President’s Hydrogen Fuel Initiative

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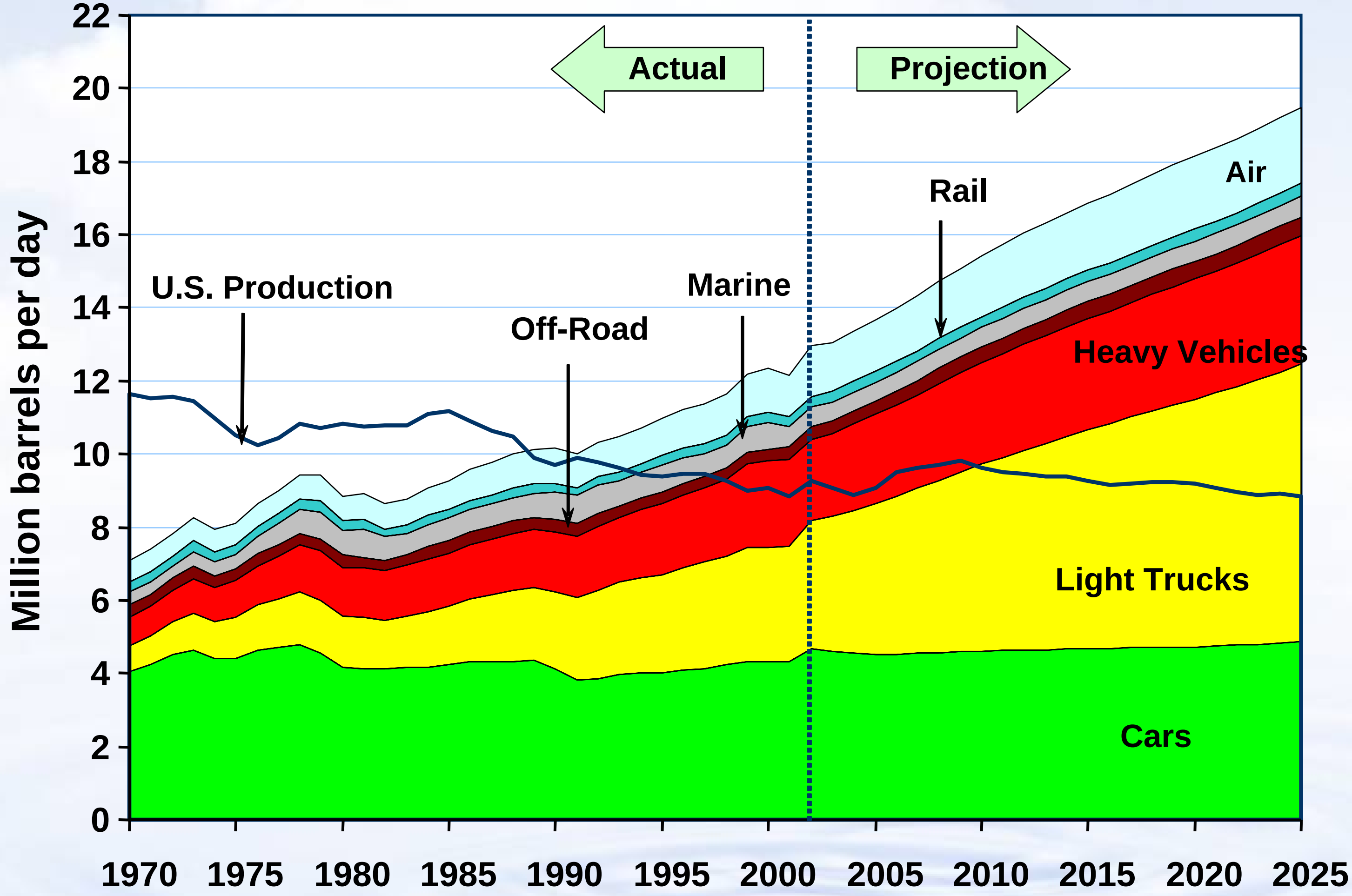
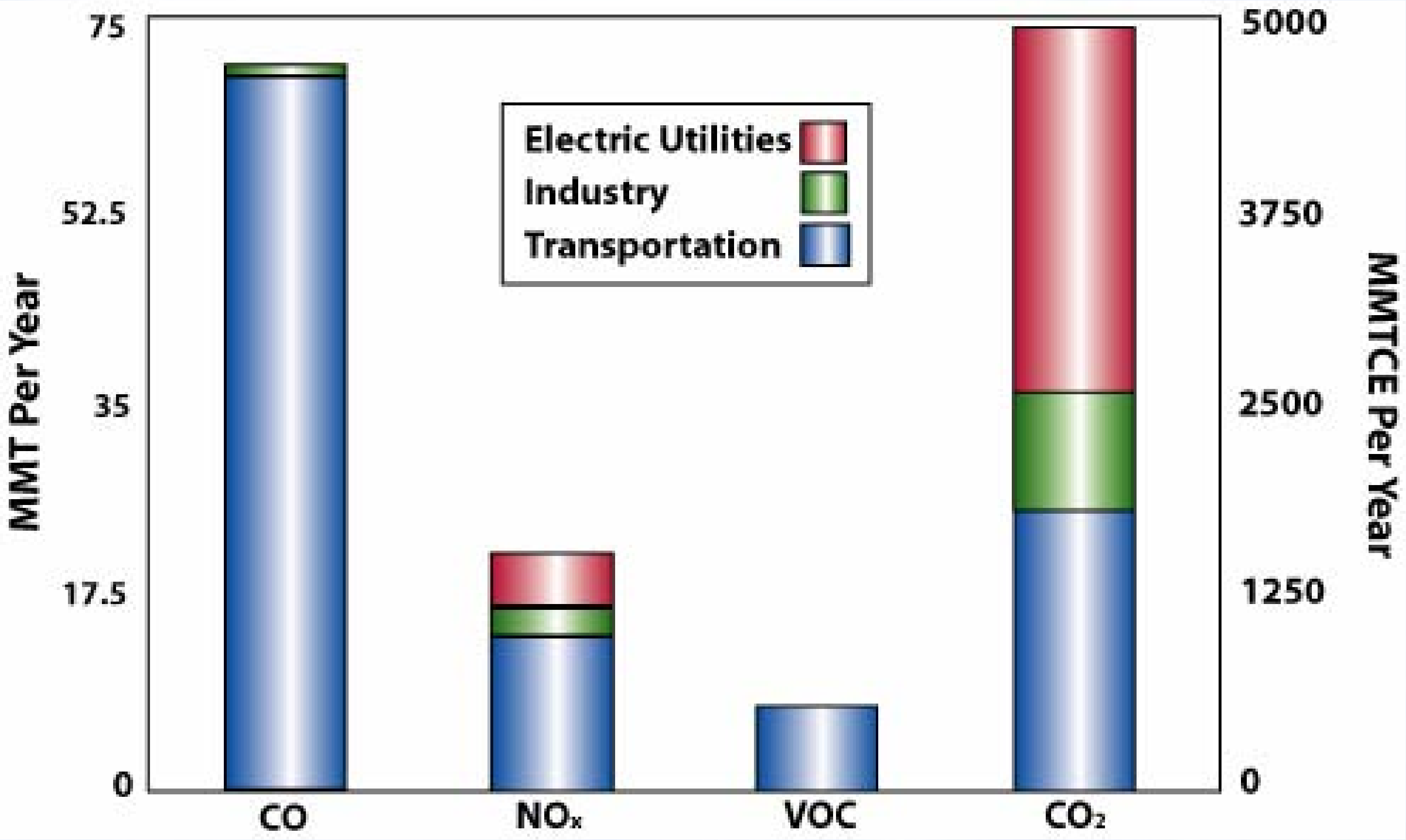
August 2005

U.S. Energy Dependence is Driven By Transportation



- Transportation accounts for 2/3 of the 20 million barrels of oil our nation uses each day.
- The U.S. imports 55% of its oil, expected to grow to 68% by 2025 under the status quo.
- Nearly all of our cars and trucks currently run on either gasoline or diesel fuel.

Emissions from Fossil Fuel Combustion



Vehicles and power plants are significant contributors to the nation's air quality problems.

Hydrogen Infrastructure and Fuel Cell Technologies put on an Accelerated Schedule

- **President Bush commits a total $1.7 billion over first 5 years:**
  - $1.2 billion for hydrogen and fuel cells RD&D ($720 million in new money)
  - $0.5 billion for hybrid and vehicle technologies RD&D

- **Accelerated, parallel track enables industry commercialization decision by 2015.**

Fuel Cell Vehicles in the Showroom and Hydrogen at Fueling Stations by 2020

Hydrogen Fuel Initiative

DOE

EERE-<u>HFCI</u>

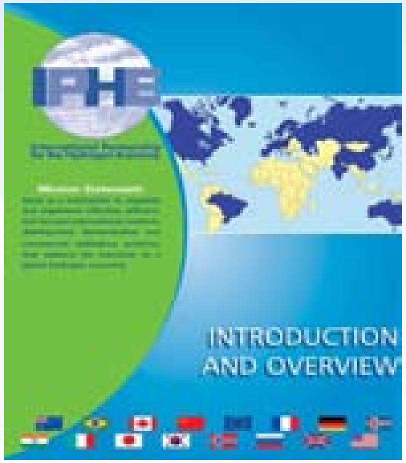
EERE-Vehicles Technology

EERE-Solar, Wind, Biomass

FE

NE

SC



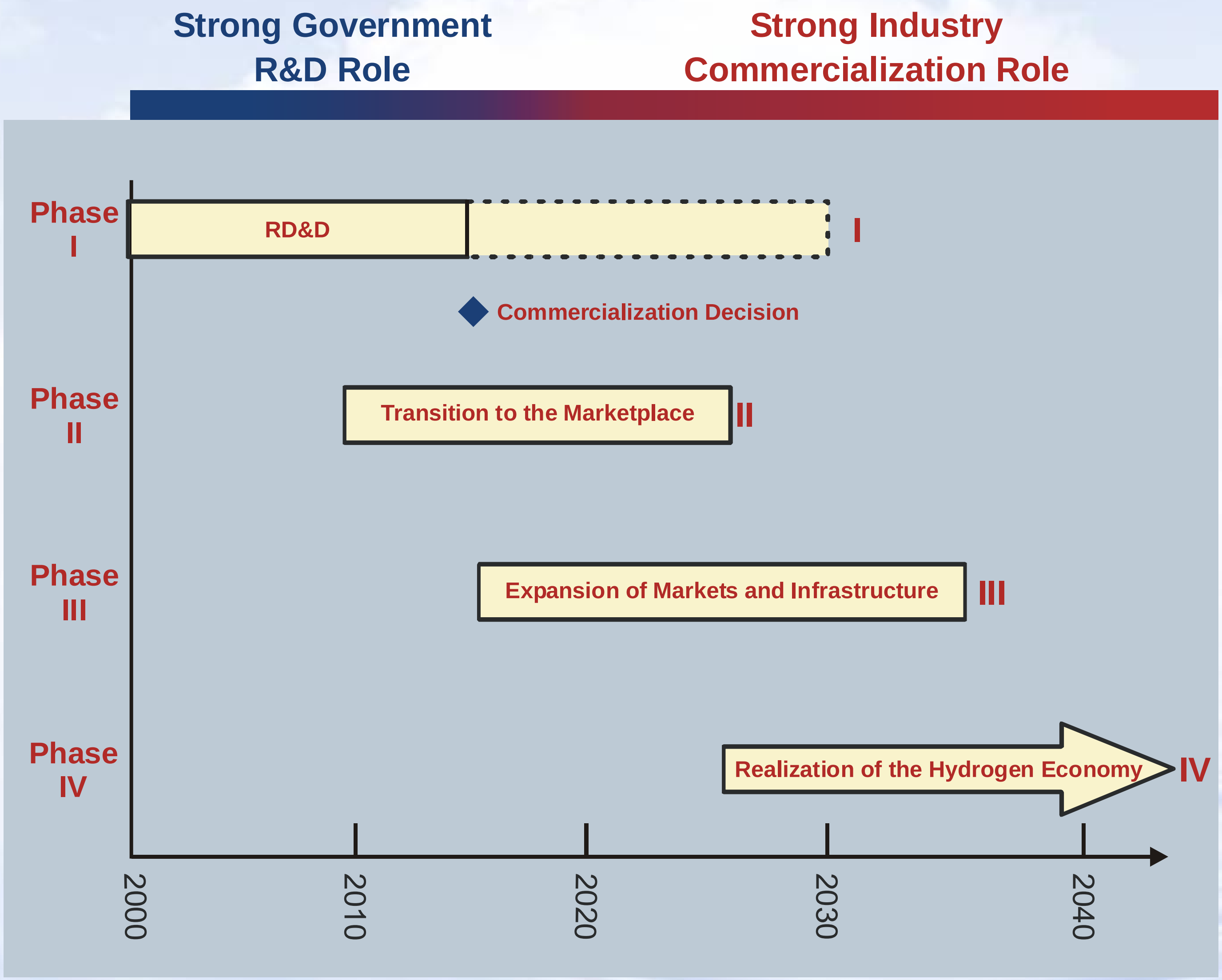
Production
Delivery
Storage
Fuel Cells
Tech Validation
Safety, Codes & Standards
Systems Analysis/Integration
Education

FreedomCAR & Fuel Partnership

Interagency Task Force

OSTP, DOE, DOT, NASA, DOD, USDA, DOC-NIST, EPA. NSF

Hydrogen Economy Timeline



Transitional Phases

I. Technology Development Phase

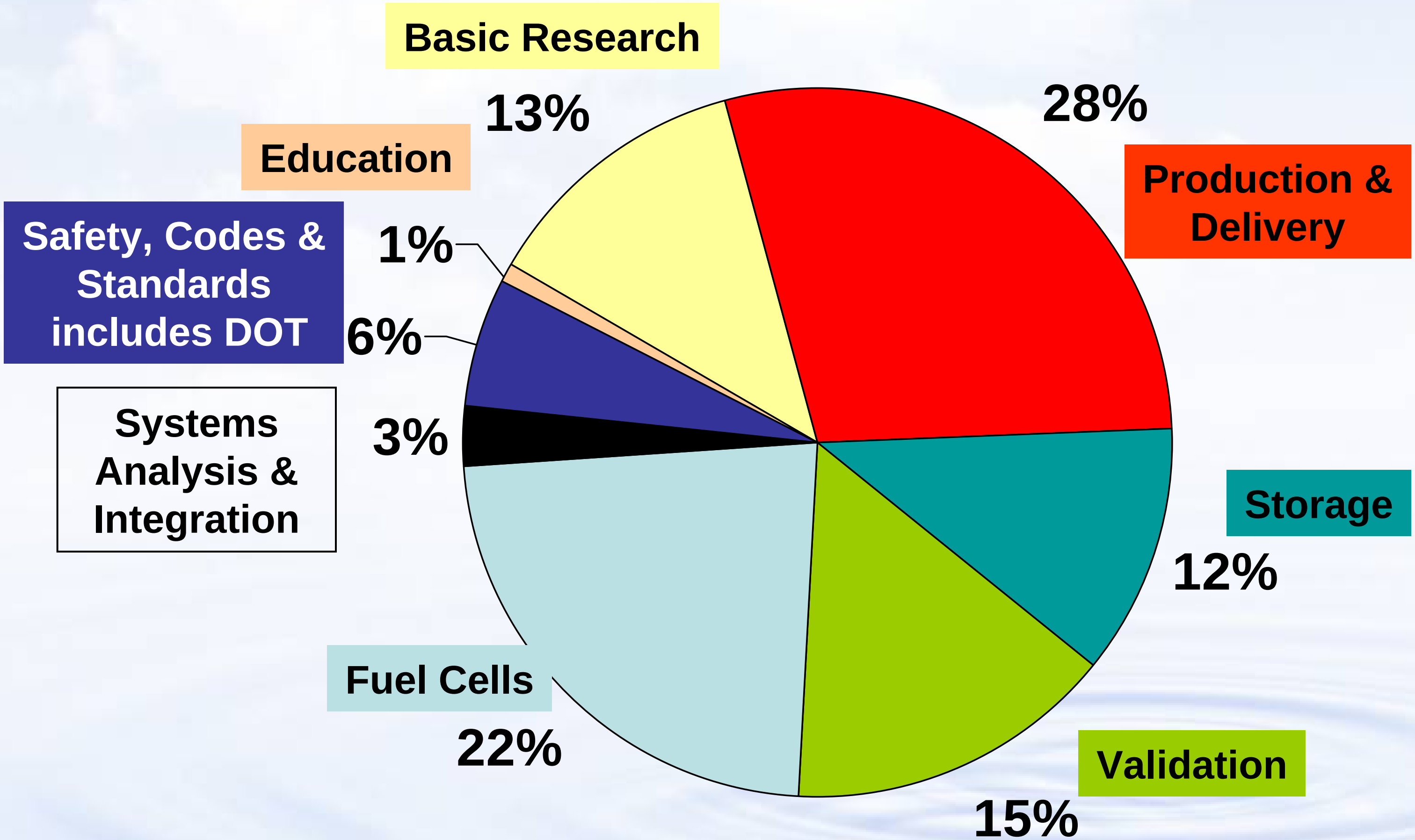
II. Initial Market Penetration Phase

III. Infrastructure Investment Phase

IV. Fully Developed Market and Infrastructure Phase

Positive commercialization decision in 2015 leads to beginning of mass-produced hydrogen fuel cell cars by 2020.

FY2006 Hydrogen Fuel Initiative Budget Request



Total FY06 Request $259.5M

President's Hydrogen Fuel Initiative Budget

MAJOR LINE ITEMS	FY 04 Appropriations ($000)	FY 05 Appropriations ($000)	FY 06 Request ($000)
EERE Fuel Cell	63,782	74,944	83,600
EERE Hydrogen	80,412	94,006	99,094
NE Hydrogen	6,201	8,929	20,000
FE Hydrogen	4,879	17,085	22,000
SC Hydrogen	0*	29,183	32,500
DOT	555	549	2,350
Hydrogen Fuel Initiative	**155,847**	**224,696**	**259,544**

*Excludes $8M of baseline activities not counted as part of initiative

FreedomCAR and Fuel Partnership

<u>Energy Company/DOE Technical Teams</u>

- Hydrogen Production
- Hydrogen Delivery
- Fuel Pathway Integration

<u>Auto/DOE Technical Teams</u>

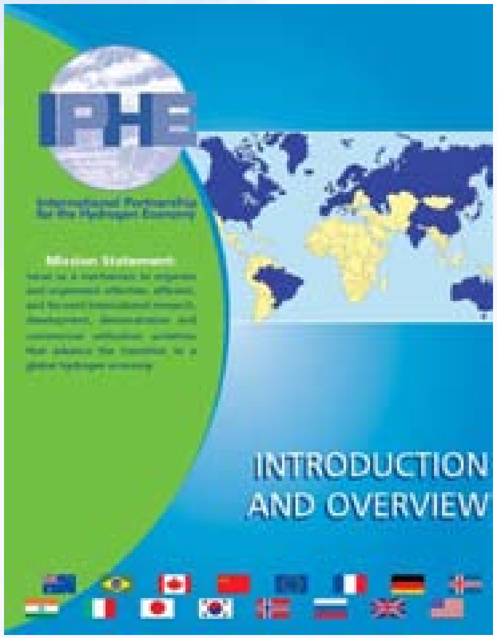
- **Fuel Cells**

<u>Joint Auto/Energy/DOE Technical Teams</u>

- Codes and Standards
- Hydrogen Storage

Technology Roadmaps have been developed by each Technical Team

International Partnership for the Hydrogen Economy (IPHE)



Vision:

"… consumers will have the practical option of purchasing a competitively priced hydrogen powered vehicle, and be able to refuel it near their homes and places of work, by 2020."

- Secretary Abraham, April 2003

Partners' Economy:

> $35 Trillion, 85% of world GDP

~ 3.5 billion people

> 75% of worldwide electricity used

> 2/3 of energy consumption and CO2 emissions

Current Status: Evaluating 30 projects for IPHE cooperation.

Hydrogen Production Strategy

Produce hydrogen from renewable, nuclear, and coal with technologies that will all yield virtually zero criteria and greenhouse gas emissions

Coal

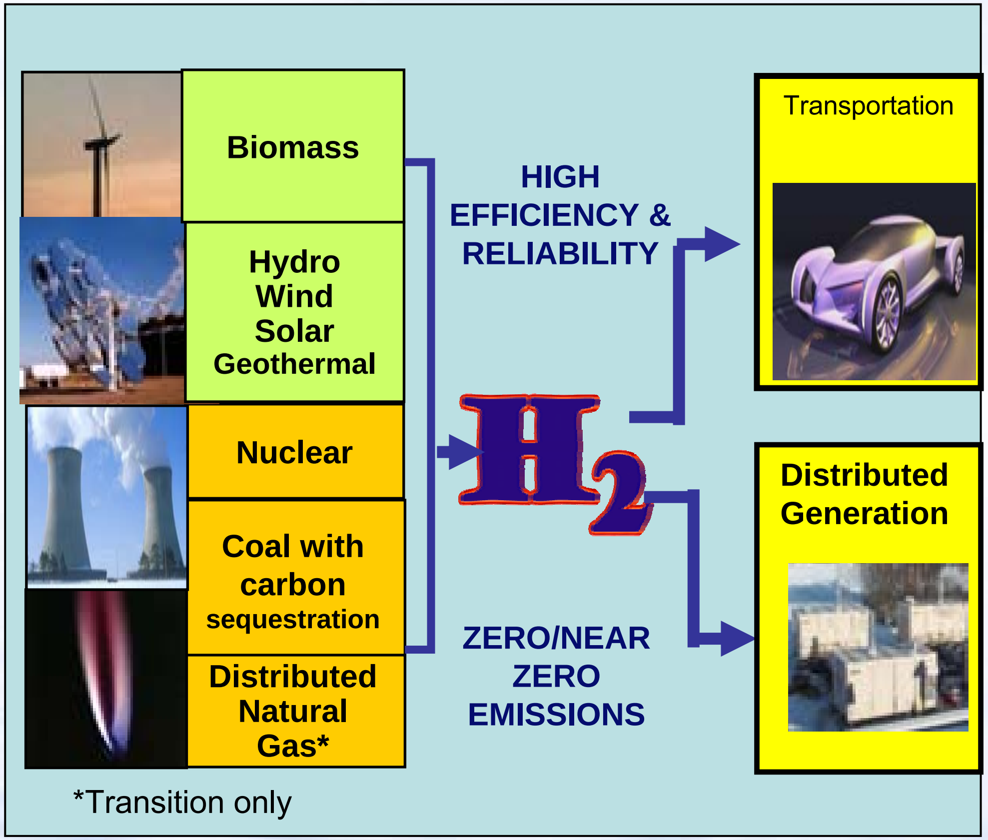
- Only with carbon capture & sequestration

Distributed Natural Gas

- Transition strategy
- “Not a long-term source for hydrogen (imports and demand in other sectors)

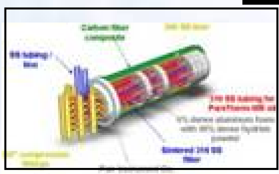
Nuclear/Renewable

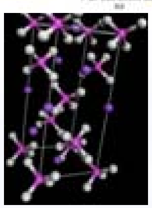
- Reforming of renewable liquids
- Biomass gasification
- Thermchemical Water Splitting Cycles (solar and nuclear)
- Photoelectrochemical
- Photobiological



Hydrogen Storage

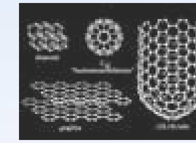
Focused on *materials-based* technologies for >300-mile range
$150M planned over 5 years, subject to appropriations

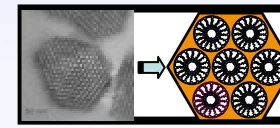




National Hydrogen Storage Project[1]

- **Centers of Excellence**
  - Metal hydrides
  - Chemical Hydrogen Storage
  - Carbon-Based Materials
- **Testing & Analysis Cross Cutting**
- **Basic Science[2]**
- **Independent Projects**
  - New materials/processes for on-board storage
  - Compressed/Cryogenic & Hybrid approaches
  - Off-board storage systems





Materials reversible on-board

- Can “refill” H_2 at the fueling station, directly onto the vehicle
- Advanced metal hydrides (alanates, borohydrides, Li-Mg amides)
- Carbon-based materials, high surface-area adsorbents
- Focus on capacity and thermal management

Materials regenerable off-board

- Take depleted material off vehicle & regenerate off-board
- Liquid or solid materials, high binding energy of hydrogen, high capacity
- Organic liquids, boron-based materials, polymeric systems
- Focus on capacity and regen efficiency

New Materials and Concepts: Nanoporous materials, clathrates, MOFs, perhydrides, other

[1] Coordinated by DOE Energy Efficiency and Renewable Energy, Office of Hydrogen, Fuel Cells and Infrastructure Technologies

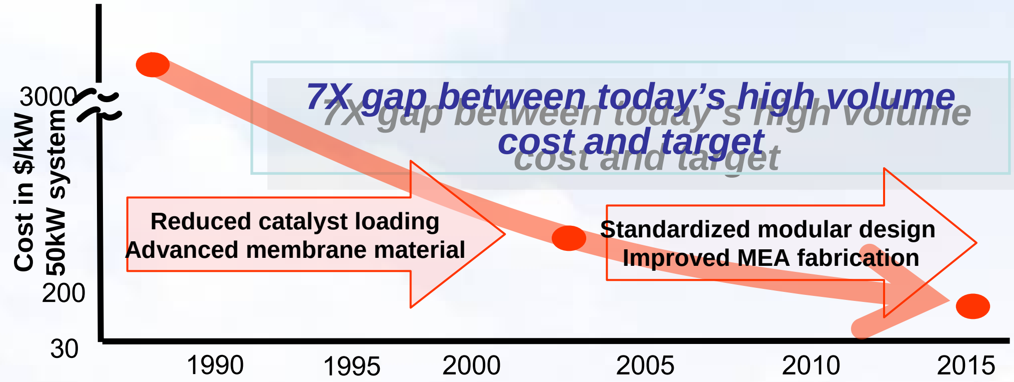
[2] Basic science for hydrogen storage conducted through DOE Office of Science, Basic Energy Sciences

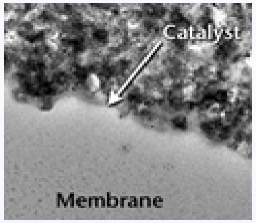
Fuel Cells

Stack Component R&D

UTC Fuel Cells, 3M, DeNora, Cabot Superior Micropowders, Englehard, Arkema (previously Atofina) Chemicals, DuPont, Plug Power, Ion Power, Ballard, U. of South Carolina, Porvair, LANL, NIST, NRL, NASA, ANL, LBNL, ORNL, PNNL, NREL, SNL and BNL

- polymers, proton conducting membranes
- MEAs in high volume manufacturing
- electrocatalysts, platinum recycling
- bipolar plates





Distributed Energy Systems

IdaTech, UTC Fuel Cells, Plug Power, ANL, NREL, and Battelle

- demonstrations of integrated stationary systems
- modeling and analysis

Transportation Systems

UTC Fuel Cells, Honeywell, Delphi Automotive Systems, Cummins Power Generation, PolyFuel, MTI MicroFuel Cells, IdaTech, NREL, LLNL, PNNL, ANL, and LANL

- system modeling & analyses
- physical and chemical sensors
- turbo compressor / expander
- compact humidifiers / heat exchangers
- auxiliary power in trucks
- portable power applications

Fuel Processor R&D

Nuvera, Texaco Energy Systems, ANL, LANL NETL, PNNL

- fuel processor catalysts & systems for stationary applications
- diesel or propane fuel processing for APUs

Technology Validation Strategy

- 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

<u>Major Objectives</u>

- 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

GM / Shell

DaimlerChrysler / bp (1)

Ford / bp (1)

Air Products / ConocoPhillips / Toyota / Honda / Nissan / BMW / UTC Fuel Cells

Chevron / Hyundai / Kia / UTC Fuel Cells

(1) Fuel cells supplied by Ballard

Codes and Standards

Goal : Perform underlying research to enable codes and standards to be developed for the safe use of hydrogen in all applications. Facilitate the development and harmonization of international codes and standards

Objectives

- **Support and facilitate the drafting of model building codes for hydrogen applications (i.e., NFPA 5000) by the National Fire Protection Association (NFPA)**
- **Facilitate in the adoption of the ICC codes in key US regions:**
- **Complete R&D on hydrogen release scenarios; provide a sound basis for model code development and adoption.**
- **Support and facilitate the completion of ISO standards for refueling and on-board storage and the completion of bulk storage standards (e.g., NFPA 55) with experimental data and input from the Tech Validation program element.**
- **Facilitate development of Global Technical Regulations (GTR) for H2 vehicle systems under the United Nations Economic Commission for Europe, World Forum for Harmonization of Vehicle Regulations, and Working Party on Pollution and Energy Program (ECE-WP29/GRPE).**

Safety

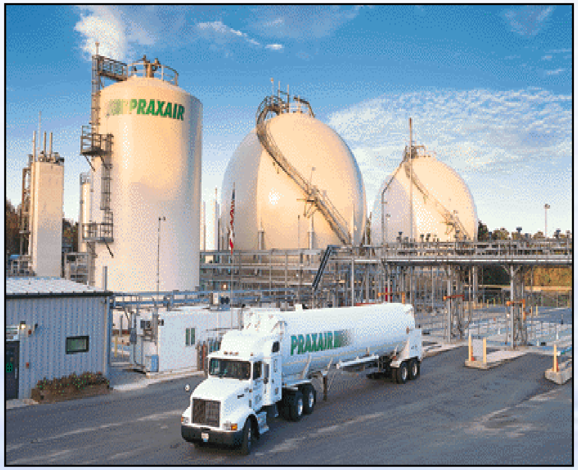
Goal : Develop and implement the practices and procedures that will ensure safety in the operation, handling and use of hydrogen and hydrogen systems for all DOE funded projects and to utilize these practices and lessons learned to promote the safe use of hydrogen throughout the emerging hydrogen economy.

Objectives

- **Develop a comprehensive Program Safety Plan, establishing Program safety policy and guidance and continue activities of the Safety Review Panel to provide expert guidance.**
- **Integrate safety procedures into all DOE project funding procurements.**
- **Publish a handbook of Best Management Practices for Safety. The Handbook will be a "living" document that will provide guidance for ensuring safety in future hydrogen endeavors, by 2007.**
- **R&D to provide critical hydrogen behavior data and hydrogen sensor and leak detection technologies. This data will support the establishment of setback distances in building codes.**
- **Promote widespread sharing of safety-related information, procedures and lessons learned to first responders, jurisdictional authorities and other stakeholders.**

Hydrogen Delivery Goal

- Develop hydrogen delivery technologies that enable the introduction and long-term viability of hydrogen as an energy carrier for transportation and stationary power



Delivery: Scope

From the end point of central or distributed production

(300 psi H_2) to and including the dispenser at a refueling station or stationary power site

(Includes forecourt compression, storage and dispensing)

Objectives

- By **2007**, define the criteria for a cost-effective and energy-efficient hydrogen delivery infrastructure for the introduction and long-term use of hydrogen for transportation and stationary power.

- By **2010**, develop technologies to reduce the cost of hydrogen delivery from central and semi-central production facilities to the gate of refueling stations and other end users to <***$0.90/kg*** of hydrogen.
- By **2010**, develop technologies to reduce the cost of compression, storage, and dispensing at refueling stations and stationary power sites to less than ***<$0.80/kg*** of hydrogen.

- By **2015**, develop technologies to reduce the cost of hydrogen delivery from the point of production to the point of use in vehicles or stationary power units to <***$1.00/kg*** of hydrogen in total.

- (By **2015**, develop technologies to reduce the cost of hydrogen delivery during the transition to <***$xx/kg*** of hydrogen.)

Delivery Tech Team

Jim Simnick
BP

Maria Curry-Nkansah BP**

Nick Burkhead
Shell

George Parks*
ConocoPhillips

Dan Casey
Chevron

Mark Paster*
DOE

Jim Kegerreis
ExxonMobil

Steve Pawel
ORNL

*Co-lead
**FOG Liaison

Facilitator: Shawna McQueen
Energetics

DTT Accomplishments

- Roadmap Completed!
- Technical Targets Established
- DOE R&D Projects Initiated
- Reviews/Mini-Workshops
- NRC Review

Research Areas

Pathways

- Gaseous Hydrogen Delivery
- Liquid Hydrogen Delivery
- Carriers

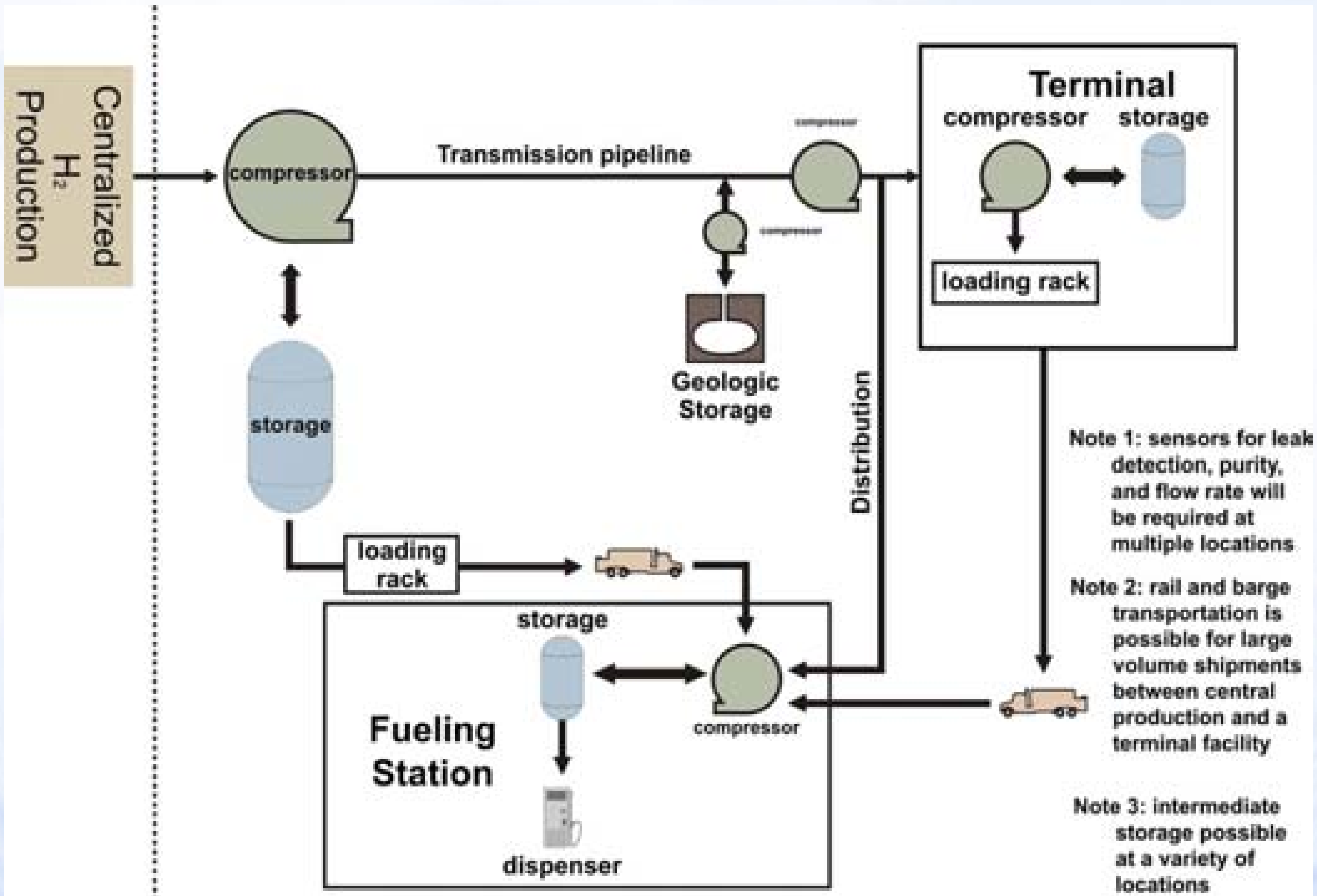
} Including mixed pathways

Components

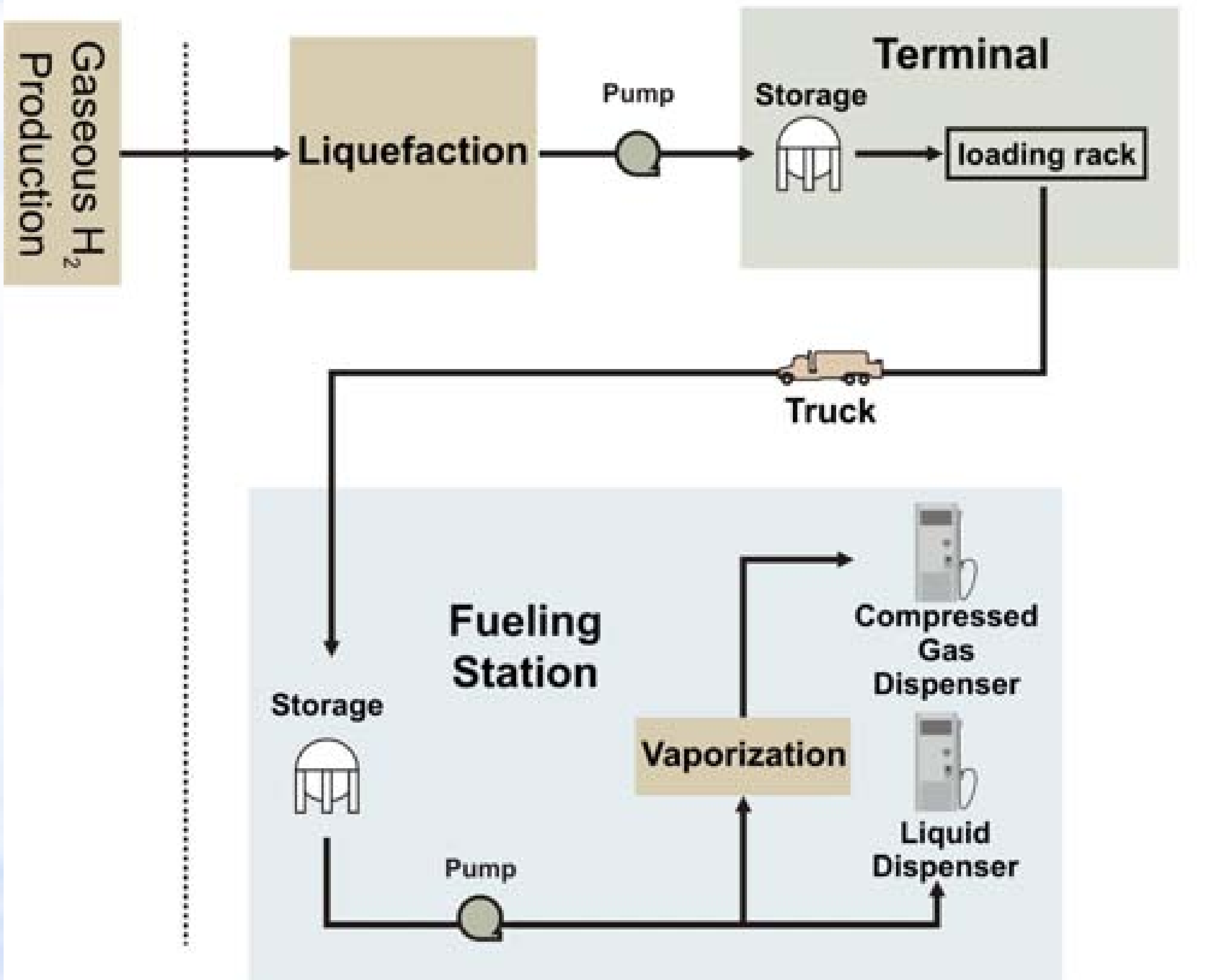
Pipelines
Compression
Liquefaction
Carriers & Transformations
Gaseous Storage Tanks
Geologic Storage
GH2 Tube Trailers

Terminals
Separations/Purification
Dispensers
Liquid Storage Tanks
Mobile Fuelers
Liquid Trucks, Rail, Ships

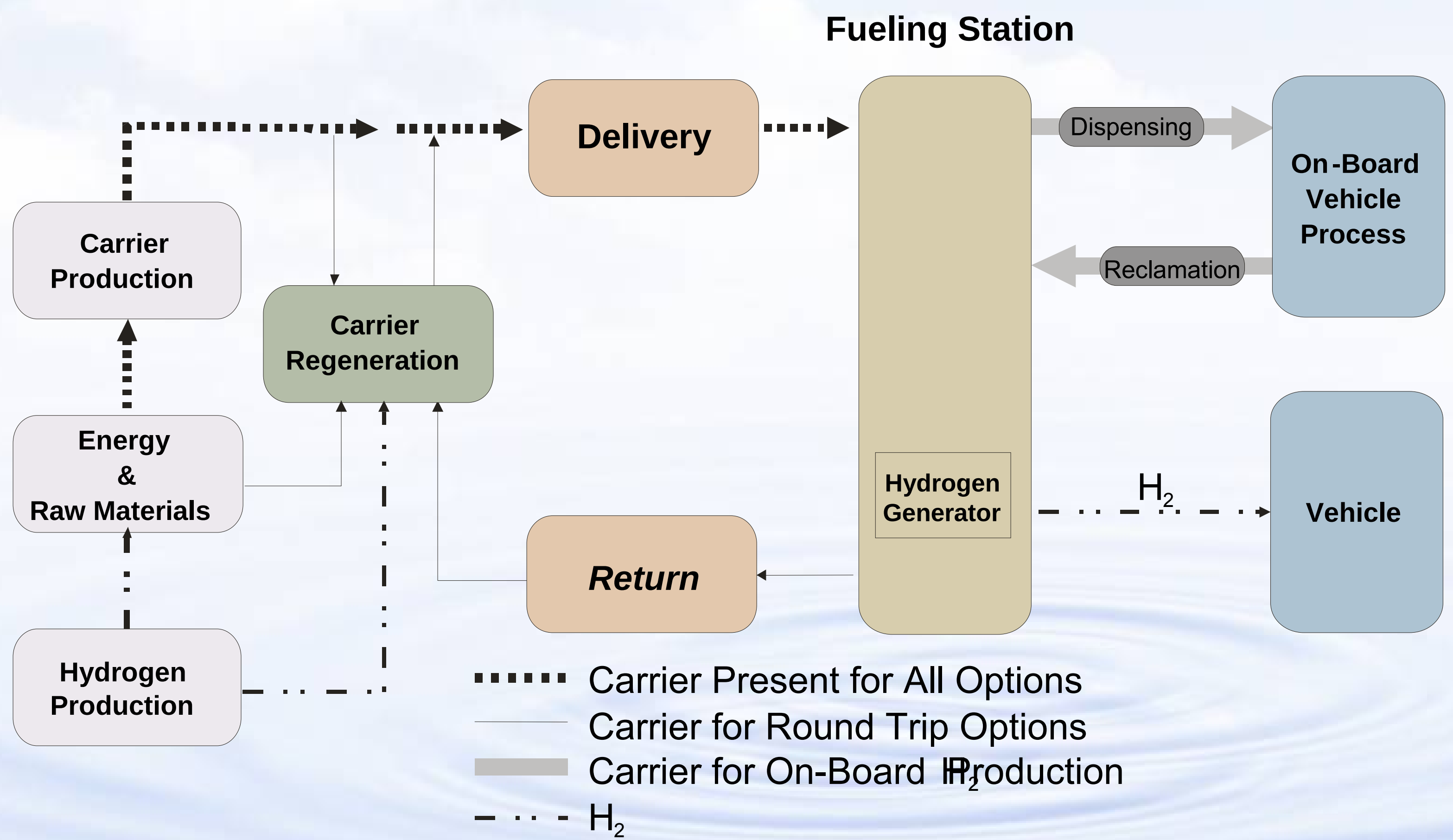
Gaseous Hydrogen Delivery Pathway



Liquefaction Distribution Pathway



Hydrogen Carrier Delivery Pathway



Carrier Examples

- ***Ammonia:*** *A* potential one-way carrier that can be easily transported and simply transformed by cracking to nitrogen and hydrogen:

  $$NH_3 \rightarrow N_2 + 3H_2$$

- ***Liquid Hydrocarbons:*** A liquid hydrocarbon is catalytically dehydrogenated at a station or on a vehicle and "dehydrided" is then returned to a central plant or terminal for rehydriding:

  $$C_nH_{2n} \leftrightarrow C_nH_n + n/2\ H_2$$

- ***Hydrates/Clathrates:*** A clathrate is a stable structure of water molecules formed around a light molecule. The most common are methane hydrates. Clathrates formed around hydrogen molecules have been recently discovered. Clathrates would likely be handled as slurries or solids for delivery of hydrogen.

  $$(H_2O)_n(CH_4)_m(H_2)_p \rightarrow nH_2O + mCH_4 + pH_2$$

Carrier Examples

- ***Metal Hydrides***
- ***Nanostructures:*** Single-wall carbon nanotubes (SWNTs). Other Nonostructures
- ***“Bricks”, Flowable Powders, Slurries:*** Stable solid carriers might be delivered in many different ways. Slurries have been mentioned, but novel systems such as flowable powders or solid “bricks” might also be potential delivery mechanisms.

Hydrogen Delivery Targets

Category	2003	2005	2010	2015
Pipeline: Transmission				
Total Capital Cost ($M/mile)[2]	$1.20	$1.20	$1.00	$0.80
Pipeline: Distribution				
Total Capital Cost ($M/mile)[2]	$0.30	$0.30	$0.25	$0.20
Pipeline: Transmission and Distribution				
Reliability (relative to H_2 embrittlement concerns, and integrity)[3]	Undefined	Undefined	Understood	High (metrics TBD)
H_2 Leakage[4]	Undefined	Undefined	<2%	<0.5%
Compression: Transmission				
Reliability[5]	92%	92%	95%	>99%
Hydrogen Energy Efficiency (%)[6]	99%	99%	99%	99%
Capital Cost ($M/compressor)[7]	$18	$18	$15	$12
Compression: At Refueling Sites				
Reliability[5]	Unknown	Unknown	90%	99%
Hydrogen Energy Efficiency (%)[6]	94%	94%	95%	96%
Contamination[8]	Varies by Design	Varies by Design	Reduced	None
Cost Contribution ($/kg of H_2)[9,10]	$0.60	$0.60	$0.40	$0.25

Category	2003	2005	2010	2015
Liquefaction				
Small-Scale (30,000 kg H_2/day) Cost Contribution ($/kg of H_2)[11]	$1.80	$1.80	$1.60	$1.50
Large-Scale (300,000 kg H_2/day) Cost Contribution ($/kg of H_2)[11]	$0.75	$0.75	$0.65	$0.55
Small-Scale (30,000 kg H_2/day) Electrical Energy Efficiency (%)[11,12]	25%	25%	30%	35%
Large-Scale (300,000 kg H_2/day) Electrical Energy Efficiency (%)[11,12]	40%	40%	45%	50%
Carriers				
H_2 Content (% by weight)[13]	3%	3%	6.6%	13.2%
H_2 Content (kg H_2/liter)			0.013	0.027
H_2 Energy Efficiency (From the point of H_2 production through dispensing at the refueling site)[6]	Undefined	Undefined	70%	85%
Total Cost Contribution (From the point of H_2 Production through dispensing at the refueling site) ($/kg of H_2)	Undefined	Undefined	$1.70	$1.00
Storage				
Refueling Site Storage Cost Contribution ($/kg of H_2) [10,14]	$0.70	$0.70	$0.30	$0.20
Geologic Storage	Feasibility Unknown	Feasibility Unknown	Verify Feasibility	Capital and operating cost <1.5X that for natural gas on a per kg basis
Hydrogen Purity[15]	>98% (dry basis)			

Hydrogen Cost Analysis "H2A" Tool

- Mission
  - Improve the transparency and consistency of analysis
  - Improve the understanding of the differences among analyses
  - Seek better validation from industry
- Purpose
  - R&D portfolio development
  - Provide research direction (Not to be used to pick winners)
- History
  - Began in February 2003
  - Team of twelve analysts from national labs, industry, consulting firms
  - Activities to-date
    - H_2 production cash flow model & case studies
    - H_2 delivery model & scenarios
  - Use of Key Industrial Collaborators

H2A Analysis

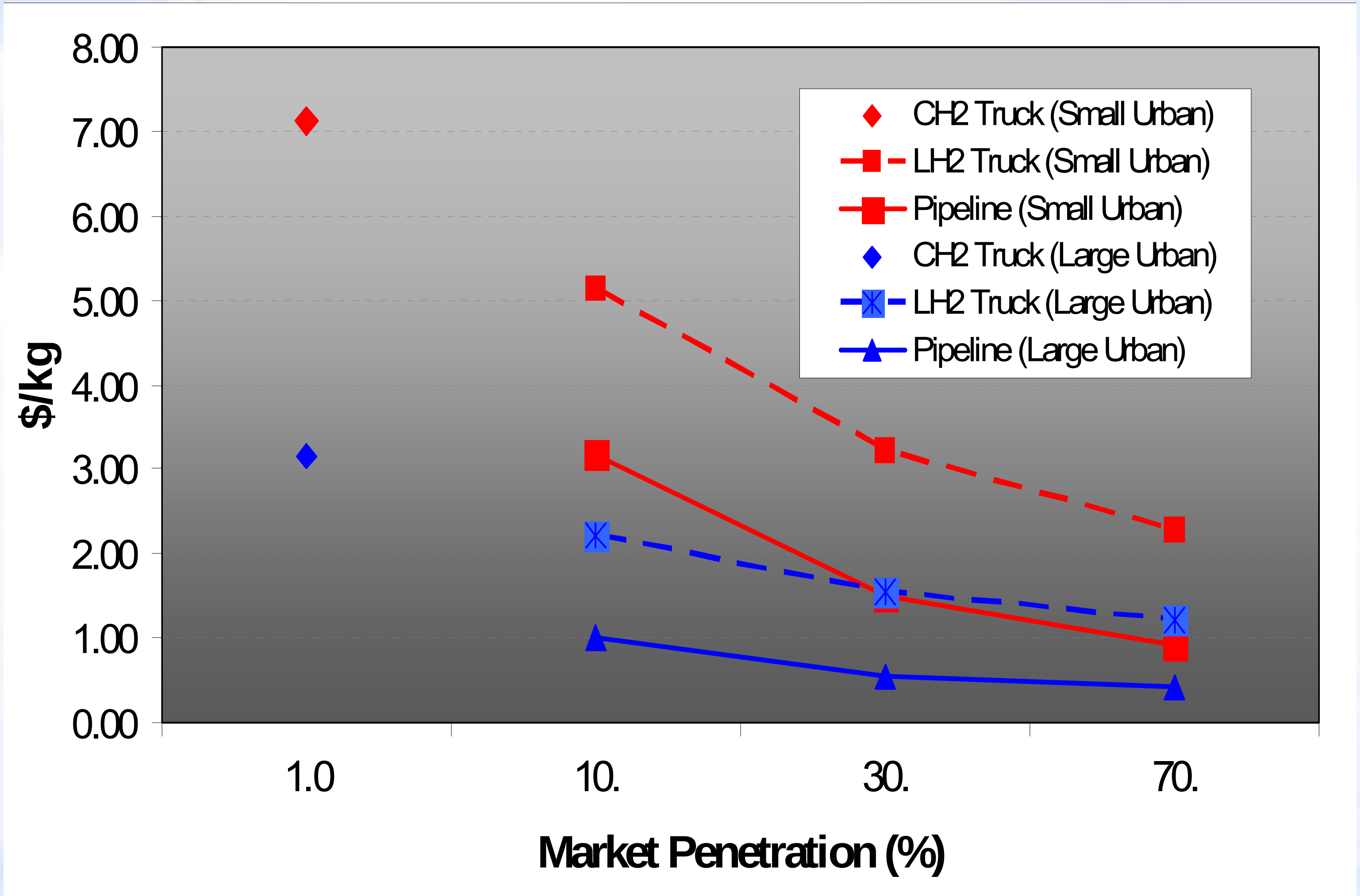
- Consistent, comparable, transparent approach to hydrogen production and delivery cost analysis
- Spreadsheet tools with common economic parameters, feedstock and utility costs, and approach
- Project Team
  - Production: DTI, TIAX, Technology Insights, PNNL, NREL, ANL
  - Delivery: U.C. Davis, ANL, PNNL, NREL
- Key Industrial Collaborators

Eastman Chemical	Ferco
AEP	Thermochem
Entergy	GE
Framatome	Stuart Energy
APCi	Chevrontexaco
Praxair	Exxonmobil
BOC	BP

H2A Delivery Analysis Goals

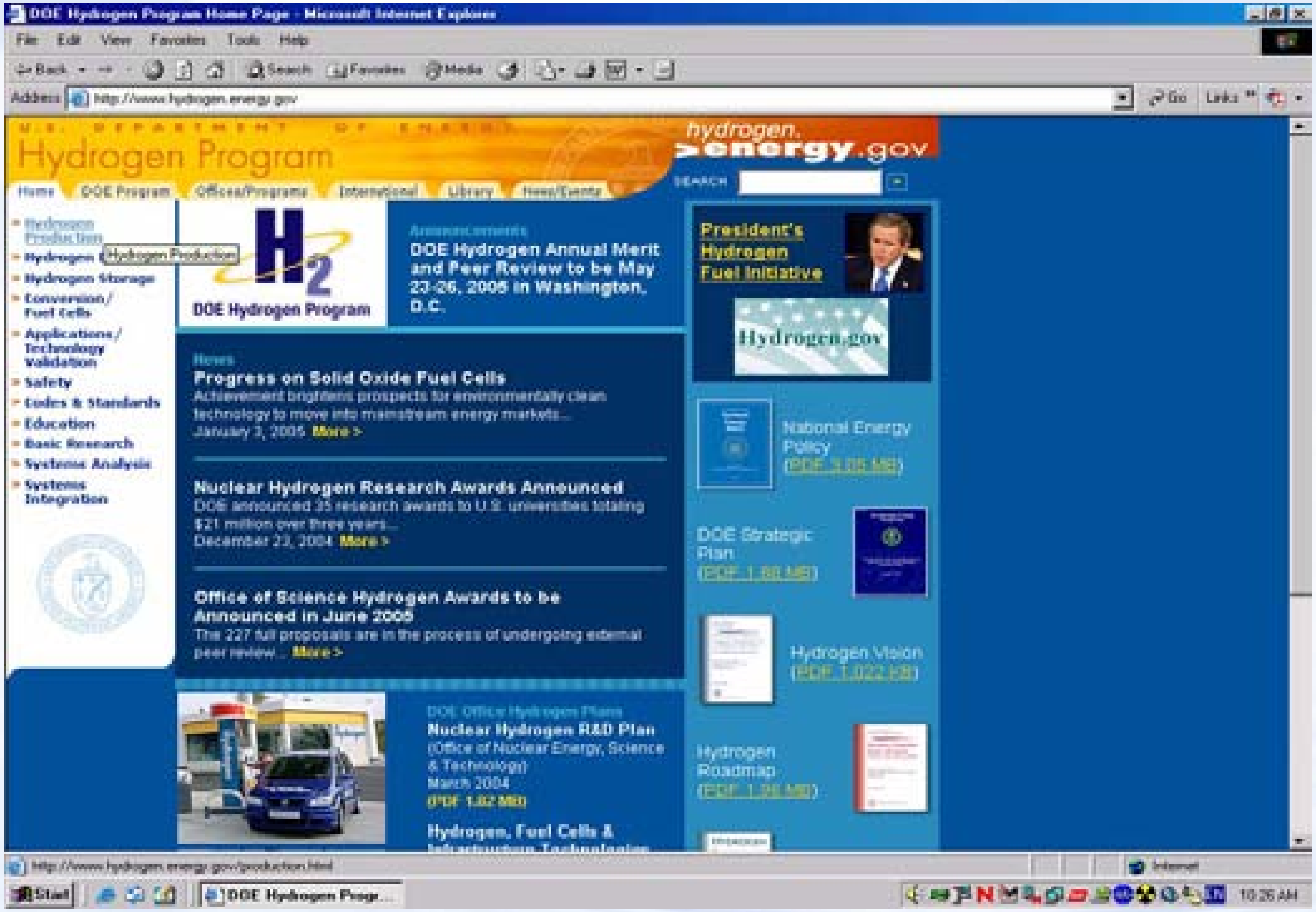
- Develop spreadsheet database on delivery system component costs and performance: Component Model
- Develop delivery scenarios for set of well defined "base cases" that span major markets and demand levels. Scenario Model
- Estimate the cost of H_2 delivery for base cases.
- Assume 2005 delivery technologies

Scenario Model Results



Note: $/kg excludes Forecourt C/S/D

For More Information
www.hydrogen.energy.gov



For Interagency Information:
www.hydrogen.gov

Back Up Slides

Hydrogen Production and Delivery

Energy from diverse, domestic sources: $103 Million Total ($77 Million Federal Share)

Distributed Reforming Using Natural Gas and Renewable Liquids

- Develop intensified, lower capital cost, more efficient NG reformer technology
- Develop improved catalysts and technology for renewable liquids reforming (e.g. ethanol, sugar alcohols, Bio-oil)
- Lead Partners: GE, APCi, H2Gen, Virent, Ohio State Research

Electrolysis

- Develop low cost and high efficiency materials and system designs
- Integrated compression
- Integrated wind power/electrolysis systems
- Lead partners: Teledyne, Giner, Materials and Systems Research

Biomass Gasification

- Developed integrated gasification, reforming, shift and separations technology to reduce capital and improve efficiency.
- Lead Partners: GTI, UTRC, SRI, Ceramatec, Arizona State U.

Solar/Photolytic

- Develop durable materials for direct photo-electrochemical solid state water splitting using sunlight
  - Lead Partners: Univ. of California, MV Systems, U, of Hawaii, Midwest Optoelectronics
- Research microorganisms that split water using sunlight
  - Lead Partners: Univ. of California, Craig Venter Institute
- Research thermochemical cycles that split water using heat (600 – 2100 C) from solar concentrators
- Lead Partners: UNLV, U. of Colorado, SAIC

Delivery

- Infrastructure options and trade-offs analysis
- Develop lower cost and robust technology for pipelines, compression, off-board storage, carriers, and liquefaction
- Lead Partners: Nexant, GEECO, NCRC, APCI, SECAT, U. of Illinois

Hydrogen Vehicles

DaimlerChrysler

Ford Motor Company

Hyundai

General Motors

Photo: Shell Hydrogen

Hydrogen Refueling Infrastructure

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

Extensive Coordination

International Partnership for the Hydrogen Economy

- IPHE.net

Interagency Hydrogen Research and Development Task Force (OSTP lead)

- www.hydrogen.gov

Federal/State/local (Example)

- California Fuel Cell Partnership
- California Hydrogen Highway Network