U.S. Department of Energy
Energy Efficiency and Renewable Energy

DOE HYDROGEN PROGRAM

Overview

The Biomass – Hydrogen Connection

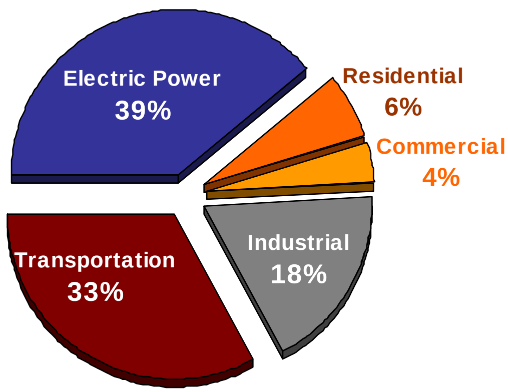
Biomass R&D Technical Advisory Committee

November 12, 2007

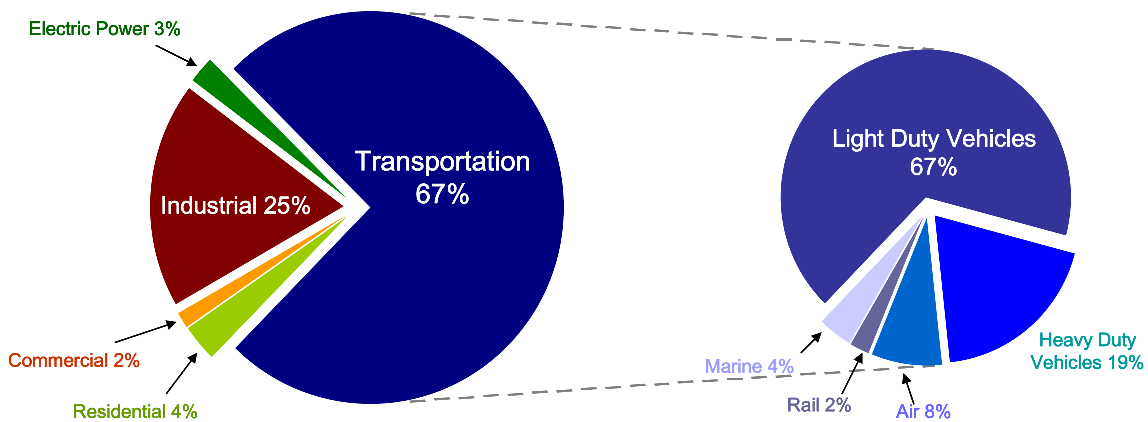
Mark Paster
Technology Development Manager
U.S. Department of Energy Hydrogen Program

Why Hydrogen?

Domestic CO_2 Emissions by Sector (2005)



Domestic Oil Consumption (2005)



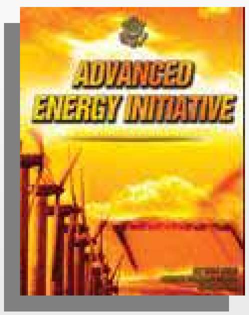
- **Transportation:** Use of Hydrogen in fuel cell vehicles can reduce oil use and carbon emissions in the transportation sector

- **Power Generation:** Hydrogen can enable clean, reliable energy for stationary and portable power generation

Hydrogen — ***The Policy Context***

HYDROGEN FUEL INITIATIVE (Jan. 2003):

- Launched the Department of Energy Hydrogen Program
- Committed $1.2 billion over five years (2004 – 2008)
- Provides funds to develop H_2, fuel cell and infrastructure technologies
- Goal: to make fuel cell vehicles practical and cost-effective by 2015



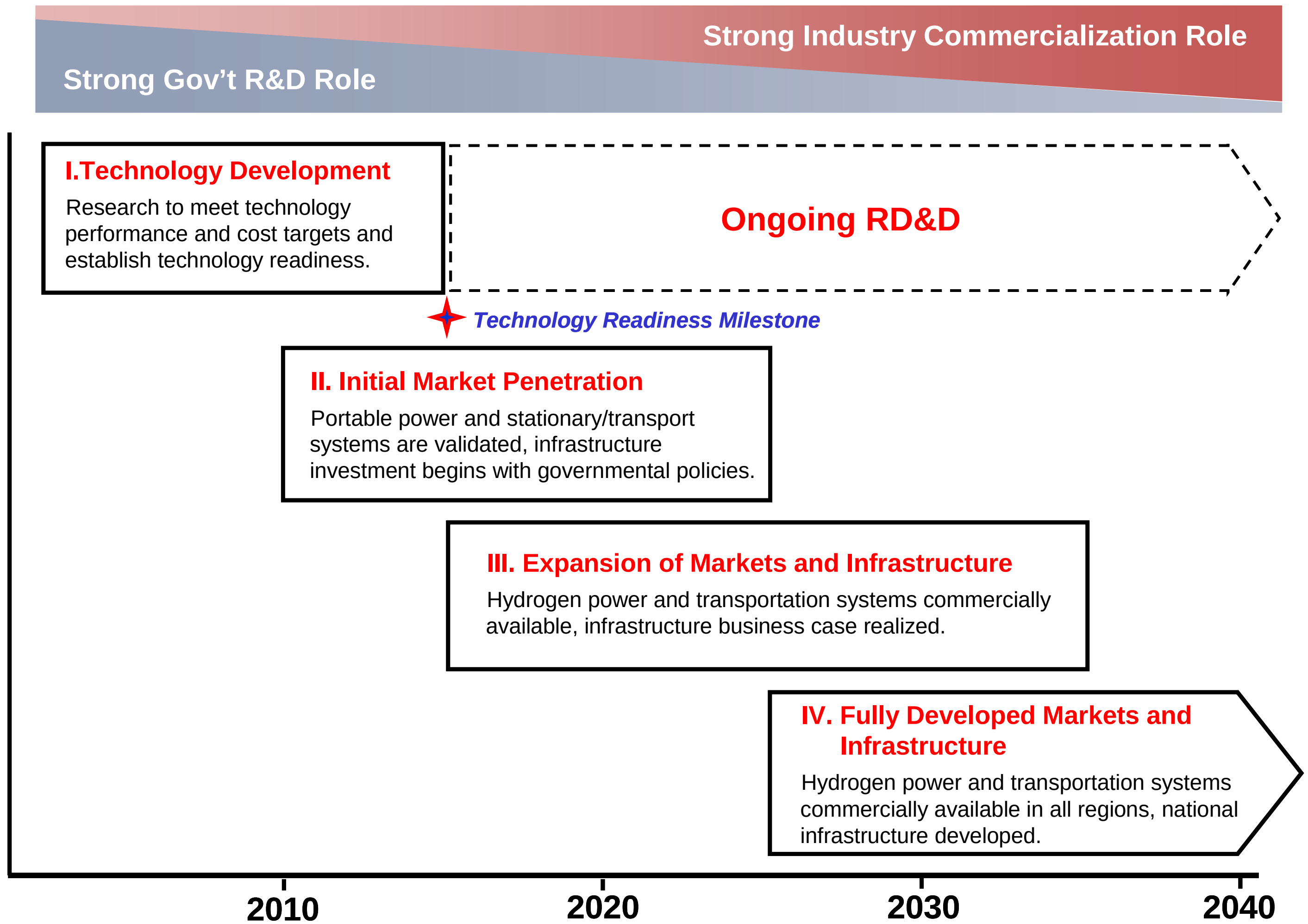
ADVANCED ENERGY INITIATIVE (Feb. 2006):

- Accelerates research on technologies for reducing dependence on oil for transportation and natural gas for power generation
- 22% increase in funding for clean energy research
- Reinforces Hydrogen Fuel Initiative
- Accelerates R&D for near-term vehicle options: biofuels & plug-in hybrids

"20-in-10" INITIATIVE (Jan. 2007):

- Sets target of 35 billion gallons of alternative fuels by 2017, to displace 15% of annual gasoline use in 2017 (plus 5% reduction in gasoline use through increased vehicle efficiency)
- Expands Renewable Fuel Standard (RFS) to "Alternative Fuel Standard" (includes corn ethanol, cellulosic ethanol, biodiesel, methanol, butanol, hydrogen, and other alternative fuels)

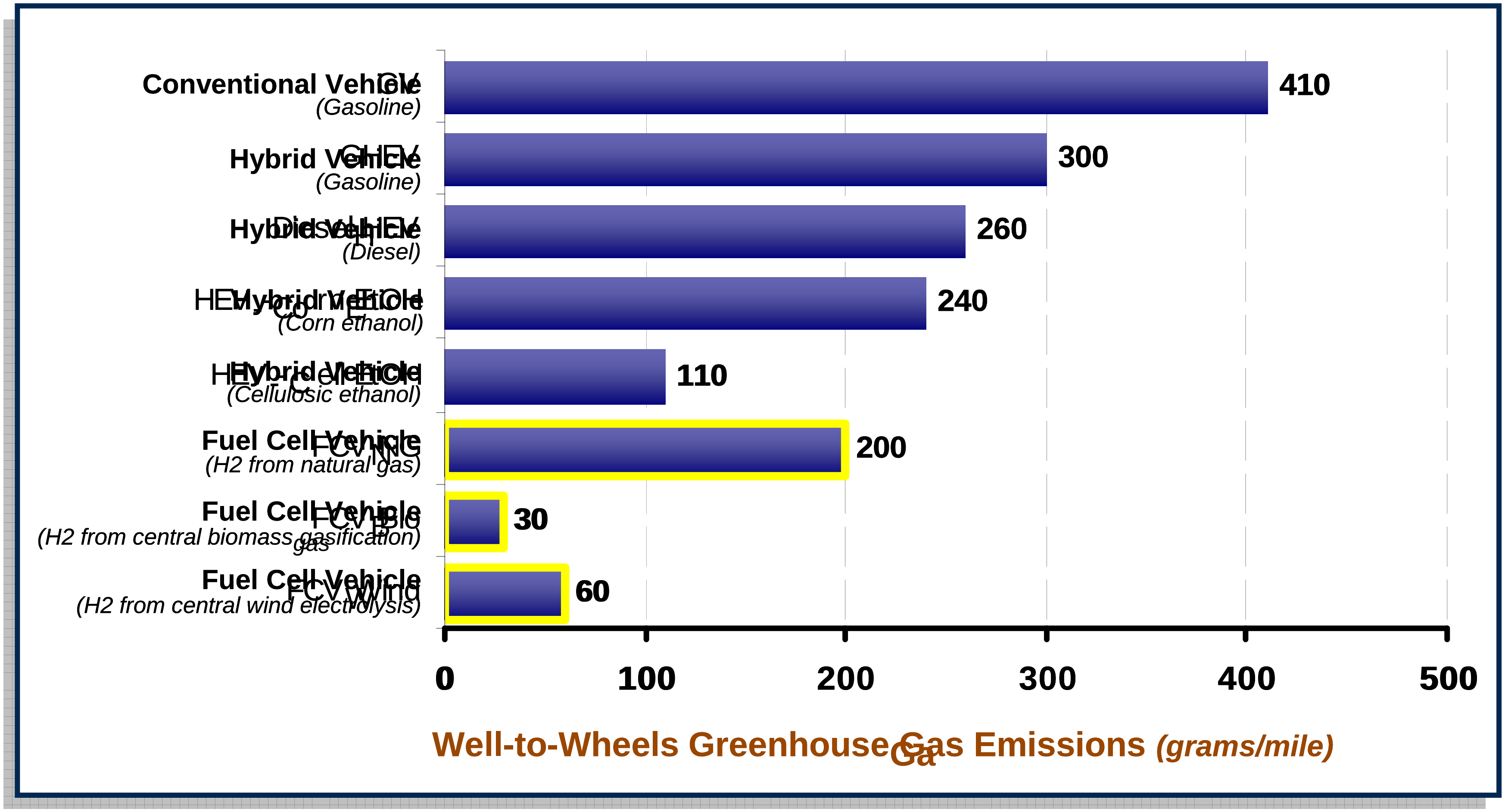
Hydrogen Economy Timeline



EPACT Title VIII authorizes $3 billion in funding (FY 2006 – FY 2010) for hydrogen and fuel cell research, development, demonstration, education, and codes and standards development. Additional funding is authorized for FY 2011 – FY 2020.

Benefits — *Reducing Greenhouse Gas Emissions*

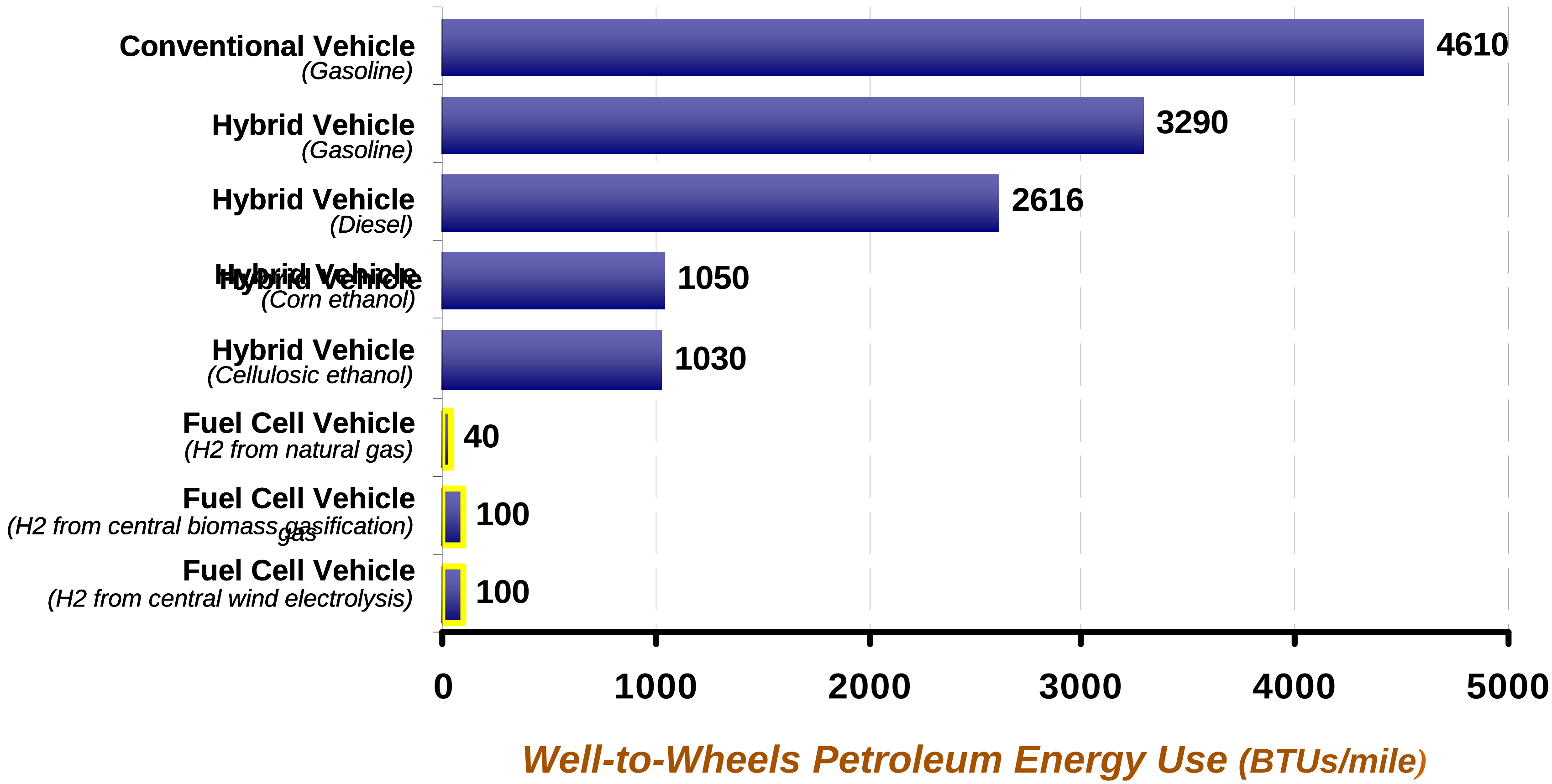
Well-to-wheels analysis shows that use of H_2—from a variety of sources—would reduce greenhouse gas emissions*



**Analysis based on technology expected to be available in 2015, except for central hydrogen production pathways, which are based on delivery infrastructure expected in 2030.*

Benefits — *Reducing Petroleum Use*

Well-to-wheels analysis shows that use of hydrogen—from a variety of sources—would reduce oil consumption*



**Analysis based on technology expected to be available in 2015, except for central hydrogen production pathways, which are based on delivery infrastructure expected in 2030.*

Challenges & Barriers

Technology Barriers

- **Hydrogen Cost**
  (target: $2 – $3/gge)
- **Hydrogen Storage Capacity & Cost**
  (targets: 2.7kWh/L, 3kWh/kg, and $2/kWh)
- **Fuel Cell Cost and Durability**
  (targets: $30 per kW, 5000-hour durability)

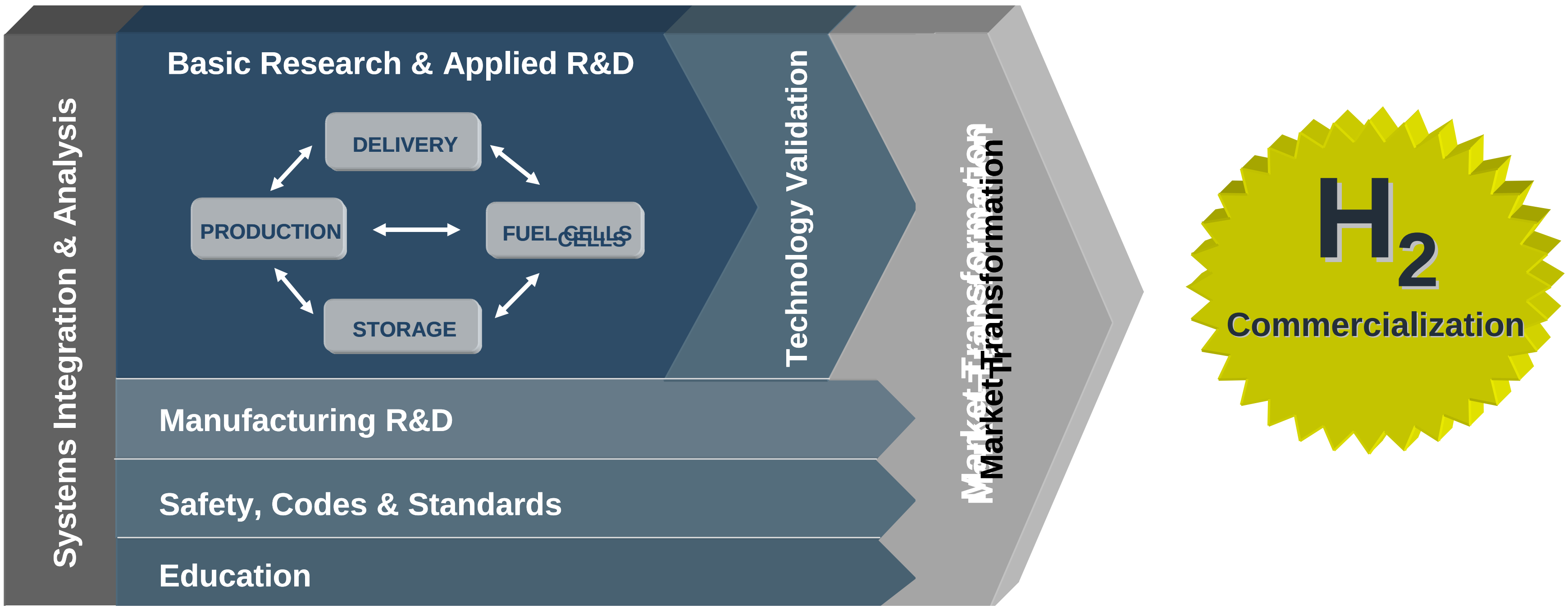
Technologies must be validated under real world conditions.

Economic & Institutional Barriers

- **Delivery Infrastructure**
  (target: <$1//gge)
- **Domestic Manufacturing and Supplier Base**
- **Safety, Codes & Standards Development**
- **Public Awareness & Acceptance**

Hydrogen Program Activities

The DOE Hydrogen Program is structured to tackle the wide range of barriers facing hydrogen and fuel cell commercialization



DOE Hydrogen Program – *Participants*

DOE – Office of Energy Efficiency & Renewable Energy

Research, develop, and validate fuel cell and H2 production, delivery, and storage technologies for transportation and stationary applications.

DOE – Office of Nuclear Energy

Operate sulfur-iodine thermochemical and high-temperature electrolysis experiments to gather data on operability and reaction rates.

DOE – Office of Science

Expand basic research on nano-materials for storage, catalysis for fuel cells, and bio-inspired and solar H_2 production. Increase emphasis on nano-structured design, novel synthesis, and theory and modeling of the physical and chemical interactions of hydrogen with materials.

DOE – Office of Fossil Energy

Continue studies for scaling up hydrogen membrane reactors and CO_2/H_2 separation technologies for coal-based hydrogen systems.

Hydrogen Fuel Initiative Funding —
By Participant Organization

Activity	Funding *($ in thousands)*				
	FY2004 Approp.	**FY2005** Approp.	**FY2006** Approp.	**FY2007** Approp.	**FY2008** Request
HYDROGEN FUEL INITIATIVE					
EERE Hydrogen (HFCIT)	144,881	166,772	153,451	189,511	213,000
Fossil Energy (FE)	4,879	16,518	21,036	22,997	12,450
Nuclear Energy (NE)	6,201	8,682	24,057	18,855	22,600
Science (SC)	0	29,183	32,500	36,388	59,500
DOE Hydrogen TOTAL	**155,961**	**221,155**	**231,044**	**267,751**	**307,550**
Department of Transportation	555	549	1,411	1,420	1,425
Hydrogen Fuel Initiative TOTAL	**156,516**	**221,704**	**232,455**	**269,171**	**308,975**

Program Partnerships

The Program maintains strong partnerships with industry and government, and coordinates extensively with other stakeholder groups.

INTERNATIONAL PARTNERSHIPS

International Partnership for the Hydrogen Economy

- Represents 16 member countries and the European Commission
- Coordinates inter-governmental research, development and deployment programs
- Provides a forum for advancing policies and common codes and standards

International Energy Agency – Implementing Agreements

- ***Hydrogen Implementing Agreement:*** 22 member countries, plus the European Commission. Currently implementing Tasks 18 – 25.
- ***Advanced Fuel Cells Implementing Agreement:*** Signed by 17 countries. Current phase (2004 – 2008) comprises six annexes (tasks).

U.S. PARTNERSHIPS

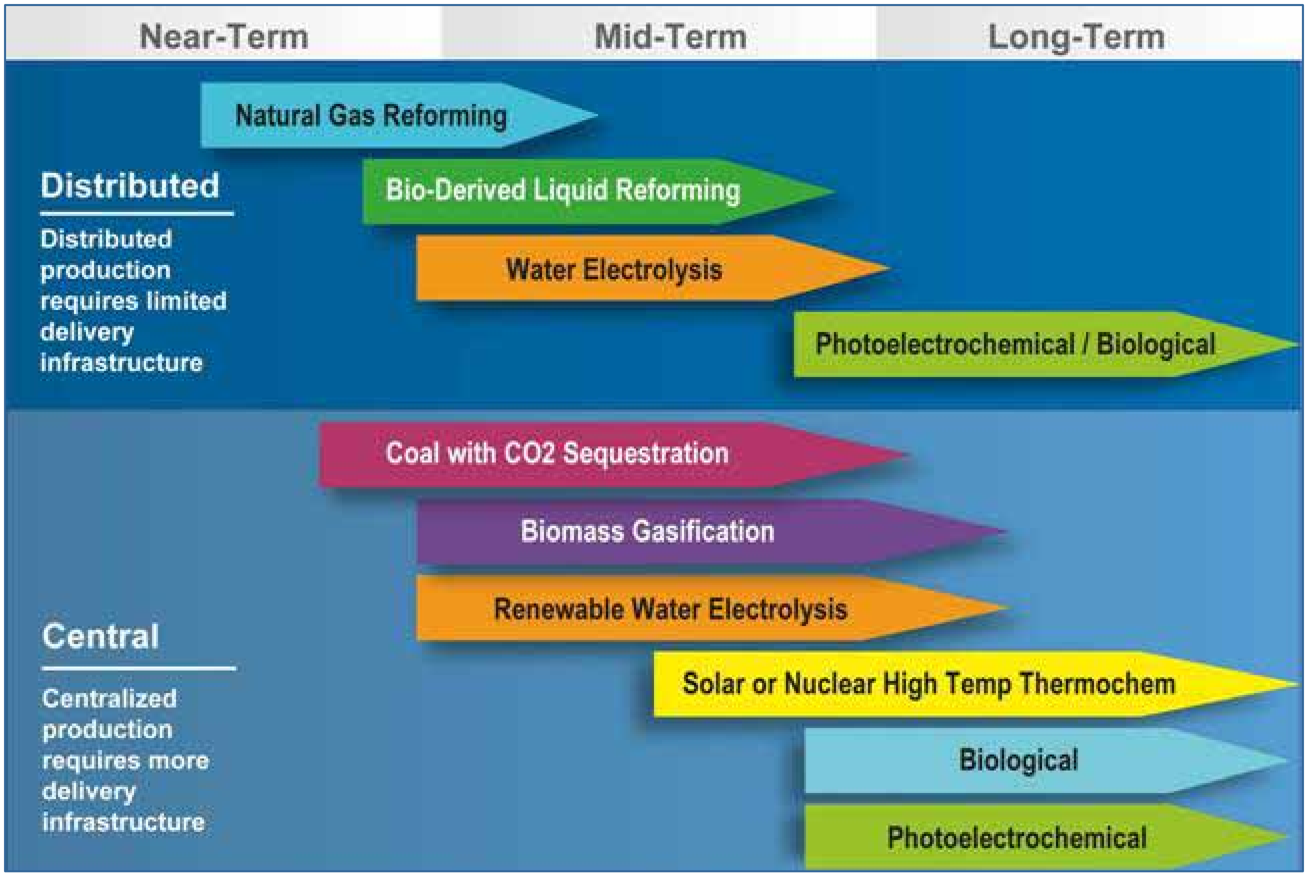
- **FreedomCAR and Fuel Partnership**
- **Hydrogen Utility Group** (e.g., Xcel Energy, Sempra)
- **Other Federal Agencies** (e.g., Interagency Hydrogen and Fuel Task Force (with OSTP), Interagency Working Group on Manufacturing R&D)
- **State/Local Governments** (e.g., California Fuel Cell Partnership, Upper Midwest Hydrogen Initiative)

Hydrogen Production & Delivery

GOAL: *Diverse, domestic pathways to hydrogen production*

KEY OBJECTIVE:

Reduce the cost to $2.00 – $3.00/gge (gallon gasoline equivalent) at the pump.

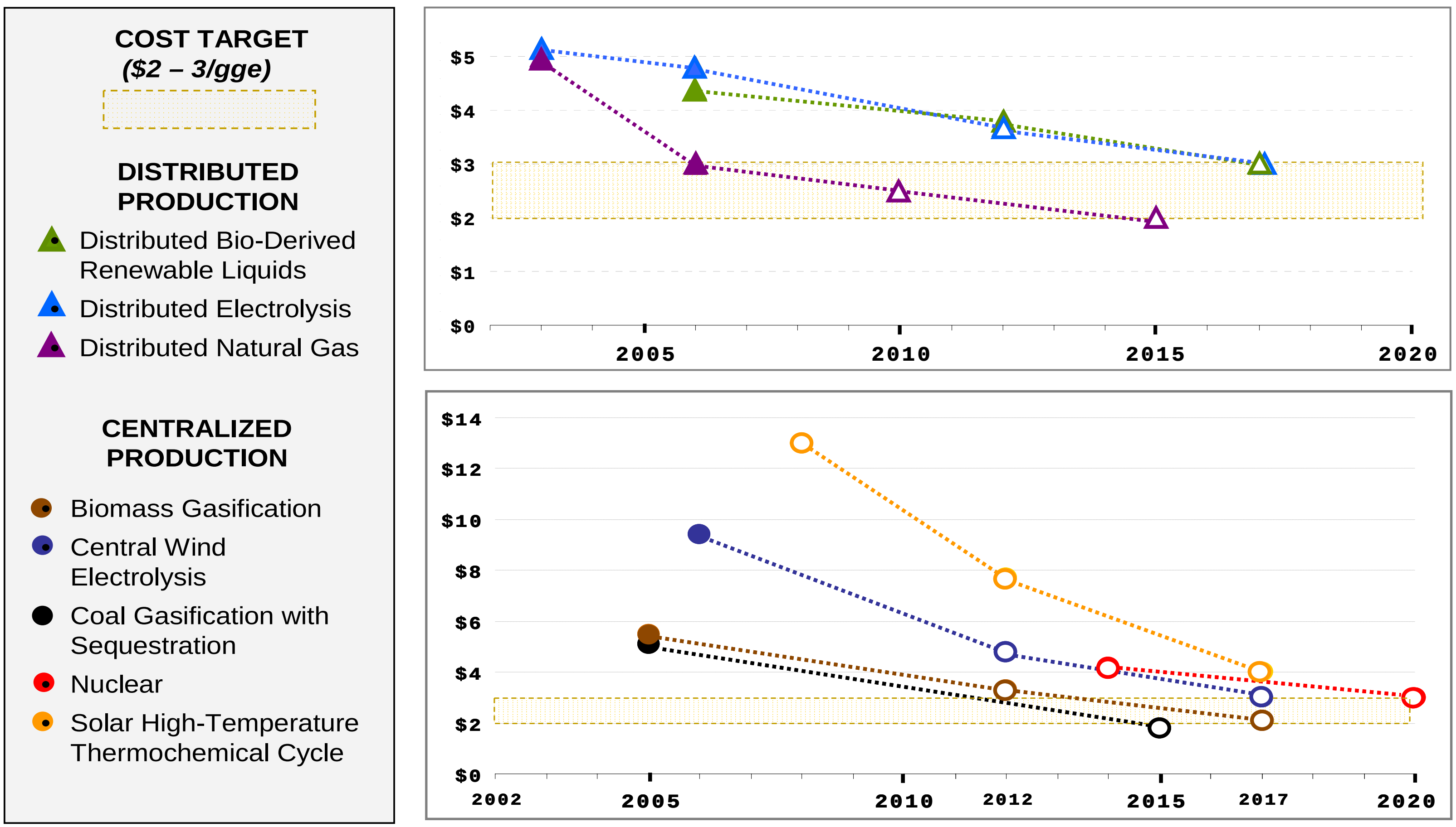


Hydrogen Production — ***Costs***

The Program has reduced the cost of producing hydrogen from multiple pathways.

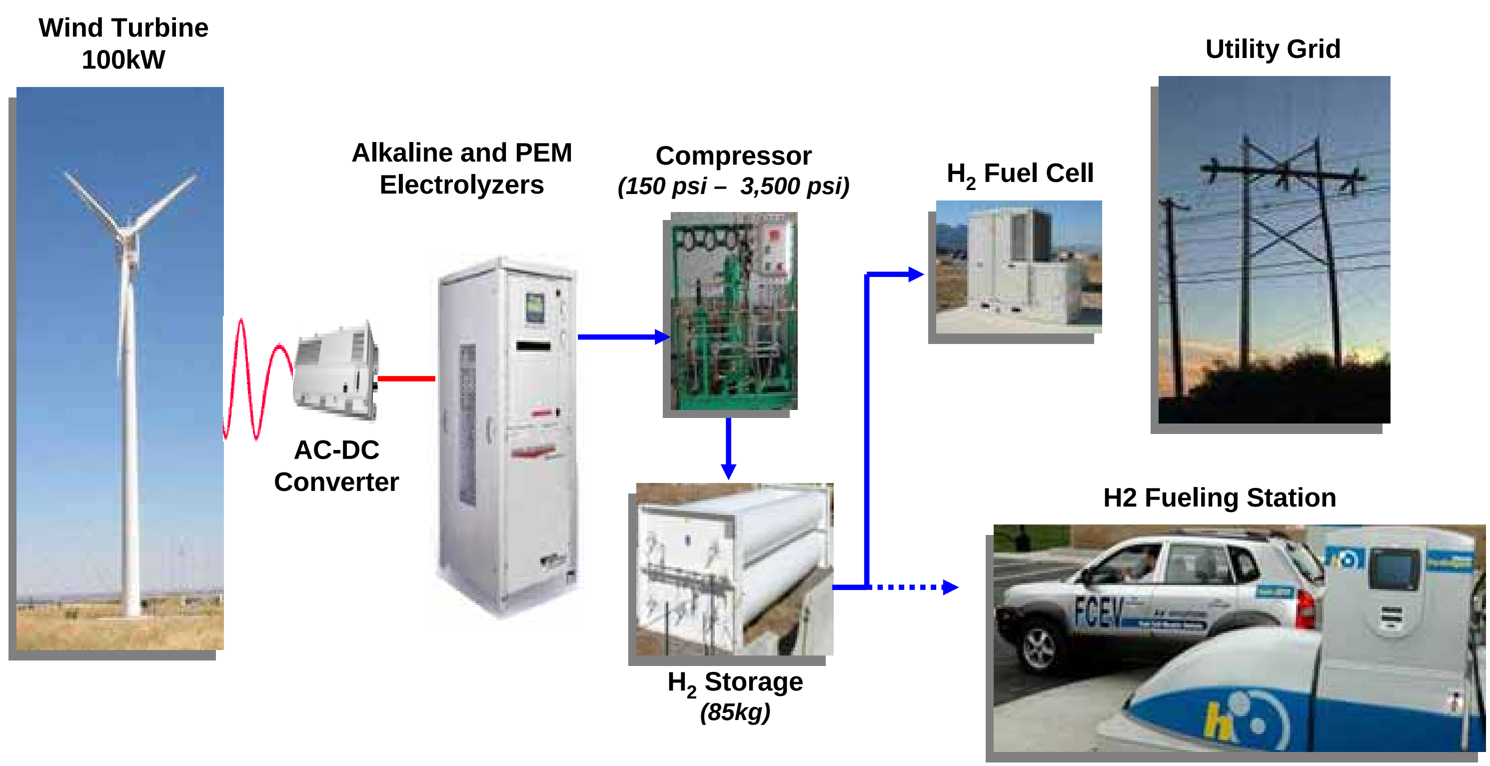
Near-term: **Distributed Hydrogen** → *Produced at station to enable low-cost delivery*

Longer-term: **Centralized Production** → *Large investment in delivery infrastructure needed*

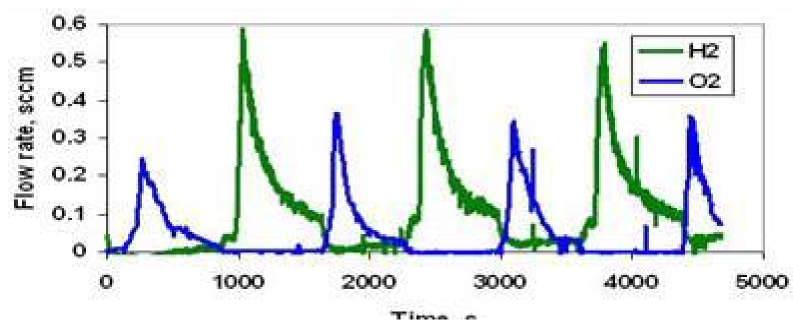


Xcel-NREL Wind2H2 Project

installation complete, initial testing begun



Demonstrated small-scale solar-driven high-temperature thermochemical water splitting



$$Co_{0.67}Fe_{2.33}O_4 \xrightarrow{1400\,^{\circ}C} Co_{0.67}Fe_{2.33}O_{4-\delta} + \frac{\delta}{2}O_2$$

$$Co_{0.67}Fe_{2.33}O_{4-\delta} + \delta H_2O \xrightarrow{1000\,^{\circ}C} Co_{0.67}Fe_{2.33}O_4 + \delta H_2$$

- On-sun reduction at 1550 °C;
  H_2 production at 1100 °C
- YSZ-stabilized ferrite shows stability, repeatability

High-temperature water splitting (a "thermochemical" process) uses high temperatures produced from concentrated solar energy to drive chemical reactions that produce hydrogen. This is a long-term technology in the early stages of development.

Hydrogen from Biomass

Biomass Supply

- 6 – 10 Quads/year currently possible (300 – 600 million metric tons)
- >20 Quads/year projected potential by 2050 (> 1.2 billion metric tons)
- (Current LDV fleet consumes ~16 Quads)

Key Issues: Feedstock Cost, Technology Improvements, and Infrastructure.

Centralized Hydrogen Production Options

- Gasification/Pyrolysis → Hydrogen
- Biomass Hydrolysis → Aqueous Phase Reforming → Hydrogen
- Anaerobic Fermentation (e.g. landfill gas) → Methane → Hydrogen
  - Agriculture, MSW or industrial sites
- Biomass Hydrolysis to Sugars → Fermentation → Hydrogen

Central Biomass to Hydrogen R&D

- NREL: Pilot/Bench Scale integrated "standard biomass gasification
- GTI: Integrated gasification, reforming, membrane separation
- UTRC: Central biomass hydrolysis and aqueous phase reforming

Distributed Reforming of Bio-Derived Liquids

- Hydrolysis to Sugars → Fermentation → Ethanol → Hydrogen
- Gasification/Pyrolysis → Syngas → Ethanol, Mixed Alcohols, FTs → Hydrogen
- Pyrolysis → Bio-Oil → Hydrogen
- Hydrolysis to Sugars, etc. → Hydrogen (Aqueous Phase Reforming)

Distributed Bio-Derived Liquids-to-H_2 R&D

Aqueous-Phase Reforming
- Virent Energy Systems, Inc.; U. of Wisconsin; ADM; Universal Oil Products LLC, Sugars (glucose); sugar alcohols; glycerol
- Pacific Northwest National Lab, Sorbitol

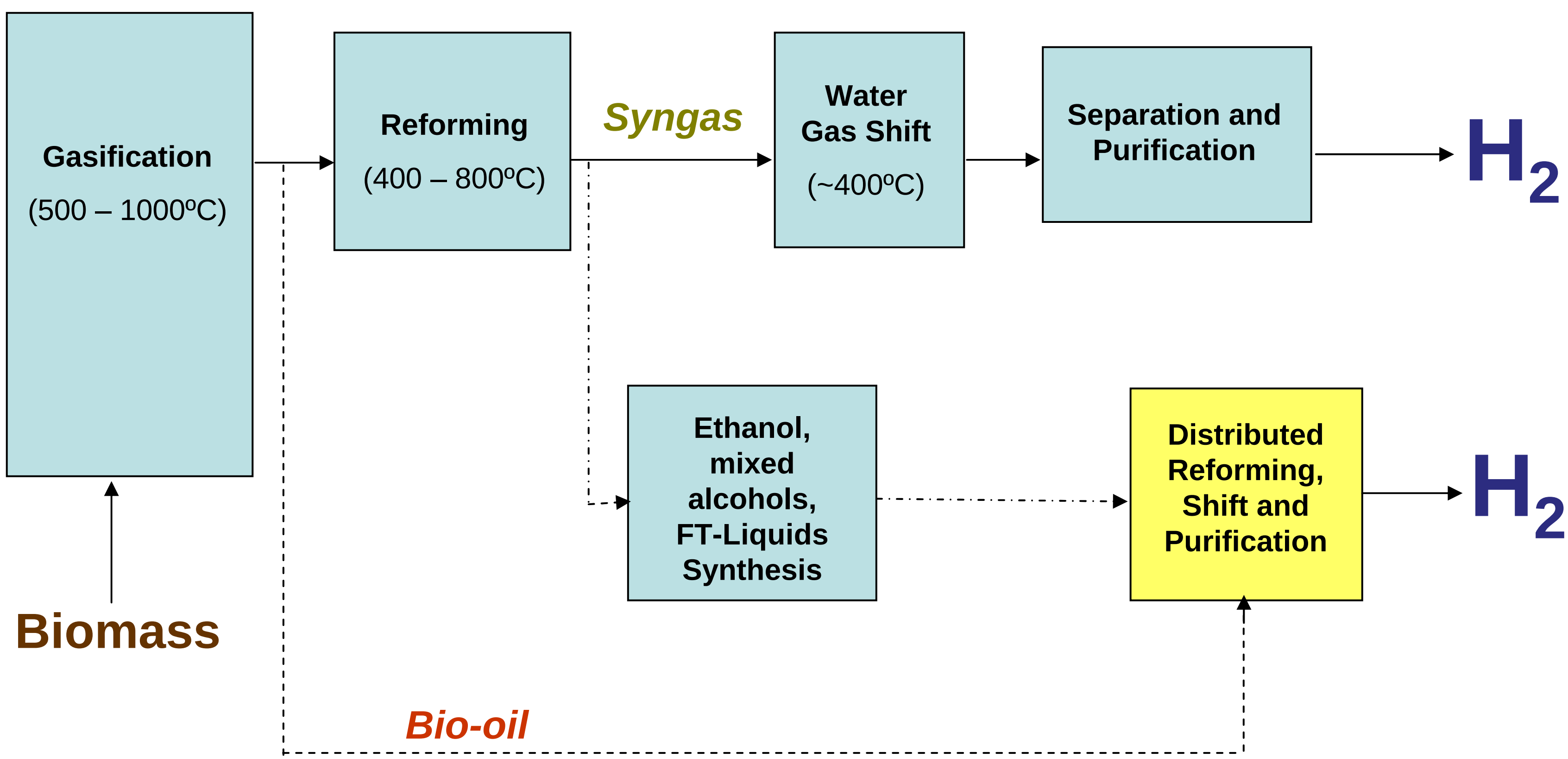
High-Pressure Micro-Reactor and Membrane Reactor
- Argonne National Lab, Ethanol

Investigation of Reaction Networks and Active Sites in Bio-Ethanol Steam Reforming over Co-Based Catalysts
- Ohio State University, Ethanol

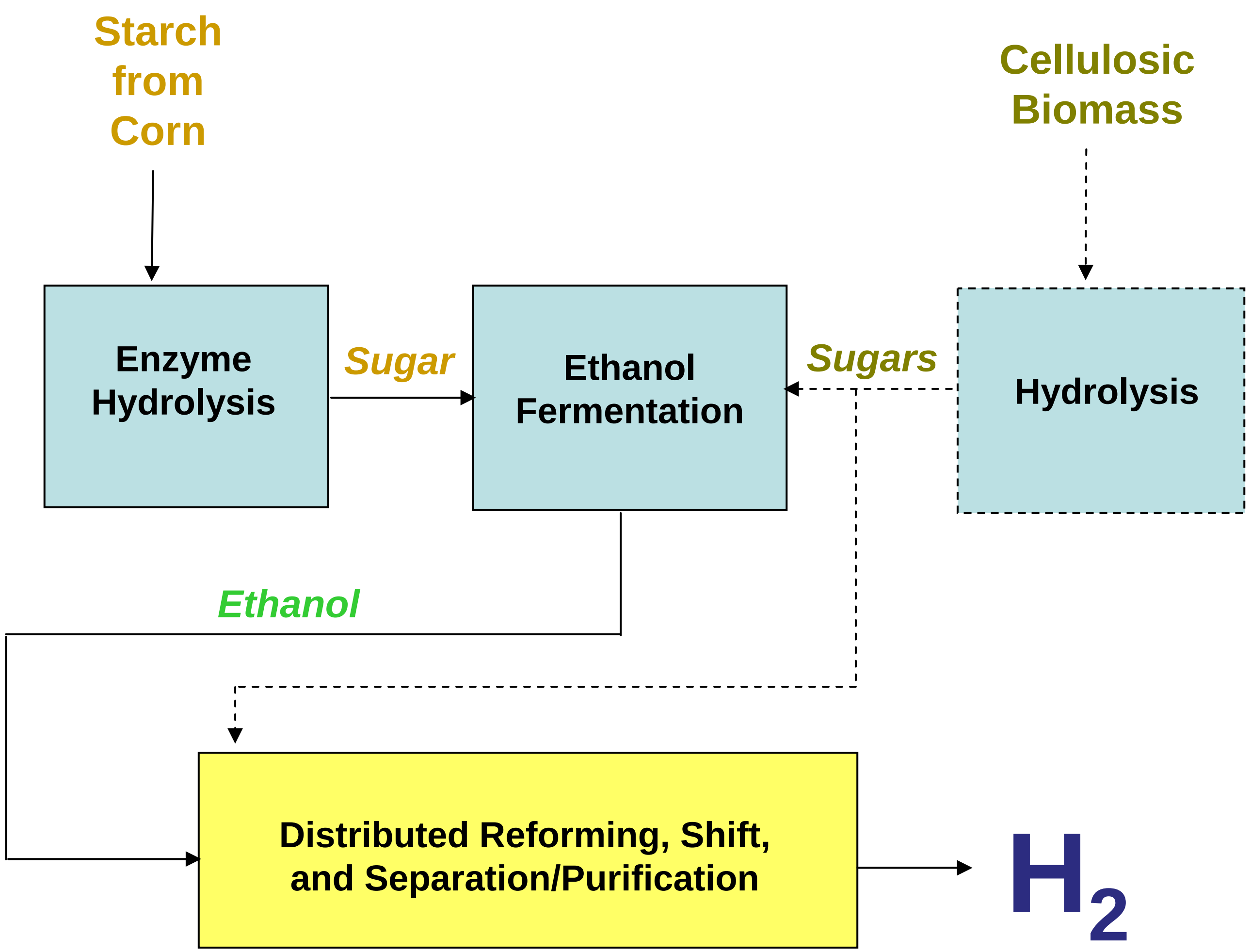
Distributed Bio-Oil Reforming
- National Renewable Energy Lab, Bio-oil (36.5% carbon, 8.4% hydrogen, 55.0% oxygen)

Distributed Bio-Derived Liquids Reforming
- GE, U. of Minnesota: SCPO

Biomass Gasification/Pyrolysis Options



Sugar-Based Liquids for Distributed Reforming



Hydrogen Production Options — ***Summary***

Process Option	**$/kg *(Current)***	**$/kg *(Projected)***	**Challenges**
Coal: Central Gasification	$0.90 – $1.80	$0.50 – 1.40 (Plus $1/kg delivery)	***O_2 Separations, H_2 Separations, CO_2 sequestration***
Natural Gas: Distributed Reforming	$3.00 ($2.75 – $3.50)	$2.00 – 3.00	***Capital cost, NG Cost***
Biomass: Central Gasification/Pyrolysis	$2.00 ($1.60-$2.20)	$1.00 – $2.00 (Plus $1/kg delivery)	***Capital Cost, Process Intensification, Biomass Cost***
Biomass: Central Hydrolysis and APR	--	--	***Process Research/Feasibility, Biomass Cost***
Biomass: Central Anaerobic Fermentation/Methane/H2	--	--	***?***
Biomass: Central sugar fermentation	Very high	??	***Breakthrough in Yield on Sugars***
Biomass: Distr. Ethanol Reforming	$4.40 ($4.20 – $5.00)	<$3	***Capital Cost, Catalyst Life, Coking, Ethanol Cost***
Biomass: Distr. Liquids Reforming	--	<$3	***Capital Cost, Catalyst Life, Coking, Feedstock Cost***
Biomass: Distr. APR	--	<$3	***Capital Cost, Yield, Feedstock Cost***

Biomass Potential

Biofuel yields per biomass dry ton	Hydrogen	Biochemical Conversion	Thermochemical Conversion	Combined BC/TC[1]
Feedstock / Year	Biomass (H_2/ton)	Corn Stover (ETOH/ton)	Wood Chips (ETOH/ton)	Stover/Lignin (ETOH/ton)
2005: State of Technology	54 Kg 623 L 6.14 MBTU	65 gal 246 L 4.94 MBTU	56 gal 212 L 4.26 MBTU	
2012: Target		90 gal 341 L 6.84 MBTU	76 gal 288 L 5.78 MBTU	
2030: Estimate	> 85 Kg > 980 L > 9.6 MBTU			> 100 gal > 379 L > 7.60 MBTU

Maximum #s for each vehicle-type powered by Biomass

Vehicle type	Fuel Volume[3]	#s 15K mile vehicles[4]
Hydrogen Fuel Cell	85×10^{10} Kg	400,000,000
E85 conventional	1.18×10^{11} gal	240,720,000
E85 hybrid	1.18×10^{11} gal	328,040,000

[1]Assumes large scale, advanced, integrated technology

[2]10.4 MJ/L - George, T. 2000. DOE Hydrogen Program Review. San Ramon, CA.

[3]Estimate based on 2030 conversion technology and 1B ton of Biomass.

[4]Estimate based on PSAT model (Argonne) and 2020 vehicle technology.

Hydrogen/Biomass Programs Collaboration

- Joint participation in Annual Program Reviews
- Solicitation planning and selections
- Common research participants
- USDA/DOE MOU Ad-Hoc Hydrogen and Fuel Cell Committee
  - Thermochemical Biomass Process Teleseminars
  - Other
- Cost analysis collaboration

Hydrogen Delivery

CURRENT:

$2.50/kg (e.g., pipeline) – $12.00/kg (e.g., liguid)

TARGET:

<$1.00/kg

Pathways

- Gaseous Hydrogen Delivery
- Liquid Hydrogen Delivery
- Carriers

Including mixed pathways

Components

- Pipelines
- Compression
- Liquefaction
- Carriers & Transformations
- Gaseous Storage Tanks
- Geologic Storage
- GH2 Tube Trailers
- Purification
- Terminals
- Dispensers
- Liquid Storage Tanks
- Mobile Fuelers
- Liquid Trucks, Rail, Ships

Hydrogen Delivery — ***Challenges***

Pathway/Technology/Issue	Major Challenges
Pipelines	Hydrogen embrittlement, capital cost, urban distribution
Compression—Transmission and Refueling Stations	Reliability, capital cost, energy efficiency, new technologies
Liquefaction	Capital cost, energy efficiency
Off-Board Storage Vessels	Capital cost
Geologic Storage	Sufficient suitable sites and capacity? Contamination?
Gaseous Tube Trailers	Is 1000-kg capacity possible?
Hydrogen Quality	Must meet stringent quality requirements for PEM FC
Carriers *(leverages the onboard-storage program)*	Liquid two-way carriers: low cost and efficient hydrogenation and dehydrogenation, high (~100%) yields and selectivity

Hydrogen Storage R&D

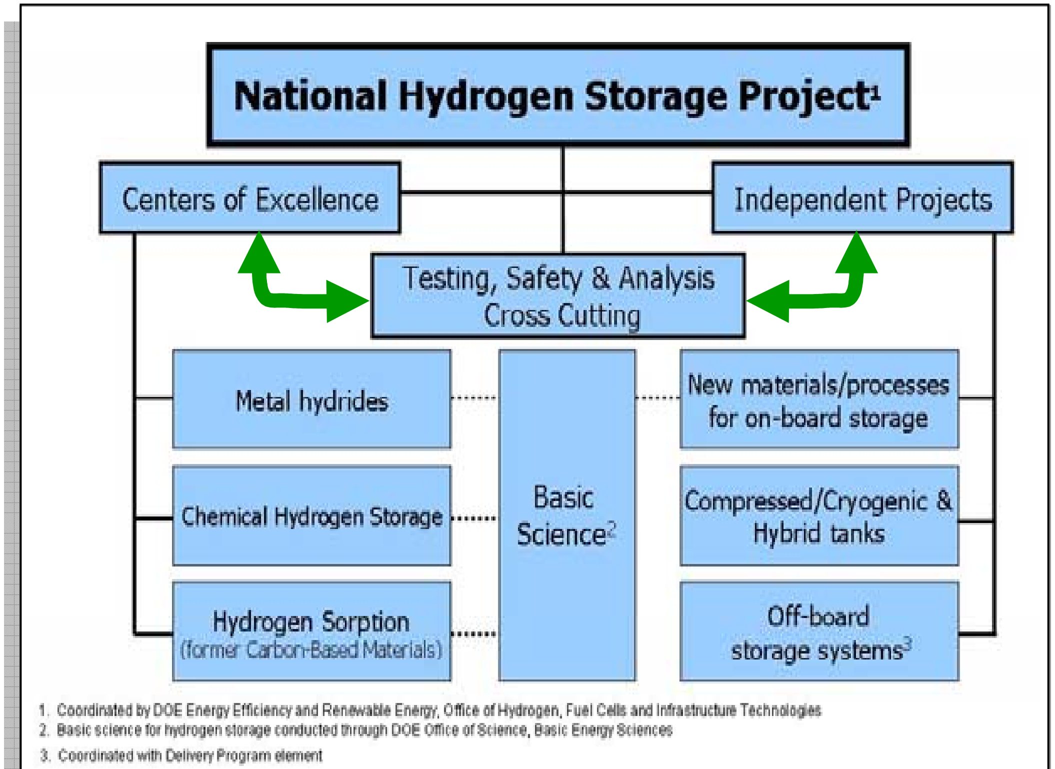
KEY OBJECTIVE: *On-board H_2 storage to enable* ***> 300 mile driving range*** *while meeting all requirements for safety, cost, & performance (weight, volume, kinetics, etc.)*

NEAR TERM: ***Allows for early market use of H_2 vehicles, but won't provide full range on all platforms***

- Pressurized tanks: *currently in use in most H_2 vehicles*
- Cryo-compressed storage: *combines low-temperature H_2 storage with pressurization*

LONGER TERM: ***Needed to enable >300-mile range***

- *Diverse portfolio with materials focus, for low-pressure storage*
- *Focus materials research on temperature, pressure, kinetics (as well as capacity)*



~ 40 universities, 15 companies, and 10 federal labs

New Engineering Center of Excellence Planned for FY08

Hydrogen Storage R&D —
Application-driven goals and targets

Capacity
- > 300 mile range
- No loss of passenger/cargo space

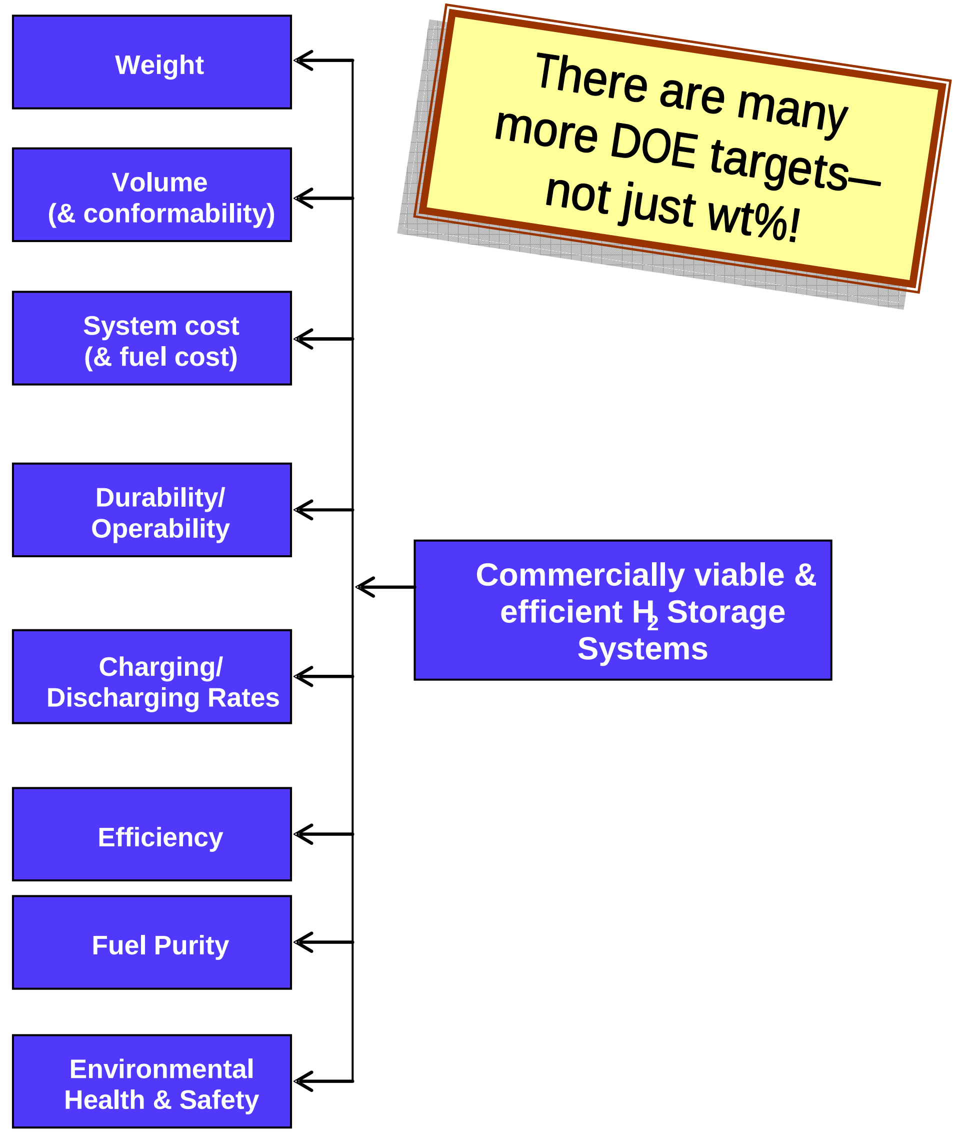
Operating temperature range
- -40 to +85 C

System cost & Fuel cost

Hydrogen supply rate/refueling rate
- 0.02 g H_2 per sec. per kW of power
- Refueling time < 3 min. for 5 kg H_2

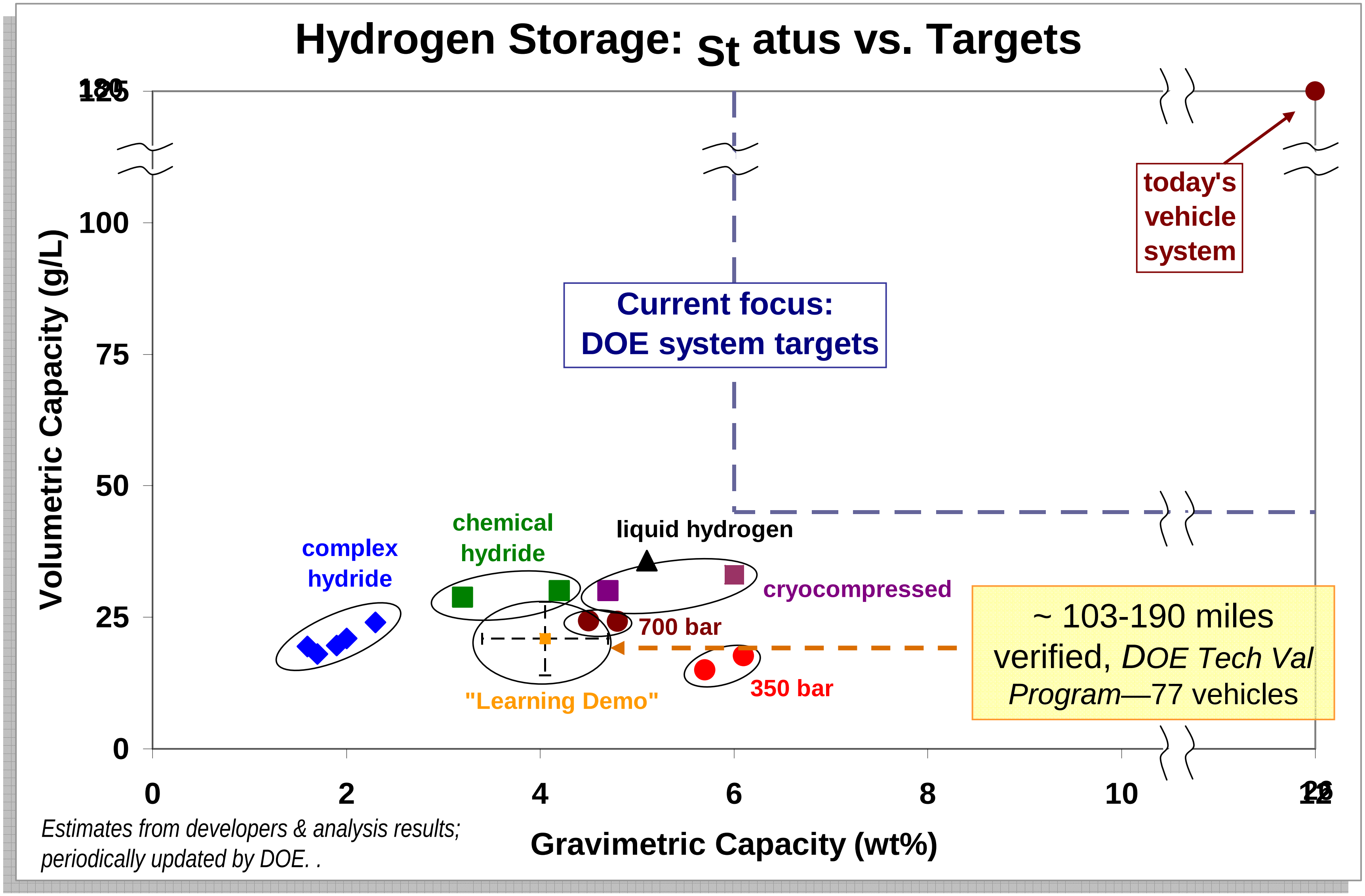
Operability
- On-board refueling with gas or liquid
- Off-board regeneration of hydrogen carrier
- Closed loop, no byproducts, energy efficient

Safety, codes & standards, reliability, cycle life, efficiency . . .

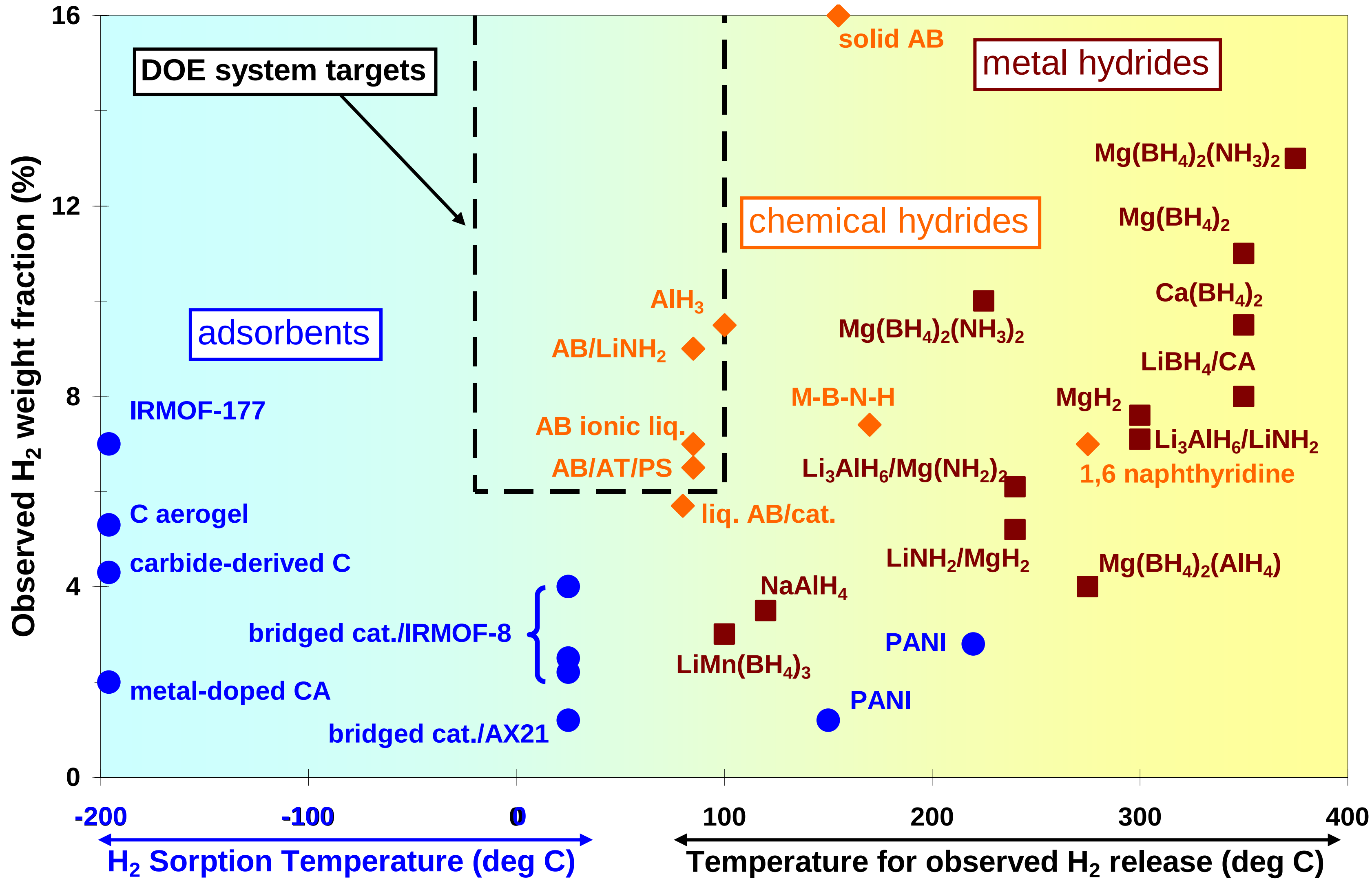


Hydrogen Storage — ***Systems Status***

No technology meets targets—Results include data from vehicle validation



Examples of H_2 Storage Progress — *Material Capacity vs. Temperature*



G. Thomas, et al., DOE (April 2007)

Fuel Cell R&D

MAJOR RESEARCH AREAS:

- Membranes
- Catalysts & Supports
- Water Transport
- Characterization & Analysis

PRIMARY FOCUS

- ***Primary focus is on fuel cells for transportation applications***
- ***R&D is focused on components rather than systems***

KEY TARGETS:

- **$45/kW by 2010; $30/kW by 2015**
- **5,000-hour durability by 2015**

SECONDARY FOCUS

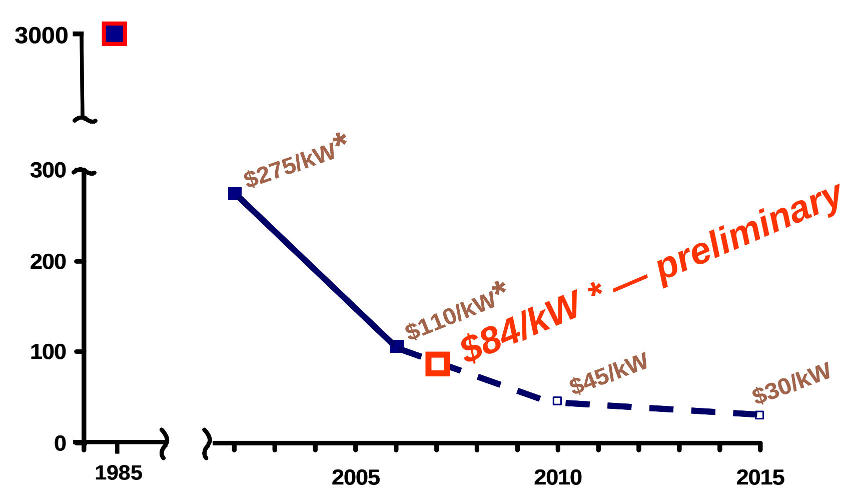
Stationary and other early-market fuel cells to establish the manufacturing base

KEY TARGETS:

- Distributed Power: $750/kW and 40,000-hour durability (with 40% efficiency) by 2011
- APUs: Specific power of 100 W/kg and power density of 100 W/L by 2010
- Portable Power: Energy density of 1,000 Wh/L by 2010

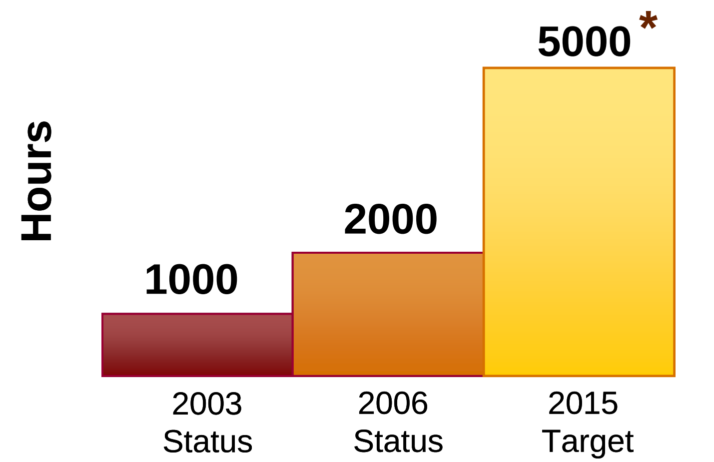
Fuel Cells — ***Progress***

Fuel Cell Cost
(80kW Direct H_2 automotive fuel cell)



**** Projected to high-volume manufacturing of 500,000 units/year***

Fuel Cell Stack Durability
(automotive)

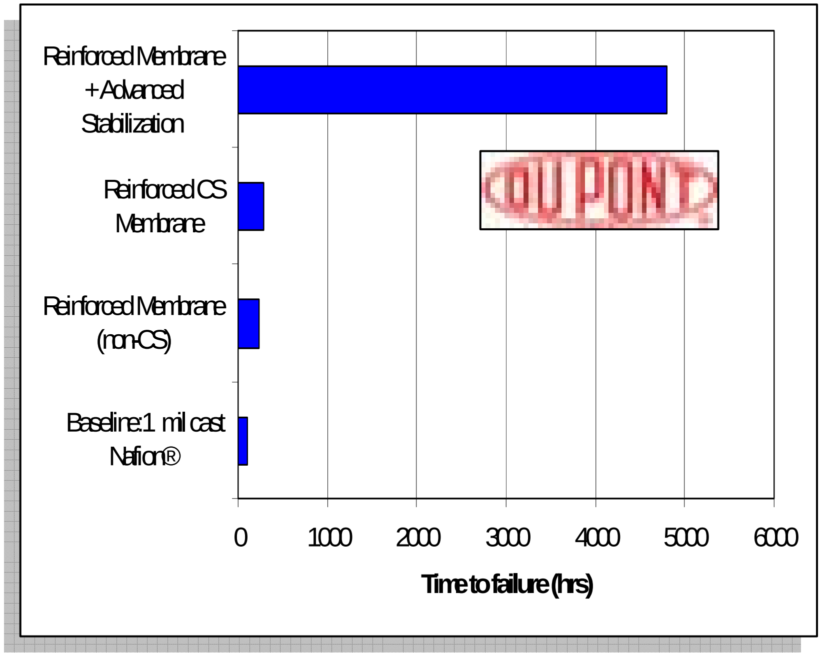


**** 5000 hours corresponds to roughly 150,000 miles of driving***

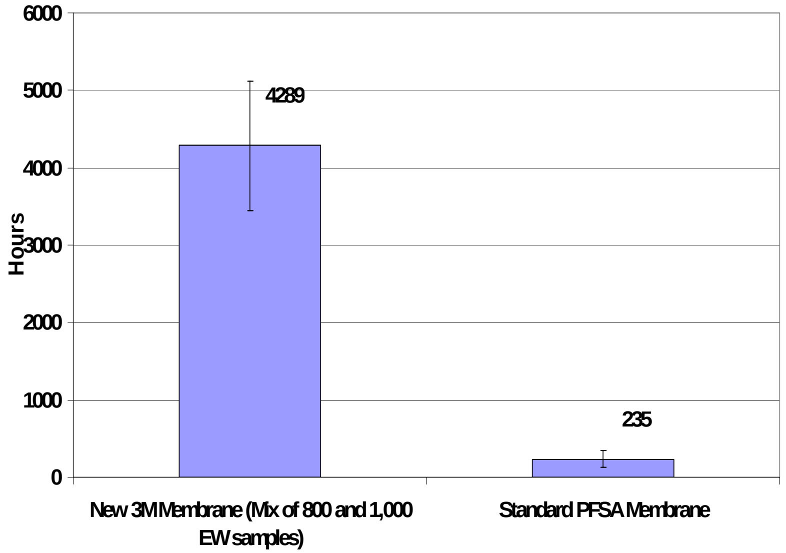
Fuel Cell Progress —
Improved Membrane Durability

Developed membrane with nearly 5,000-hour durability — with humidity and voltage cycling

- **improved durability with no performance loss**
- **more resistant to mechanical and chemical stresses**



3M Membrane Development



Technology Validation — *Vehicles & Infrastructure*

Technologies are validated and progress evaluated through learning demonstrations

DOE Vehicle/Infrastructure Demonstration

*Four teams, in 50/50 cost-shared projects, operating **77 fuel cell vehicles** and **14 hydrogen stations***

Verified fuel cell vehicle performance:

- ***EFFICIENCY: 53 – 58%** (>2x higher than internal combustion gasoline engines)*
- ***RANGE: 103 – 190 miles***
- ***FUEL CELL SYSTEM DURABILITY: 1600 hours** (~48,000 miles)*

Demonstrated Fuel Cost: $3/gge, from natural gas

DOT is demonstrating fuel cell buses and providing data to DOE for analysis

Eight buses in California, Massachusetts, New York, South Carolina, and Washington, DC

Market Transformation

***DOE is actively promoting commercialization** of PEM fuel cell technologies by supporting early adoption, and by building partnerships with the public and private sectors*

CHALLENGES

- ***Resistance to new technologies***
- ***Lack of information on life-cycle costs***
- ***Lack of user confidence related to reliability***
- ***High capital cost***

EARLY MARKET OPPORTUNITIES

Fuel Cells for Backup Power:

- Longer continuous run-time, greater durability than batteries
- Require less maintenance than batteries or generators
- Potential cost savings over batteries and generators

A 1-kW fuel cell system has been providing power for this FAA radio tower near Chicago for more than 3 years.

Photo courtesy of ReliOn

Fuel Cells for Material Handling Equipment:

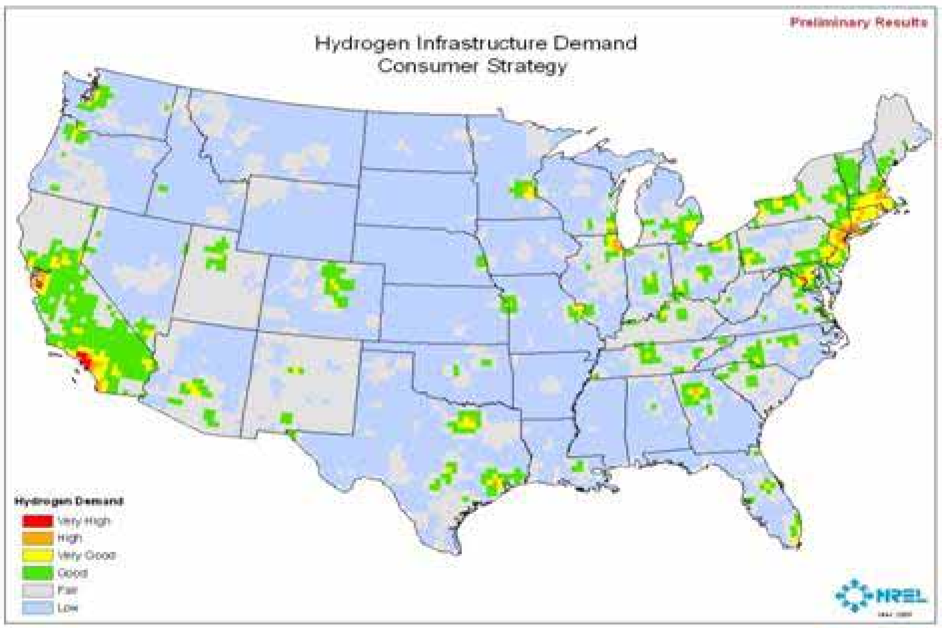
Photo courtesy of Hydrogenics

- Allow for rapid refueling — much faster than changing-out or recharging batteries
- Provide constant power — without voltage drop
- Eliminate need for space for battery storage and chargers

Looking Ahead —

Scenario analysis examines infrastructure development

Los Angeles and New York City metro areas represent the most attractive initial marketplaces for the introduction of hydrogen FCVs. This is due to these areas' high population density.



"Lighthouse" concept:
targets top urban areas

2012-2015: INITIAL INTRODUCTION

- **New York/Northern NJ/Long Island**
- **Los Angeles/Riverside/Orange County/San Diego**

2016-2019: TARGETED REGIONAL GROWTH

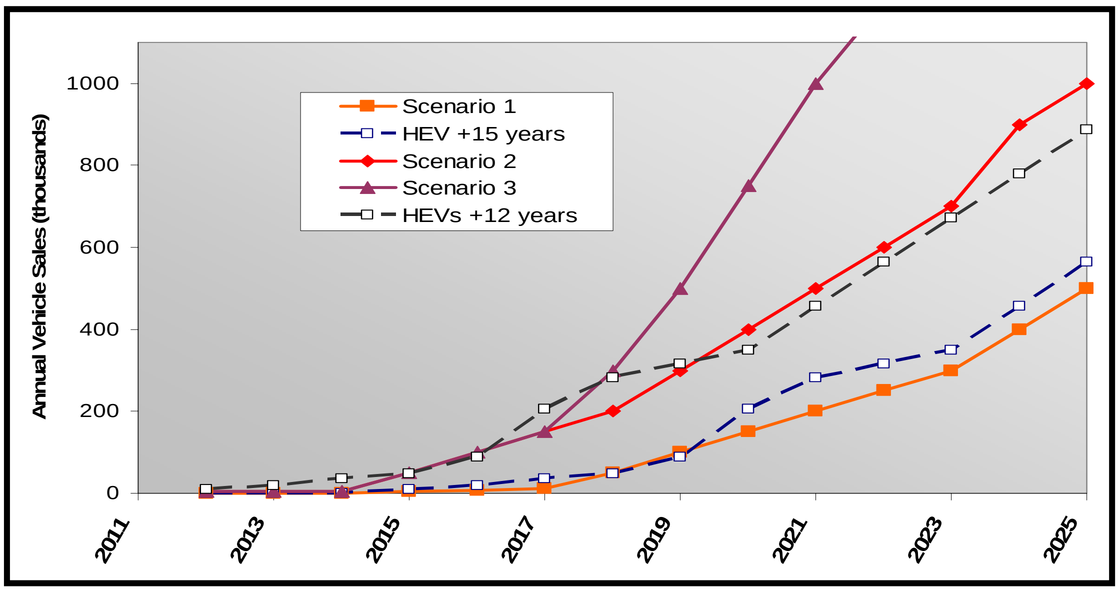
- **San Francisco/Oakland/San Jose/ Sacramento/Yolo**
- **Boston/Worcester/Lawrence**
- **Washington/Baltimore**
- **Chicago/Gary/Kenosha**
- **Detroit/Ann Arbor/Flint**
- **Dallas/Fort Worth**
- **Atlanta**

2020-2025: INTER-REGIONAL EXPANSION

- **Houston/Galveston/Brazoria**
- **St. Louis**
- **Minneapolis/St. Paul**
- **Philadelphia/Wilmington/**
- **Atlantic City**
- **Phoenix/Mesa**
- **Denver/Boulder/Greeley**

Looking Ahead – *Analysis of potential vehicle market penetration scenarios* helps to assess infrastructure needs*

	Initial Stages	Interim Growth	Market Penetration by 2025
Scenario 1	By **2012**: *hundreds to thousands* of vehicles per year	By **2018:** *tens of thousands* of vehicles per year	**2.0 million vehicles**
Scenario 2	By **2012**: *thousands of vehicles* per year	By **2015:** *tens of thousands* per year; by **2018:** *hundreds of thousands* per year.	**5.0 million vehicles**
Scenario 3	By **2012**: *thousands of vehicles* per year	By **2021:** *millions* of vehicles per year	**10.0 million vehicles**

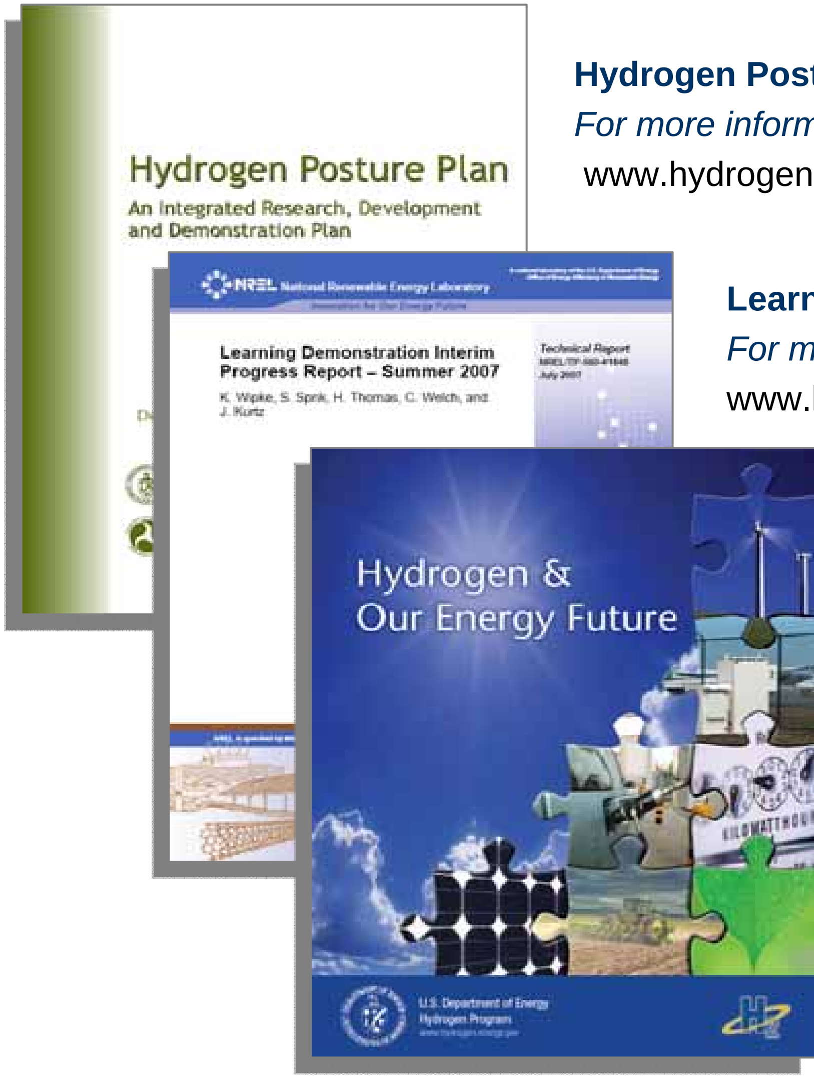


Scenarios compared with HEV penetration:
Scenarios 1 and 2 are consistent with current and projected HEV penetration rates

**These are scenarios for analysis purposes only. They do not represent a strategy or a proposal.*

Questions?

For more information visit: www.hydrogen.energy.gov



Hydrogen Posture Plan

For more information on the Hydrogen Program

www.hydrogen.energy.gov/roadmaps_vision.html

Learning Demonstration Interim Progress Report

For more information on the vehicle/infrastructure demonstration

www.hydrogen.energy.gov/news_learning_demo.html

Hydrogen Overview Book

For more information on hydrogen and fuel cell technologies

www1.eere.energy.gov/hydrogenandfuelcells/education/h2iq.html

Back-up Slides

Office of Energy Efficiency & Renewable Energy (EERE) — ***Hydrogen Budget***

Activity	Funding *($ in thousands)*				
	FY 2006 Approp.	**FY 2007** Approp.	**FY 2008** Request	**FY 2008** House Mark	**FY 2008** Senate Mark
Hydrogen Production & Delivery	8,391	33,702	40,000	40,000	40,000
Hydrogen Storage R&D	26,040	33,728	43,900	43,900	43,900
Fuel Cell Stack Component R&D	30,710	37,100	44,000	44,000	44,000
Technology Validation	33,301	39,413	30,000	30,000	45,000
Transportation Fuel Cell Systems	1,050	7,324	8,000	8,000	8,000
Distributed Energy Fuel Cell Systems	939	7,257	7,700	7,700	7,700
Fuel Processor R&D	637	3,952	3,000	3,000	3,000
Safety, Codes & Standards	4,595	13,492	16,000	16,000	16,000
Education	481	1,978	3,900	3,900	3,900
Systems Analysis	4,787	9,637	11,500	11,500	11,500
Manufacturing R&D	0	1,928	5,000	5,000	5,000
Congressionally Directed	42,520	0	0	0	0
TOTAL	**153,451**	**189,511**	**213,000**	**213,000**	**228,000**