to-Wheels Petroleum Energy Use (Btu/mile)	5,300	3,800	20	100
Well-to-Wheels Greenhouse Gas Emissions (g/mile)	470	340	50	50
Cost of Hydrogen ($/gge, Delivered)			9.50	2.70

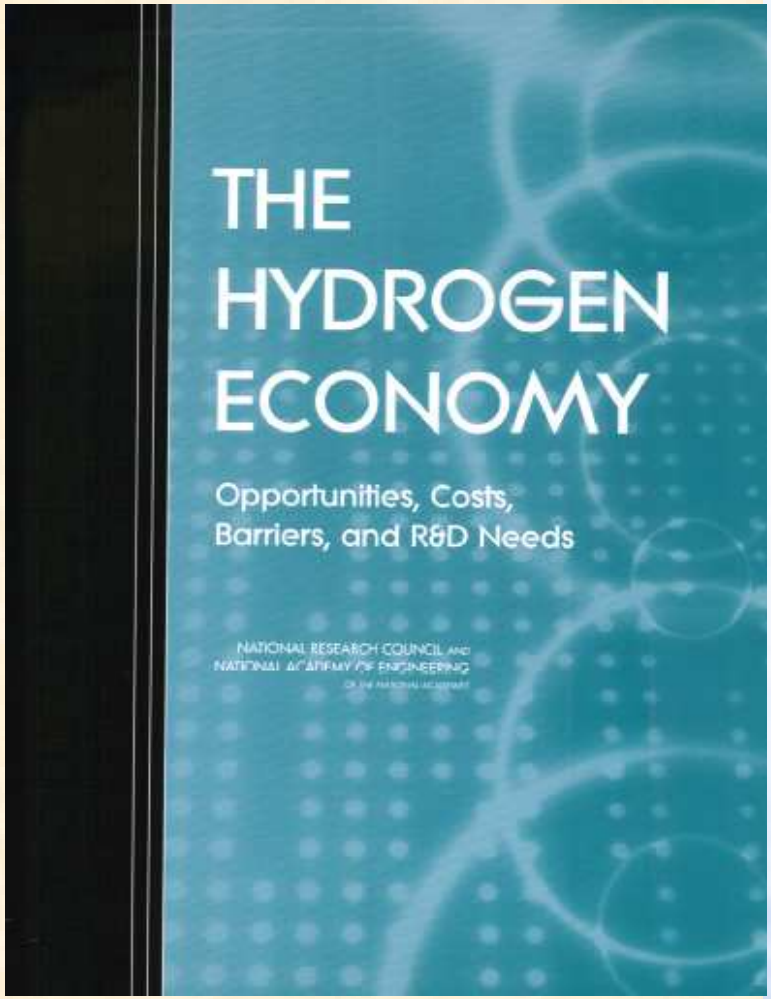
Source: NREL and H2A model
http://www.hydrogen.energy.gov/h2a_production.html

Current (2005) Case: No grid; 41% capacity factor; liquid delivery ($3.50/kg); Wind electrolysis=$0.049/kW-h; 64% LHV electrolyzer efficiency

Future (2030) Case: Grid back-up; 97% capacity factor; 85% GHG sequestration; pipeline delivery ($1.00/kg); Wind electrolysis=$0.030/kW-h; 76% LHV electrolyzer efficiency

Recommended Reading

- Extensive "well-to-wheels" analysis
  - Appendix E spreadsheets
- Independent
- Authoritative
- Comprehensive



THE NATIONAL ACADEMIES PRESS

http://fermat.nap.edu/books/0309091632/html/

Technology Validation Strategy

Provides Public, Congress, Stakeholders an Independent "risk assessment"

- Conduct learning demonstrations of hydrogen infrastructure in parallel with hydrogen fuel cell-powered vehicles to enable and assess technology readiness for a 2015 commercialization decision.
  - **Not a "Commercialization" demonstration to prepare the market**

Major Objectives

- Obtain detailed component data under real-world conditions (climatic, geographic etc.) to re-focus the Department's hydrogen and fuel cell component and materials research
- Validate the technology against time-phased performance-based targets, by 2009
  - **2,000 hour fuel cell durability**
  - **$3.00 per gge (full scale,hi vol.)**
  - **250 mile range**

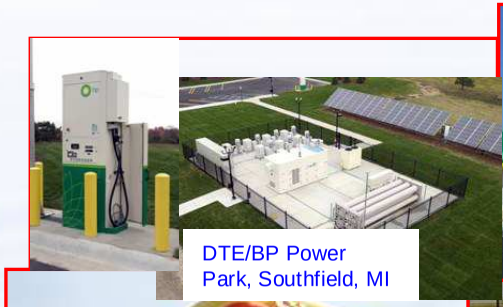
DaimlerChrysler

Ford Motor Company

Hyundai

General Motors

Photo: Shell Hydrogen



DTE/BP Power Park, Southfield, MI

BP LAX refueling station

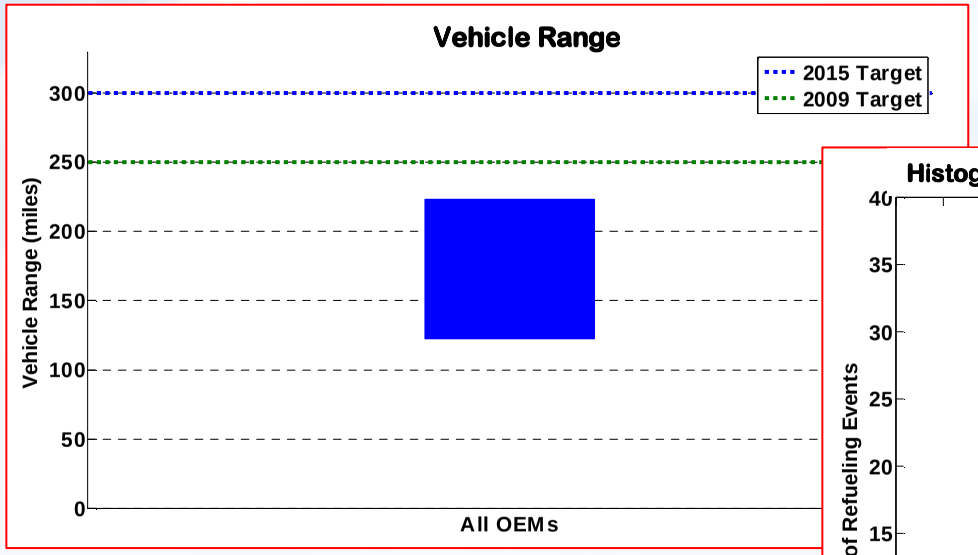
Shell hydrogen and gasoline station, WA DC

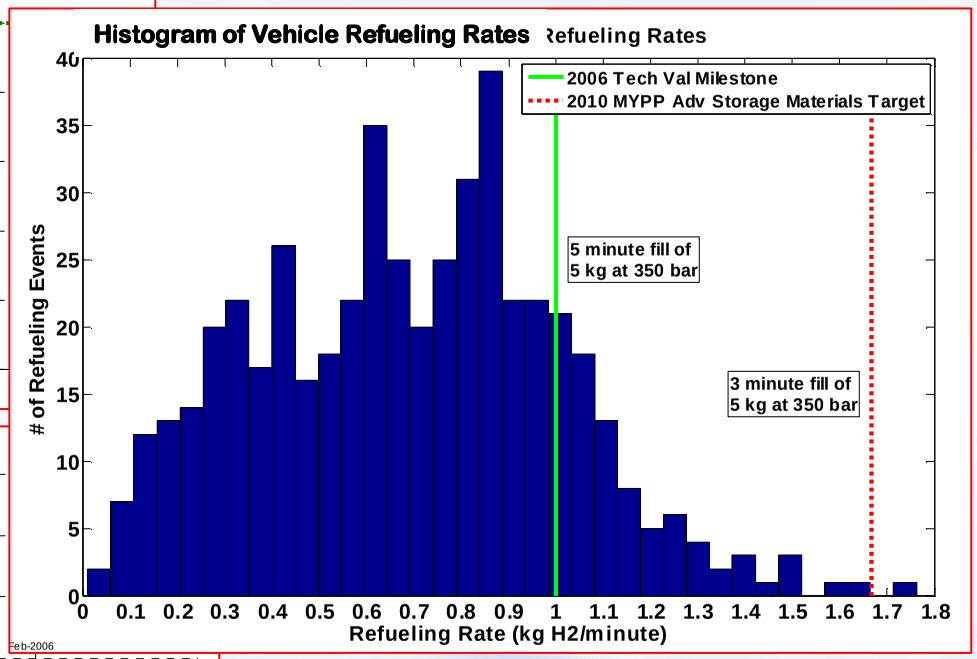
Photo:Shell Hydrogen

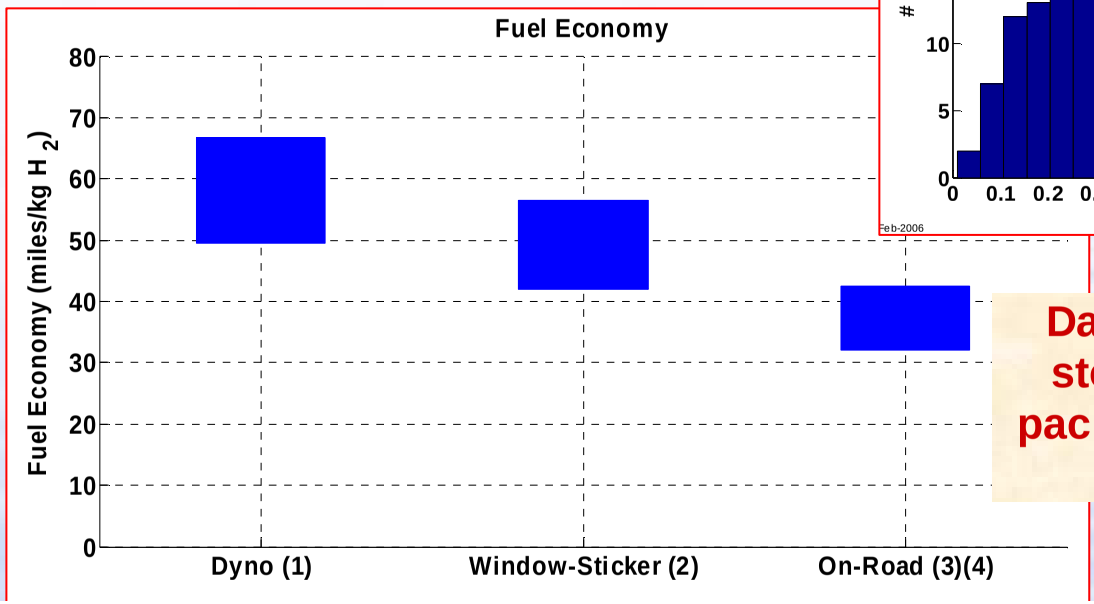
ChevronTexaco, Chino, CA

Photo: H2CarsBiz

Real – World Composite Data







Data indicate improved hydrogen storage technologies that can be packaged in a vehicle are necessary to meet range targets

Key Research Goals for FY 2006

- Independent verification of achievement of $3.00/gge of hydrogen from distributed natural gas
- Independent validation of achievement of $110/kW for PEM fuel cells at high production volume
- Independent assessment of cryo-compressed technology for on-board storage against 2010 targets
- Go/No-go decision on 6 wt.% (material) on single walled carbon nanotubes

Other New Initiatives

- Hydrogen Quality
- Advisory Panel (HTAC)

Manufacturing Initiative: Secretary Bodman Unveils *Roadmap on Manufacturing R&D for the Hydrogen Economy* for Public Comment on January 24, 2006

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