

ENERGY SECURITY for the 21ST CENTURY

Reliable, Affordable, Environmentally-Sound Energy



Challenges and Benefits of a Move Towards Hydrogen Fuel



Steven Chalk
Hydrogen Program Manager

24 April 2006

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

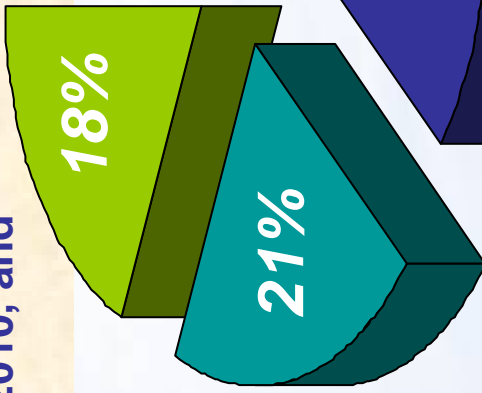
President Bush Announces Advanced Energy Initiative in 2006 State of the Union Address

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 Fossil Energy (\$444 million)

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



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

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

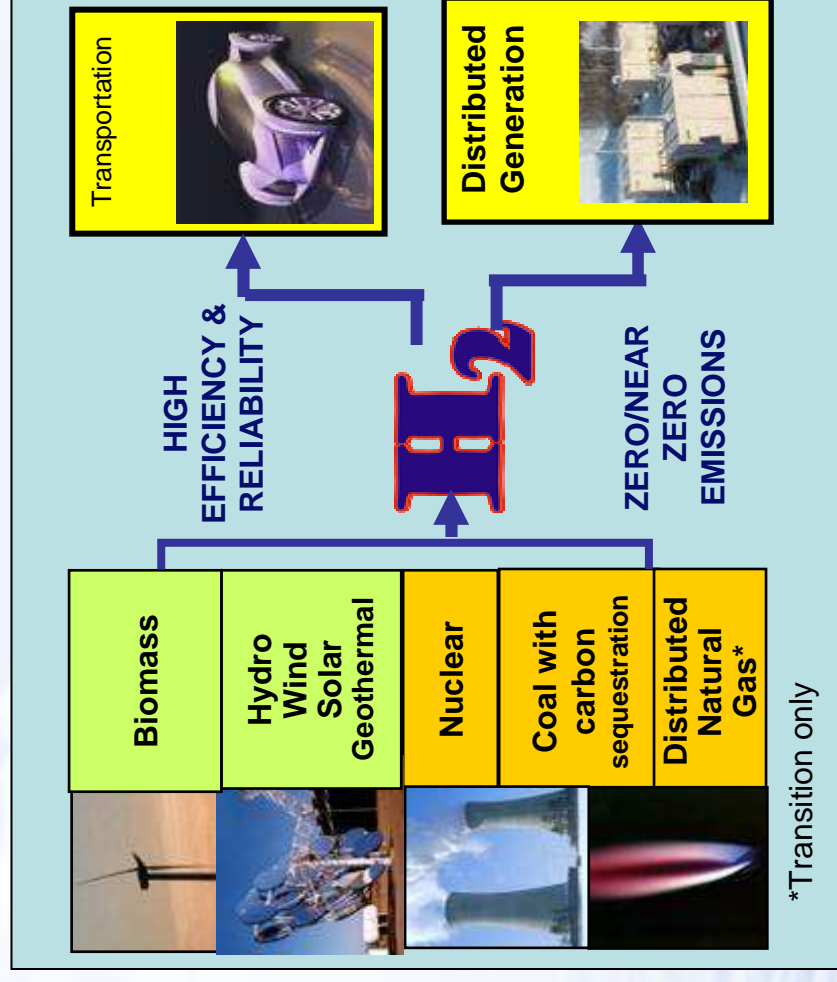
- Only with carbon capture & sequestration
- Gasification process produces hydrogen directly
- Electricity not produced as an intermediary

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

EPAc 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.

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

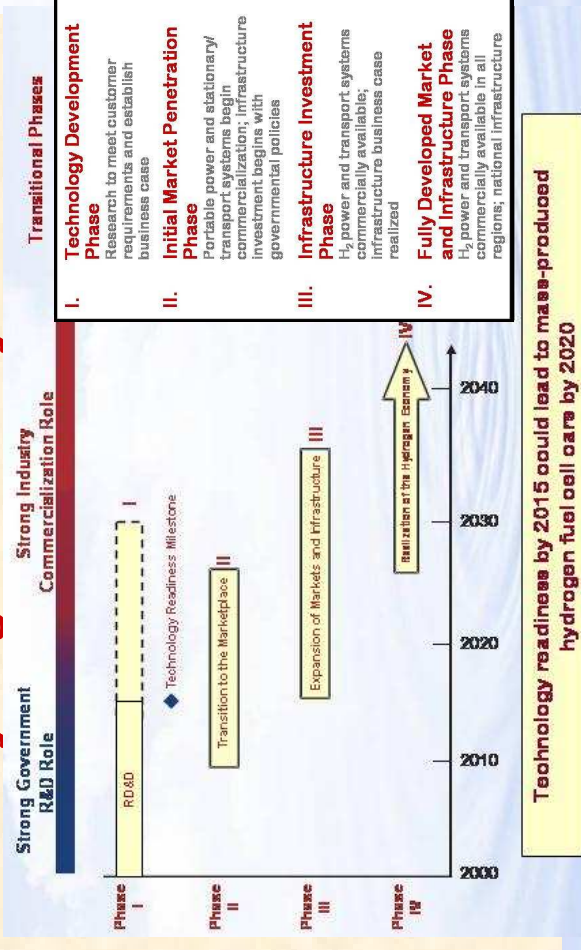
By 2020: Enable consumers to purchase vehicles and make hydrogen available

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



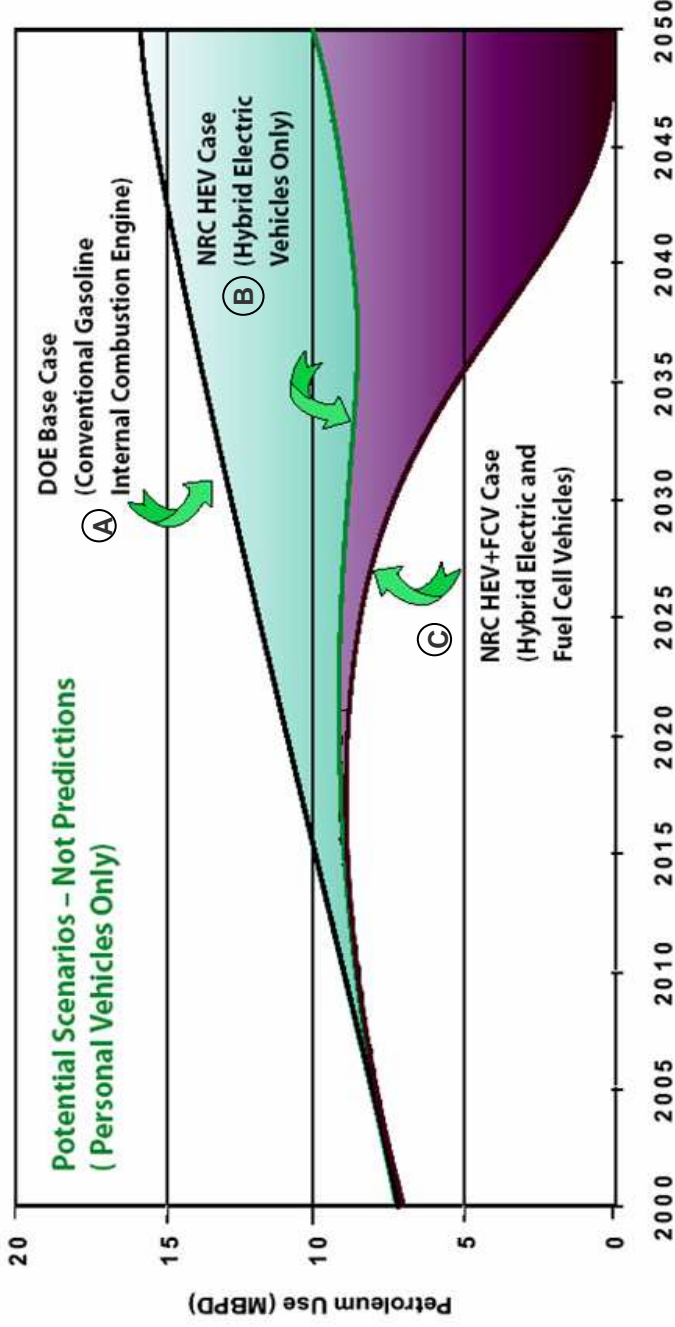
President Bush signs Energy Policy Act into law on August 8, 2005

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 CO₂ 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

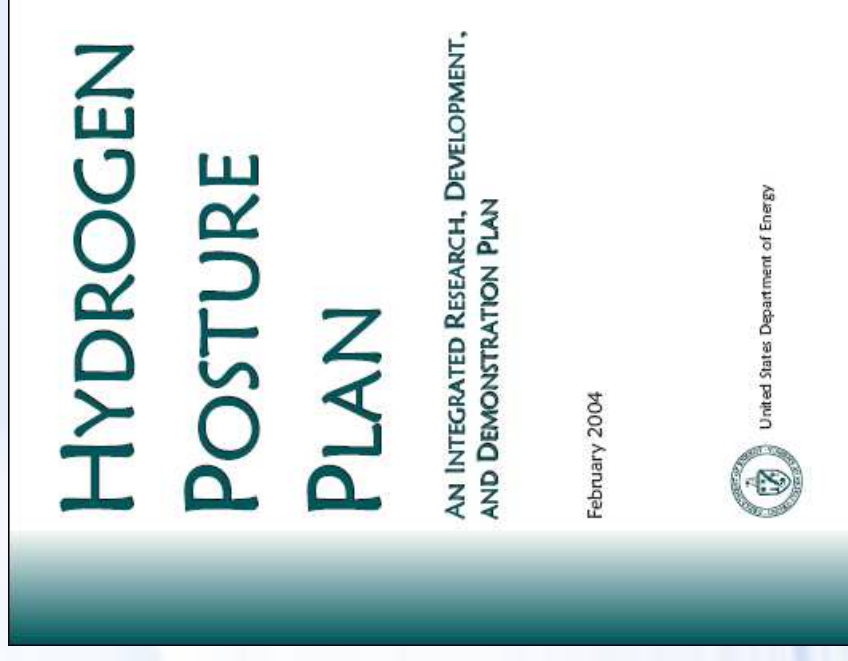
Posture Plan Describes the Research, Development & Demonstration Activities

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:

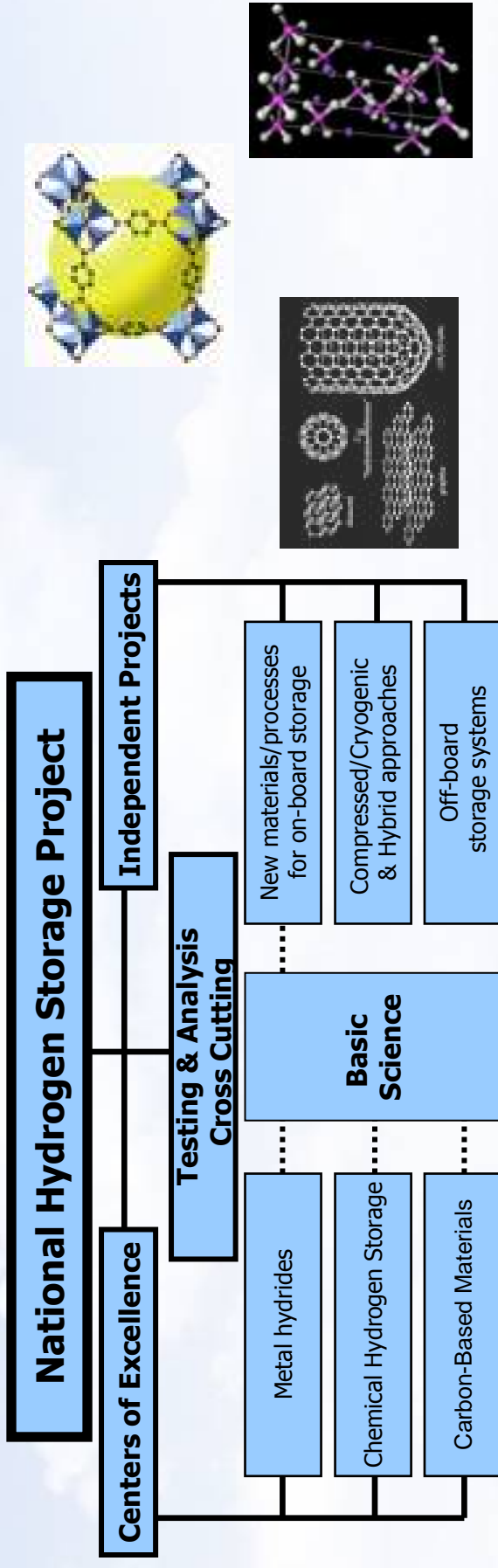
- Codes and Standards (Safety, and Global Competitiveness)
- Hydrogen Delivery (Investment for new Distribution Infrastructure)
- Education



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

Hydrogen Storage: The Grand Challenge

Focused on *Materials-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.

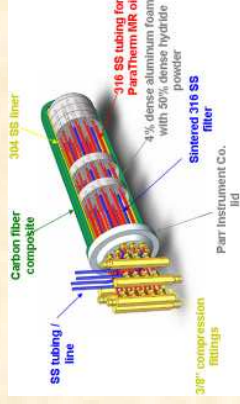
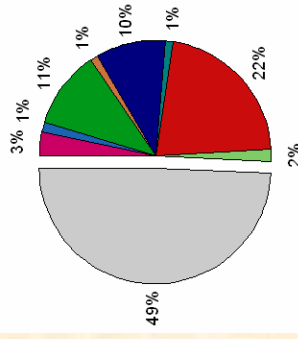
	Specific Energy	Energy Density	Cost
2015 Targets (2010)	3.0 kwh/kg (2.0)	2.7 kwh/L (1.5)	\$2/kWh (4)
5,000 psi System*	1.9 kwh/kg	0.5 kwh/L	\$15/kWh
10,000 psi System*	1.6 kwh/kg	0.8 kwh/L	\$18/kWh

* Status of tank technology, 2005

Hydrogen Storage Update

Diverse Portfolio Starting to Show Promising Results

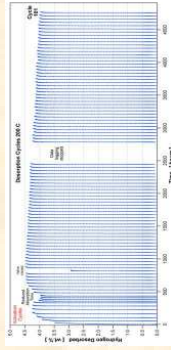
Prototype built (~50% is BOP)



Anton et al, UTRC

LiMg Amides ~5 wt%, 100 cycles

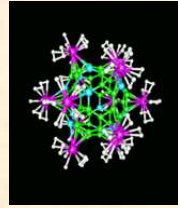
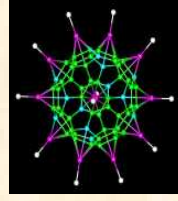
Sandia Livermore:
Luo, Gross, et al



Destabilized hydrides & nanoscience

> 9 wt% shown $\text{LiBH}_4 / \text{MgH}_2$: Vajo, et al, HRL

Materials modeled for capacity:

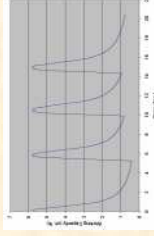


Potential for 8.8 wt%

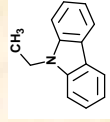
Zhao, Heben,
Dillon, et al
NREL



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

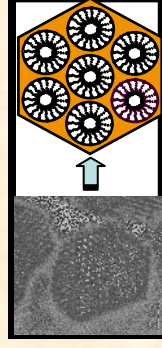


N-ethyl-carbazole



Cooper,
Pez, Air
Products

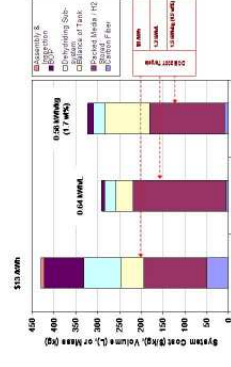
Mesoporous scaffolds with ammonia borane show >6 wt% (at < 80C & reduced byproducts)



Autrey, Gutowski,
et al, PNNL

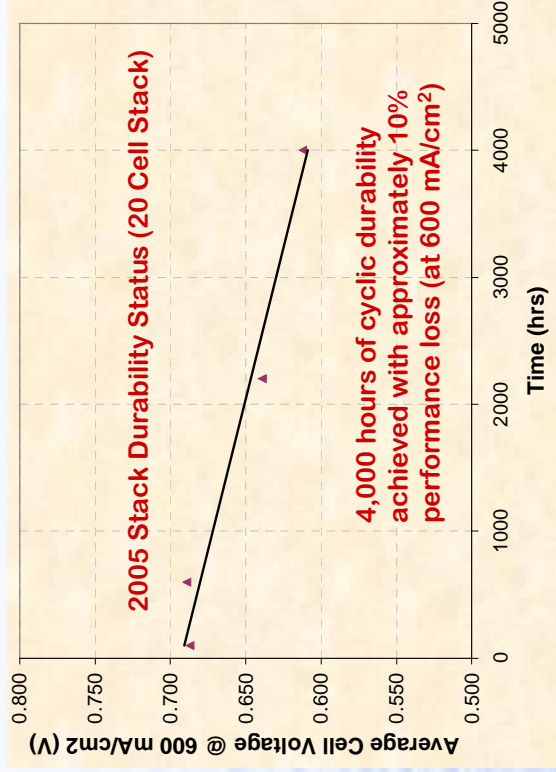
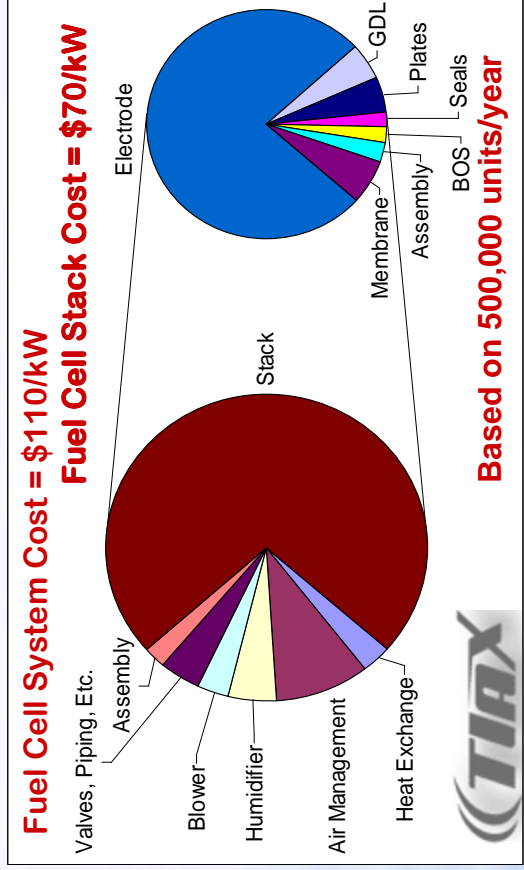
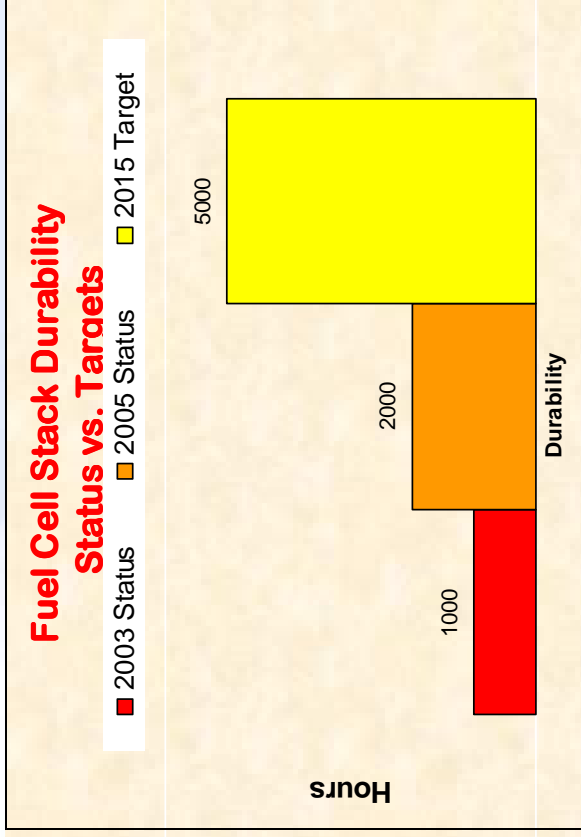
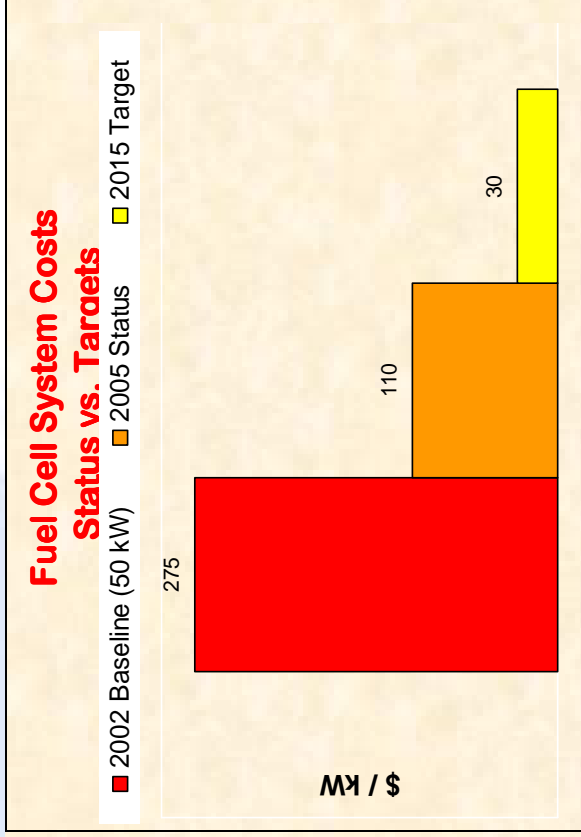
Storage Systems Analysis Working Group Established

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



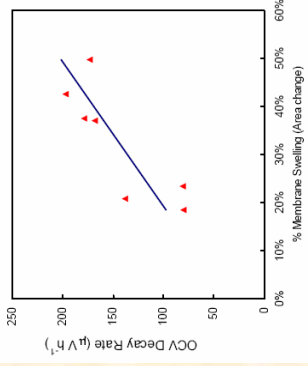
TIAX, ANL

Accomplishments: Reduced High Volume Fuel Cell Cost and Increased Durability



Fuel Cell Development Highlights

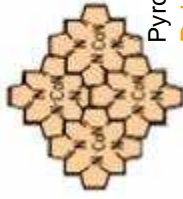
Durability improvements, MEA & PEMFC



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

DuPont/UTC

Improved high current activity of non-Pt catalysts

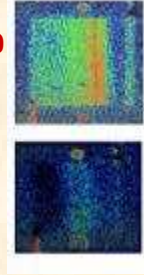
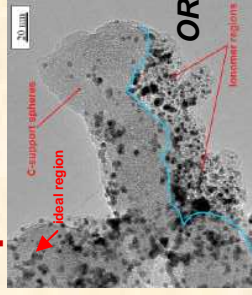


Density 2/3 that of state-of-art Pt

Pyropolymer CoTMPP
Poly (CoN₄C₃₆)_n

LANL

Improved characterization imaging



NIST, SNL, et al

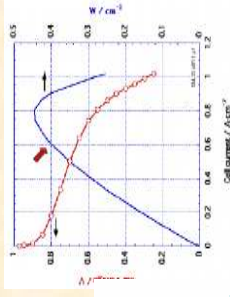
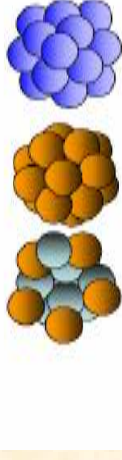
Real-time imaging of H₂O in FC components during operation

TEM imaging of new & used FC components

Higher FC catalyst activity with less Pt

Synthesis

Au + Ni co-deposit Pt deposited by replacing Cu

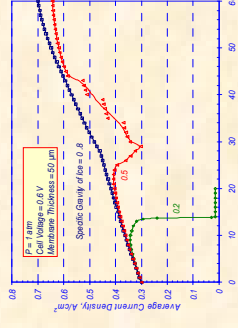
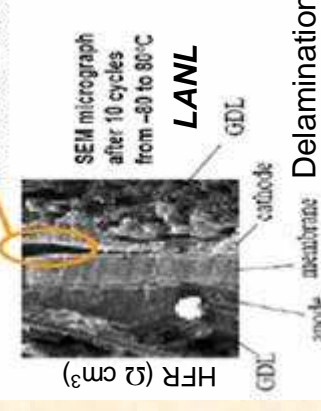


BNL, MEA testing at LANL

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

Subfreezing effects & analysis

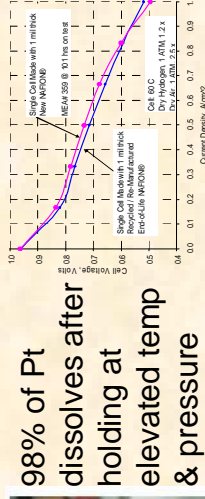
Interfacial delamination



Modeled startup from subfreezing conditions (<30 s)

Delamination of cathode catalyst at <-40°C

Developed FC with remanufactured membrane



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

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

Ion Power, Engelhard

Accomplishments: Analytical Tools Developed for Production/Delivery

Standard Price and Property Data

Feedstock and Utility Prices
Physical Property Data

Information Description
Title

Financial Inputs
Performance Assumptions

Cost Analysis

Cost Inputs
Process Flowsheet
Replacement Costs
Stream Summary

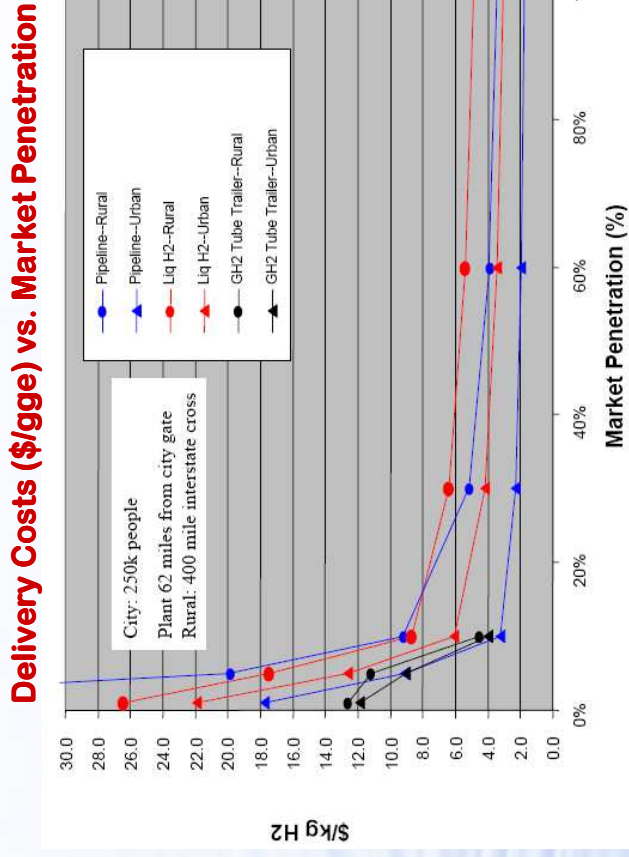
Results

Cash Flow
Cost Contribution
Sensitivity Analyses

Technical Analysis

The screenshot shows the Hydrogen Analysis Resource Center website. The main heading is "Welcome to the Hydrogen Analysis Resource Center". Below this, there is a paragraph describing the center's mission: "The Hydrogen Analysis Resource Center provides well-documented, reliable data to be used for hydrogen-related analytical activities. These data can serve as the basis for calculations, modeling, and other analytical activities. Data can be accessed from databases housed in the site itself as well as through links to important websites such as those maintained by the Energy Information Administration (EIA), U.S. Department of Energy (DOE) Programs, other U.S. Government Agencies, and non-government websites. The search feature of the site allows the user to seamlessly search available data, independent of whether the data are from internal or external sources. The website also provides guidelines and a set of assumptions for use in Hydrogen Program analysis projects (these assumptions will be updated annually). In addition, the website contains several calculator tools that do useful conversions and other simple calculations relevant to hydrogen and fuel cells and links to websites housing more sophisticated analysis tools such as the H2A website, the GREET website, and others analyses."

Navigation links include: Home, Hydrogen Data Book, Hydrogen Glossary, Related Sites, Guidelines and Assumptions, Calculator Tools, Analysis Tools, Contact Us, and Advanced Search.



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

Analysis of Distributed Hydrogen Production from Natural Gas Reforming

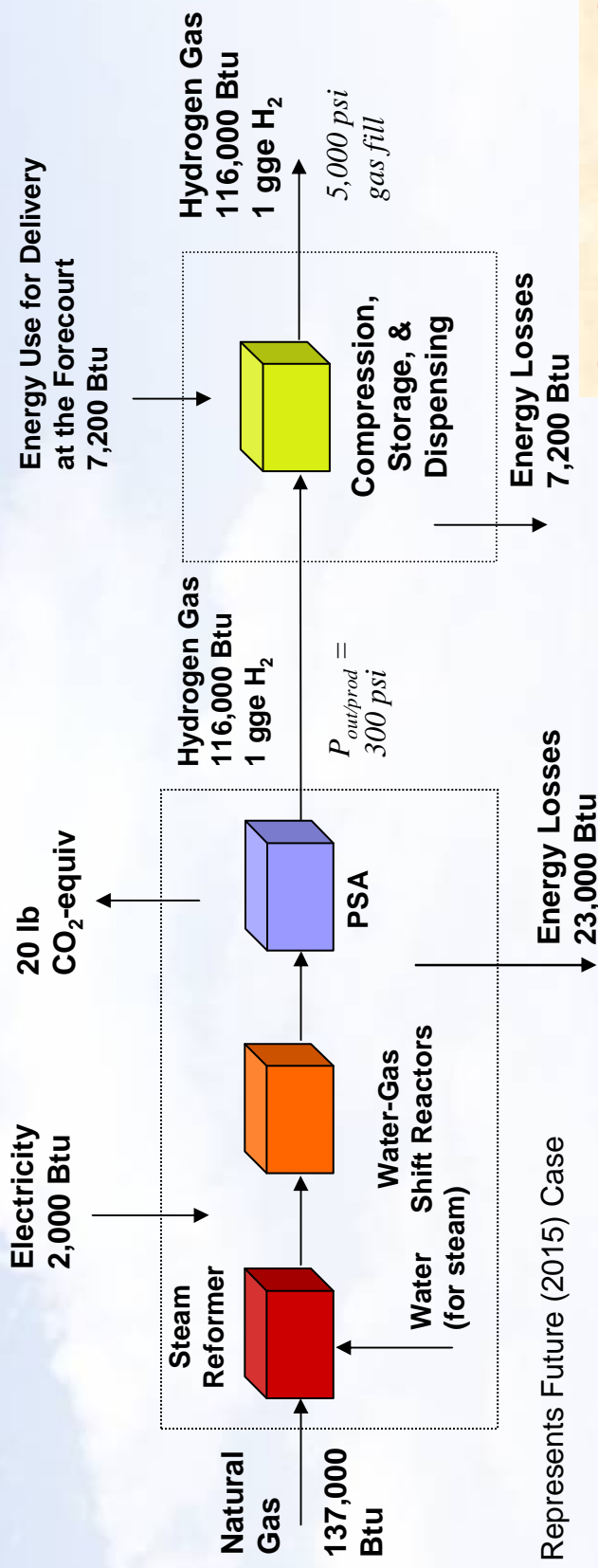


Figure Represents Future (2015) Case

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

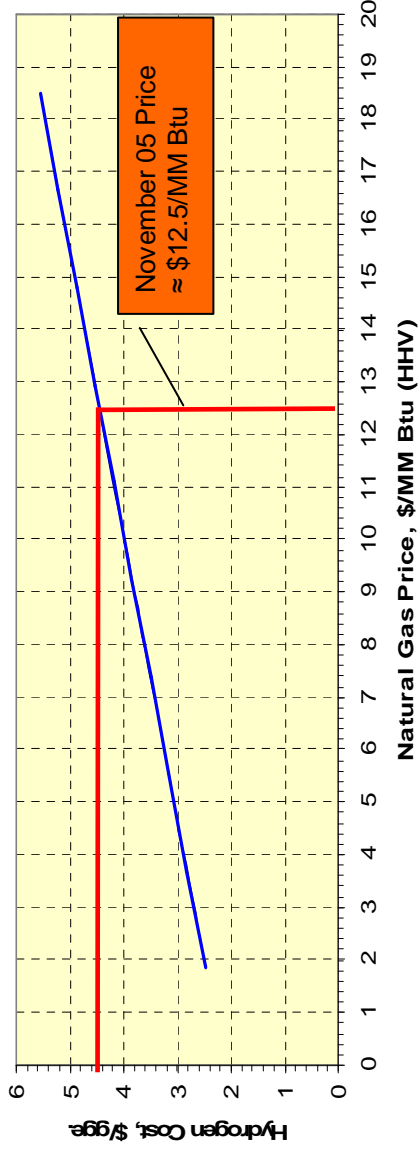
Source: NREL and H2A model
http://www.hydrogen.energy.gov/h2a_production.html

- **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

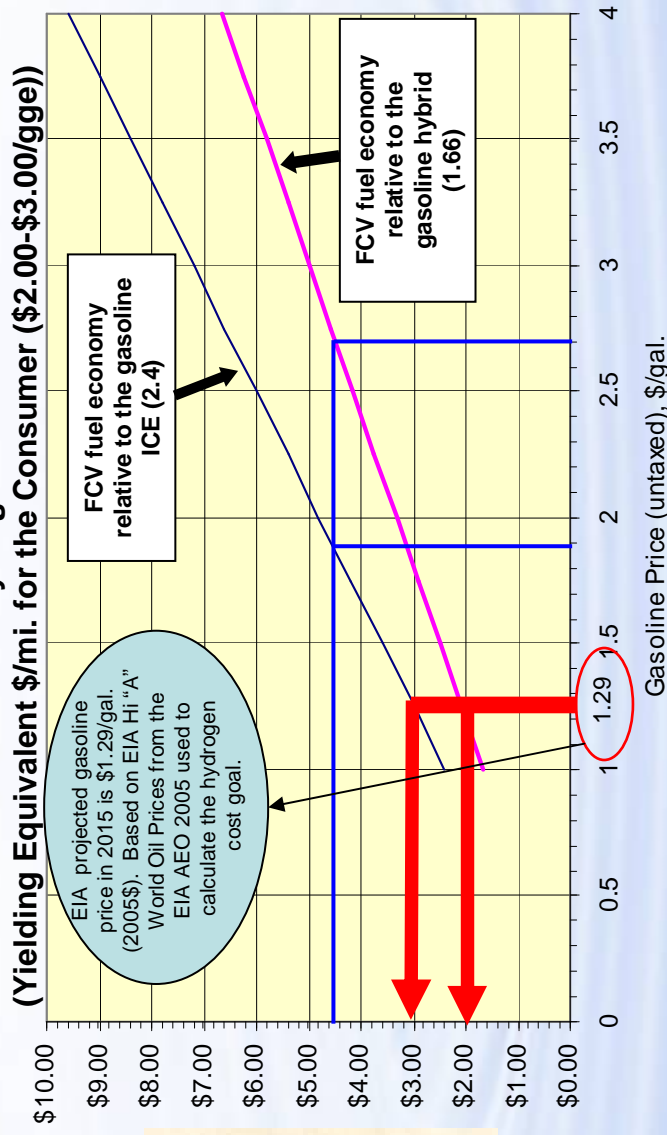
Hydrogen Production Cost from Distributed Natural Gas Versus Sensitivity to Natural Gas Price (HHV)



- 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)**

Model for Hydrogen Cost Goal



(Yielding Equivalent \$/mi. for the Consumer (\$2.00-\$3.00/gge))

EIA projected gasoline price in 2015 is \$1.29/gal. Based on EIA Hi "A" (2005\$). World Oil Prices from the EIA AEO 2005 used to calculate the hydrogen cost goal.

FCV fuel economy relative to the gasoline ICE (2.4)

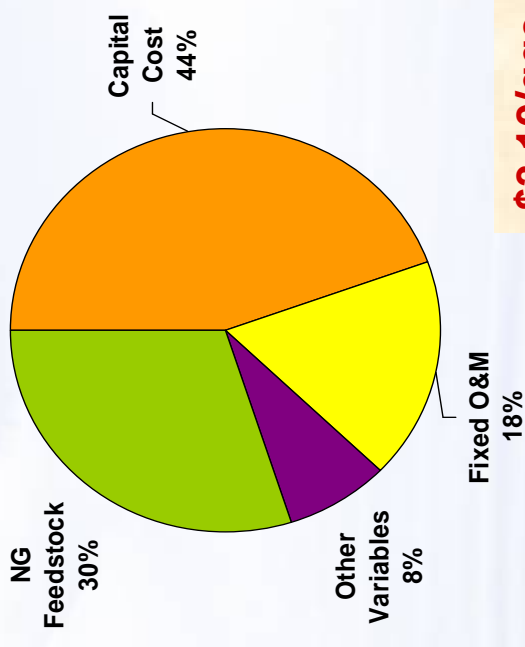
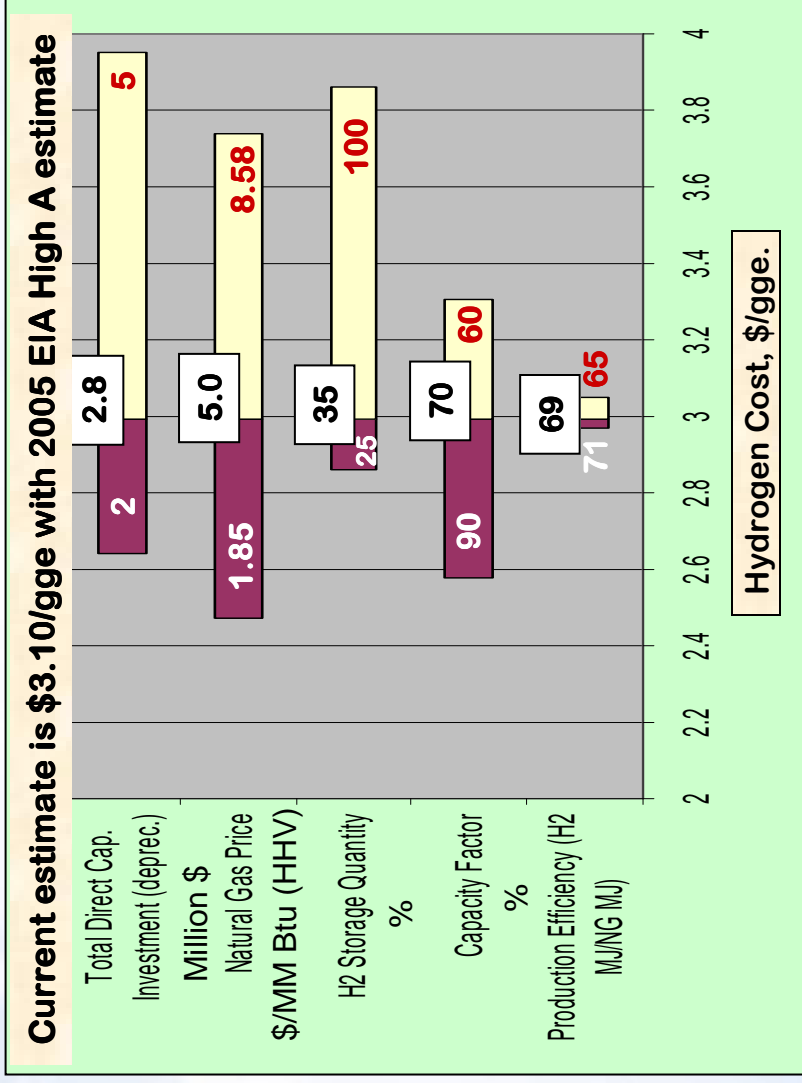
FCV fuel economy relative to the gasoline hybrid (1.66)

Gasoline Price (untaxed), \$/gal.

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

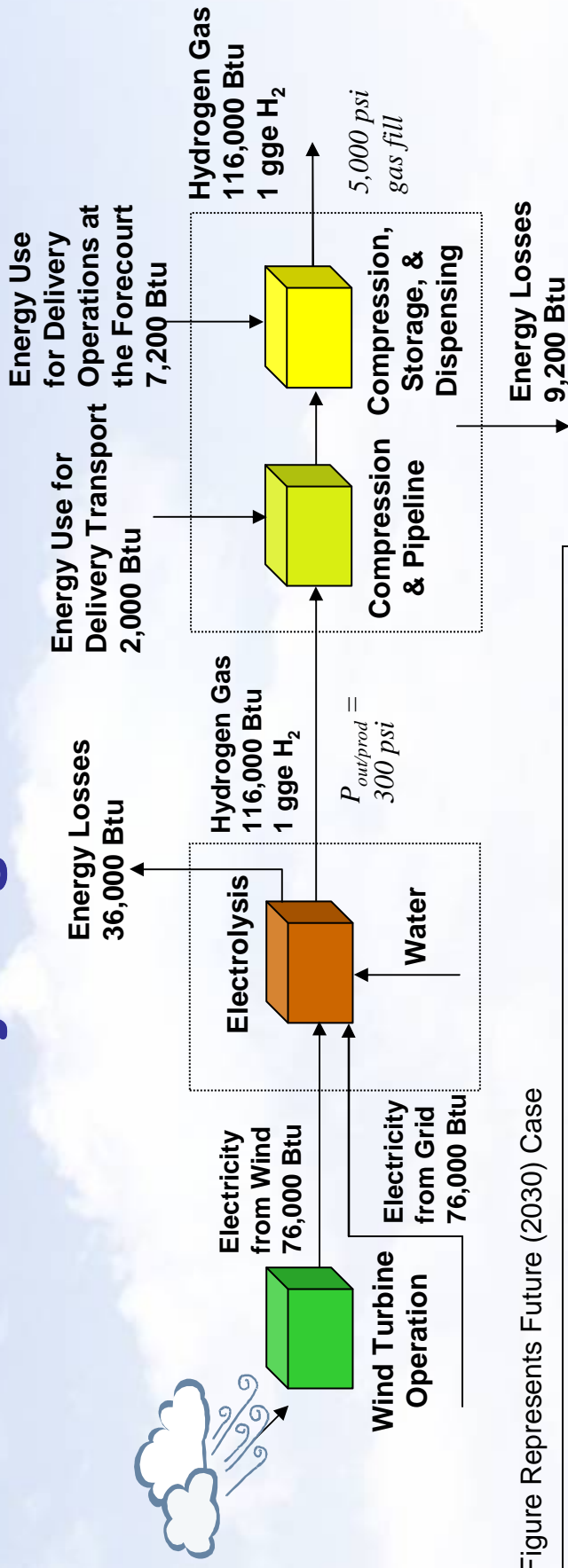


Figure Represents Future (2030) Case

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

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

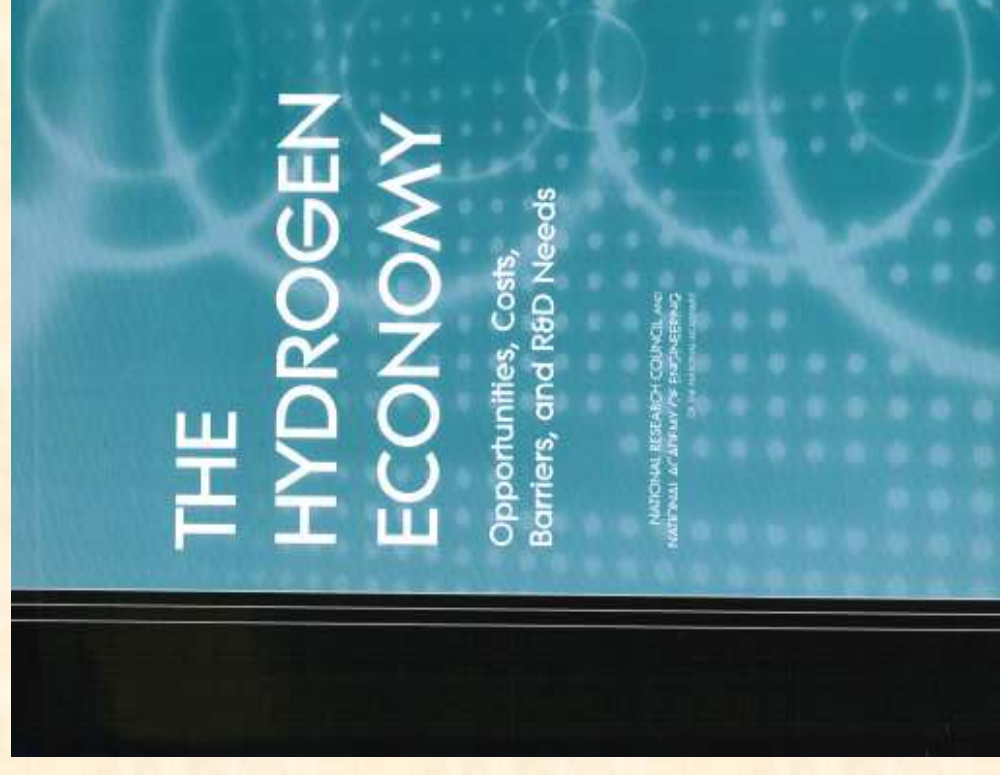
Future (2030) Case: Grid back-up; 97% capacity factor; 85% GHG sequestration; pipeline delivery (\$1.00/kg); Wind electrolysis=\$0.030/kW-h; 76% LHV electrolyzer efficiency

Capacity = 1500 kg/day

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

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



Hyundai



Ford Motor Company



General Motors

Photo: Shell Hydrogen



DTE/BP Power Park, Southfield, MI



BP LAX refueling station



Shell hydrogen and gasoline station, WA DC

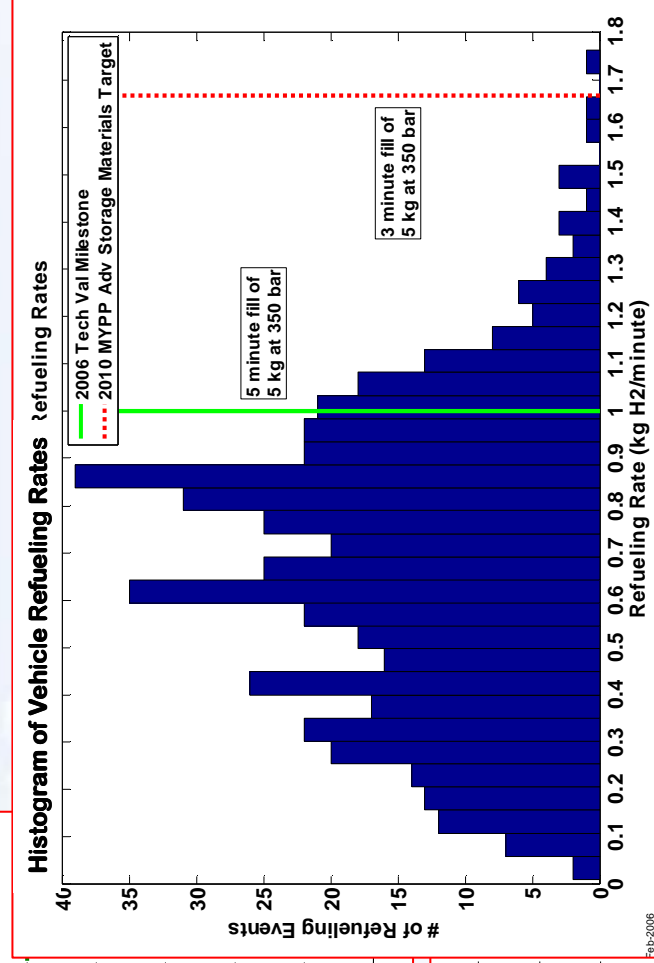
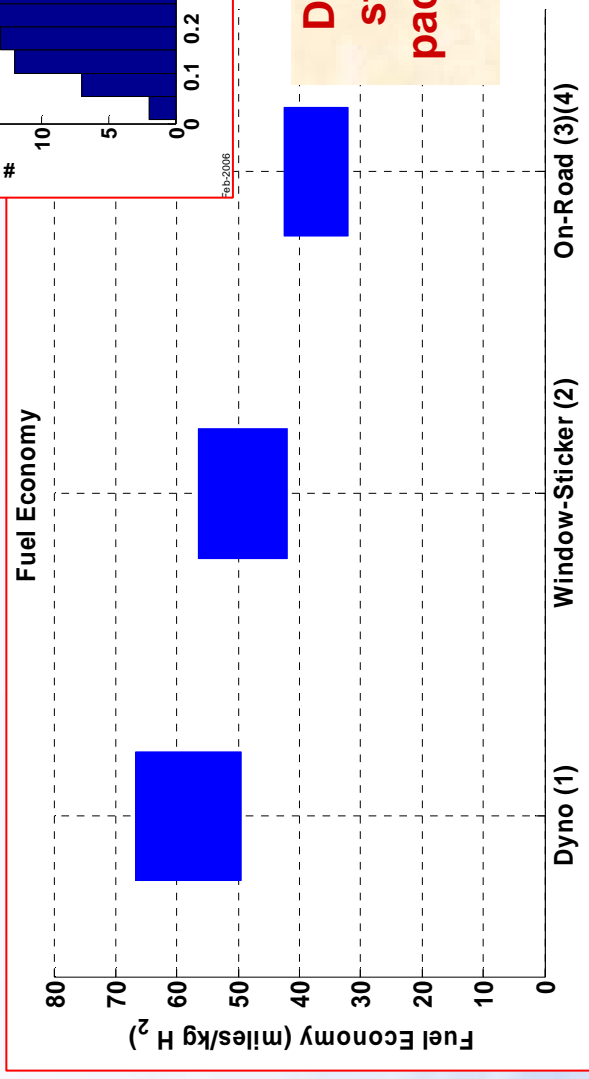
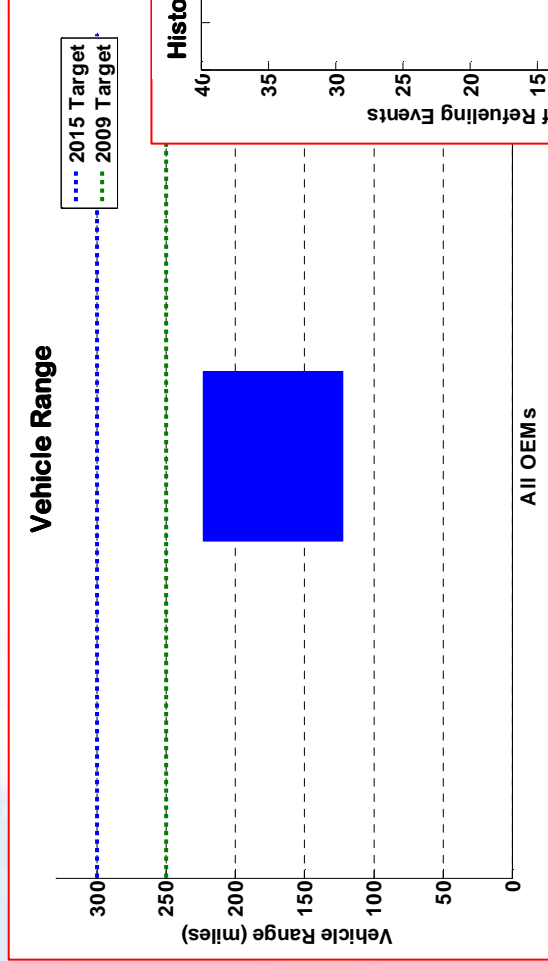
Photo: Shell Hydrogen



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

www.hydrogen.energy.gov

Find....


- The latest news, reports & announcements
- Status information about program solicitations
- Fuel cell and hydrogen "basics"

December 2005

Solar and Wind Technologies For Hydrogen Production


Report to Congress

(ESECS EE-3060)



DRAFT FOR STAKEHOLDER/PUBLIC COMMENT

Roadmap on Manufacturing R&D for the Hydrogen Economy



U.S. Department of Energy • Office of Future Energy
HYDROGEN FROM COAL PROGRAM
RESEARCH, DEVELOPMENT AND DEMONSTRATION PLAN FOR THE PERIOD 2004 THROUGH 2015
EXTERNAL DRAFT FOR REVIEW
September 26, 2005
SECURING OUR ENERGY FUTURE



U.S. DEPARTMENT OF ENERGY
Hydrogen Program

Home DOE Program Office/Programs International Library News/Events

Hydrogen Production
Hydrogen Storage
Conversion/Fuel Cells
Applications/Technology Validation
Safety
Codes & Standards
Education
Basic Research
Systems Analysis
Systems Integration

News
Progress on Solid Oxide Fuel Cells
Achievement brightens prospects for environmentally clean technology to move into mainstream energy markets...
January 3, 2005 [More >](#)

Nuclear Hydrogen Research Awards Announced
DOE announced 35 research awards to U.S. universities totaling \$21 million over three years...
December 23, 2004 [More >](#)

Office of Science Hydrogen Awards to be Announced in June 2005
The 227 full proposals are in the process of undergoing external peer review. [More >](#)

DOE Office Hydrogen Plans
Nuclear Hydrogen R&D Plan
(Office of Nuclear Energy, Science & Technology)
March 2004
(PDF 1.02 MB)
[Hydrogen, Fuel Cells & Infrastructure Technology](#)

President's Hydrogen Fuel Initiative
[Hydrogen.gov](#)

National Energy Policy
(DOE-3.05 MB)

DOE Strategic Plan
(PDF 1.68 MB)

Hydrogen Vision
(DOE-1.072 MB)

Hydrogen Roadmap
(DOE-1.56 MB)

2005 ANNUAL PROGRESS REPORT

DOE Hydrogen Program



Results of the 2005 Annual Merit Review and Peer Evaluation Report
May 23-26, 2005 Arlington, Virginia



U.S. Department of Energy
Hydrogen Program