The U.S. Department of Energy Hydrogen Delivery Program

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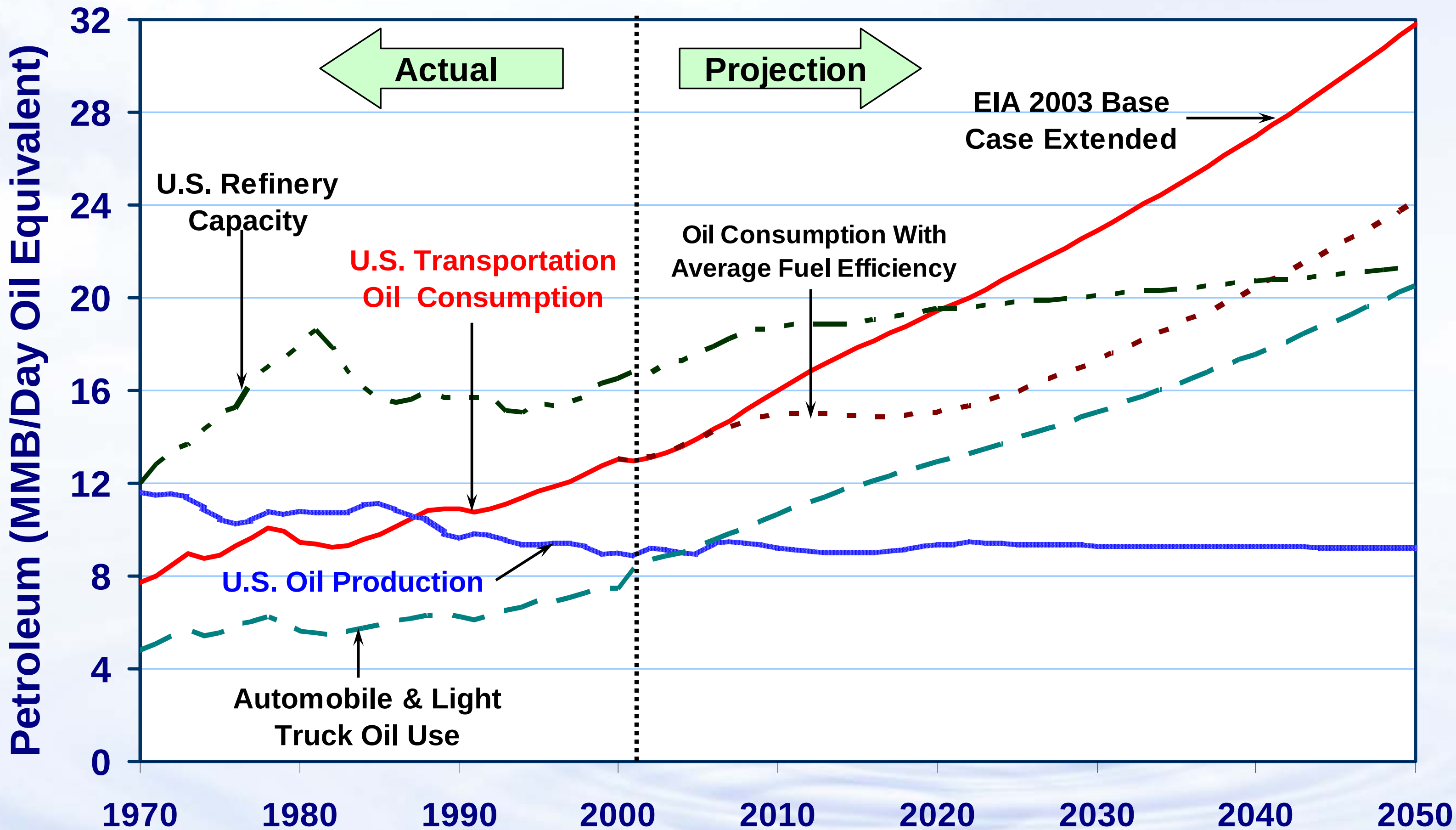
January, 2005

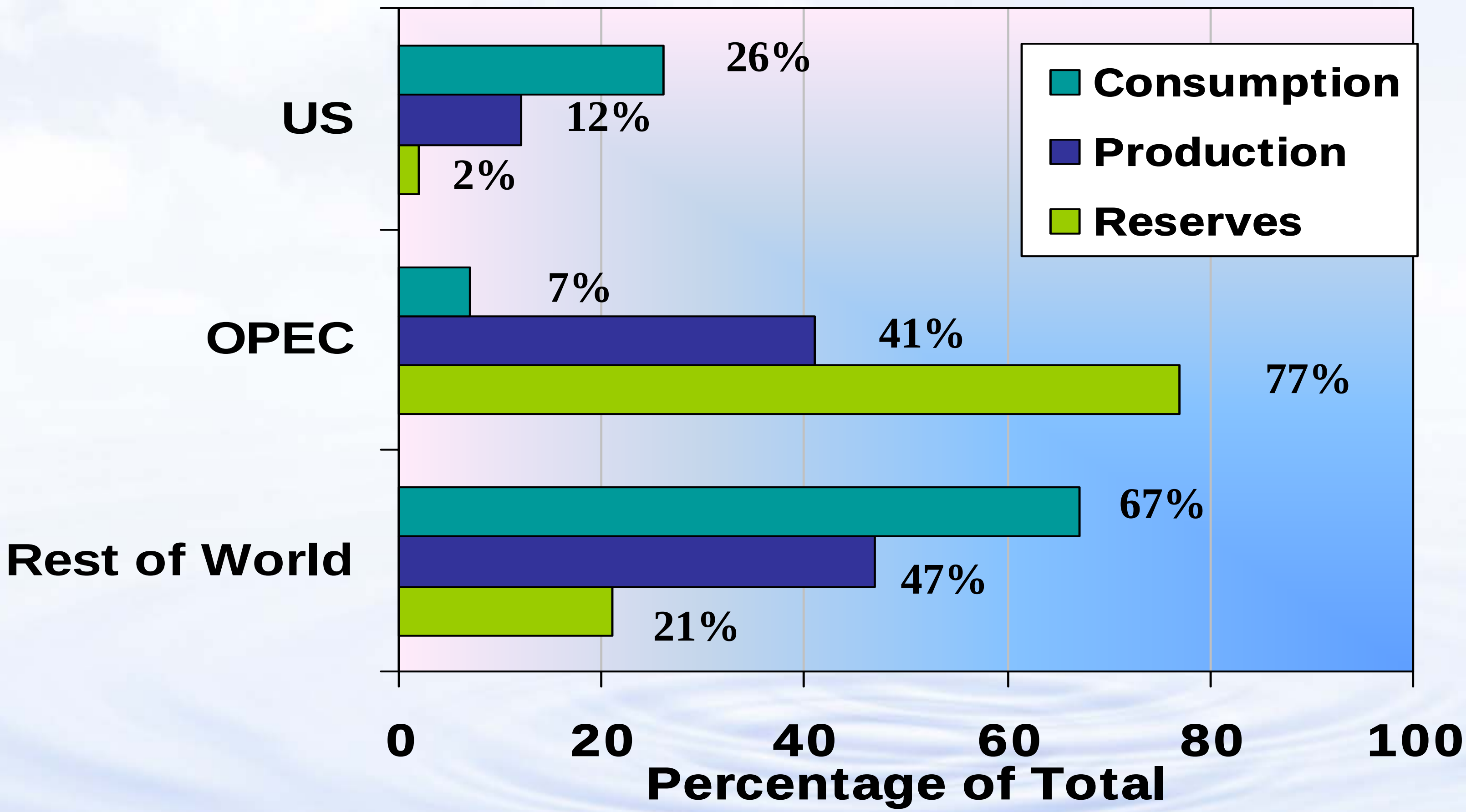
Important Numbers

- 1 kg H_2 = 1 gallon gasoline
- Eff_{FCV} = 2-3 x Eff_{ICEV} = 1.2-1.4 x Eff_{HEV}
- Energy Density
  - 10,000 psi H_2 = 1.3 kWhr/l
  - LH2 = 2.3 kWhr/l
  - Gasoline = 9.7 kWh/l

A Bold New Approach is Required

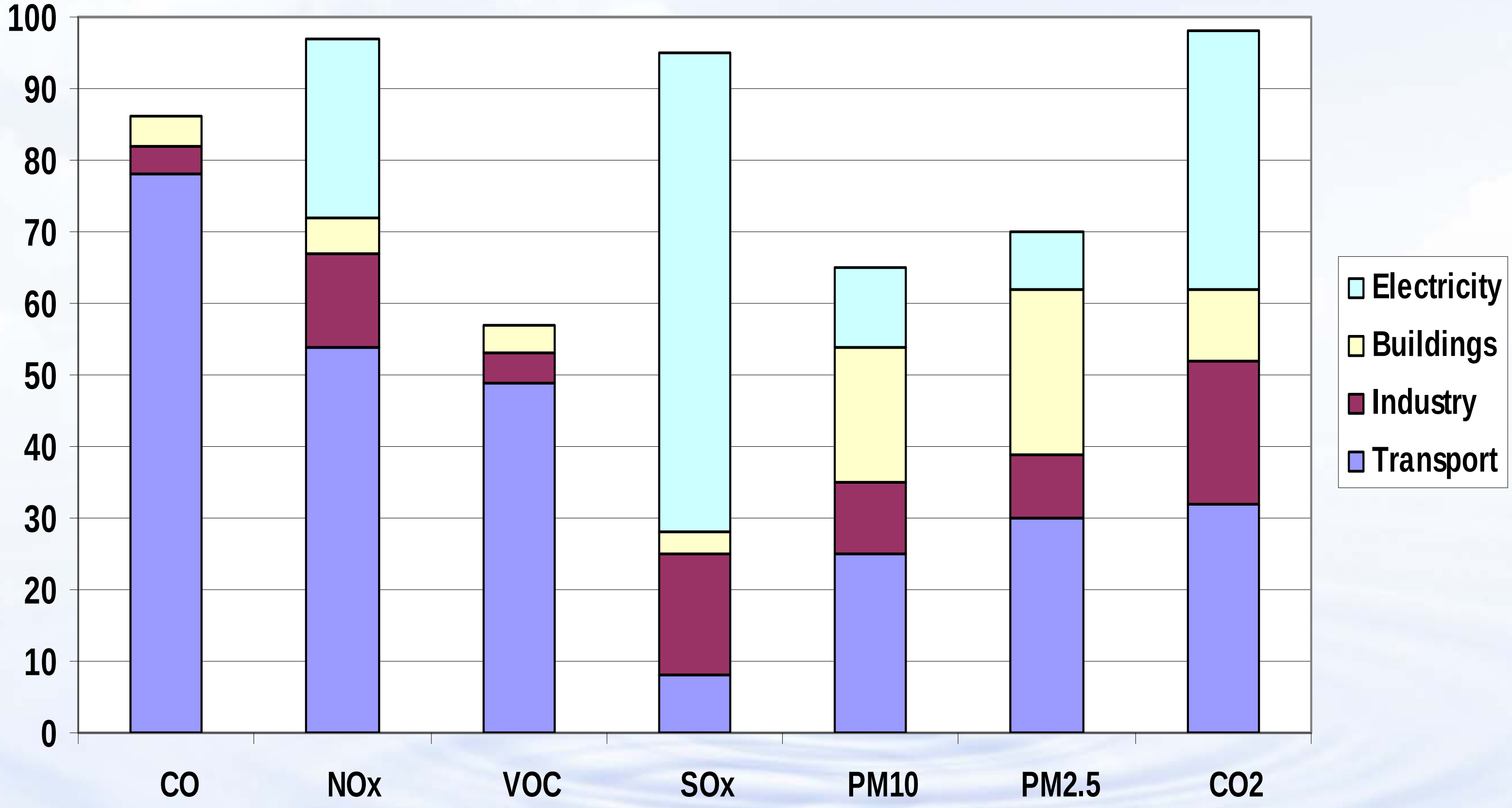


World Oil Reserves are Consolidating in OPEC Nations

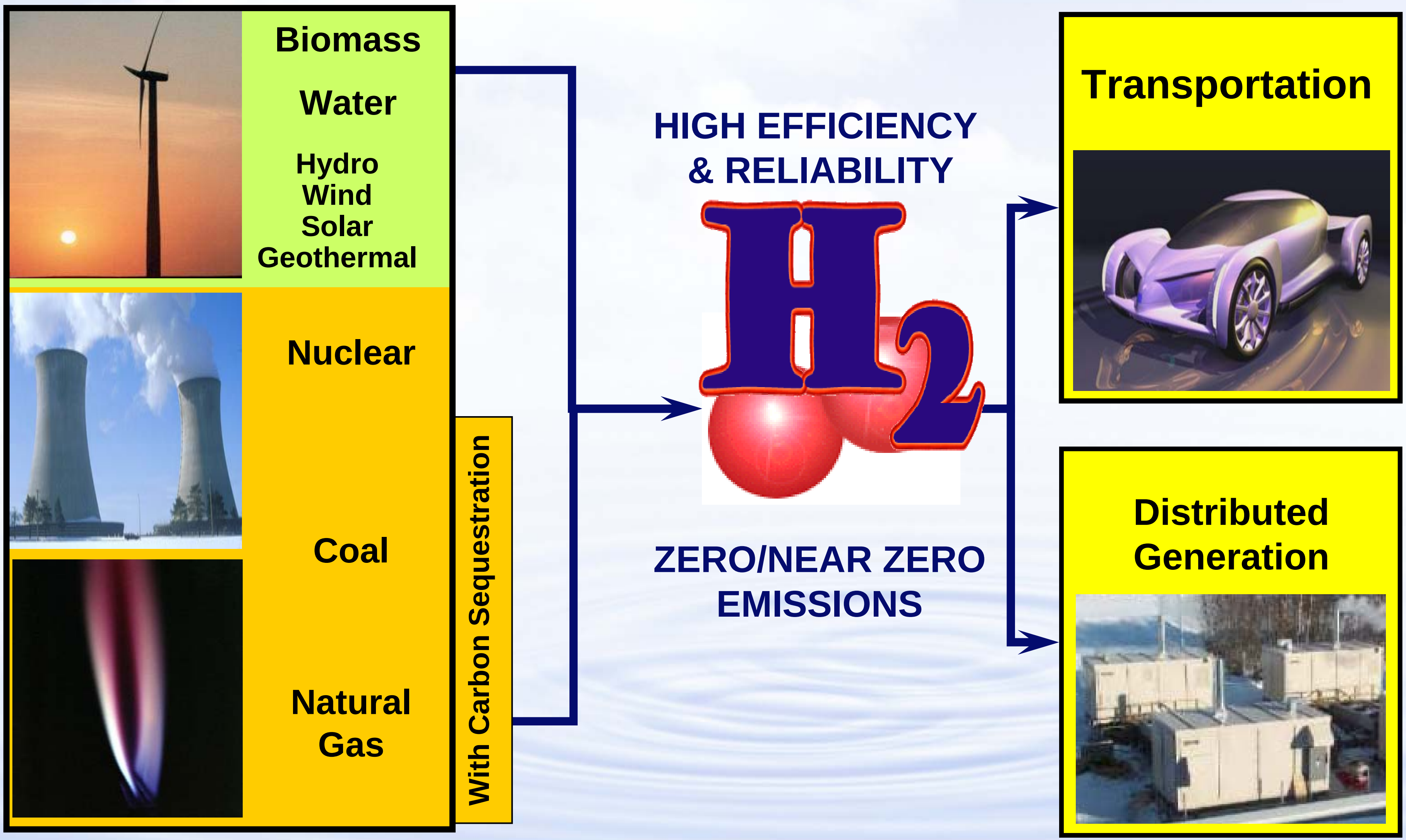


Source: DOE/EIA, International Petroleum Statistics Reports, April 1999; DOE/EIA 0520, International Energy Annual 1997, DOE/EIA0219(97), February 1999.

U.S. 1998 Energy-Linked Emissions as Percentage of Total Emissions

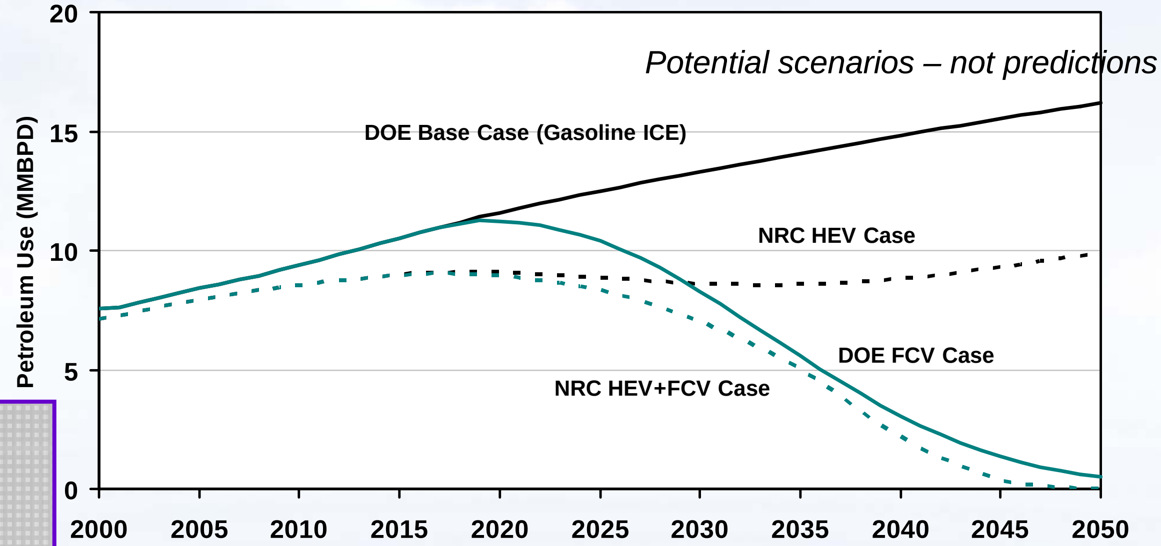


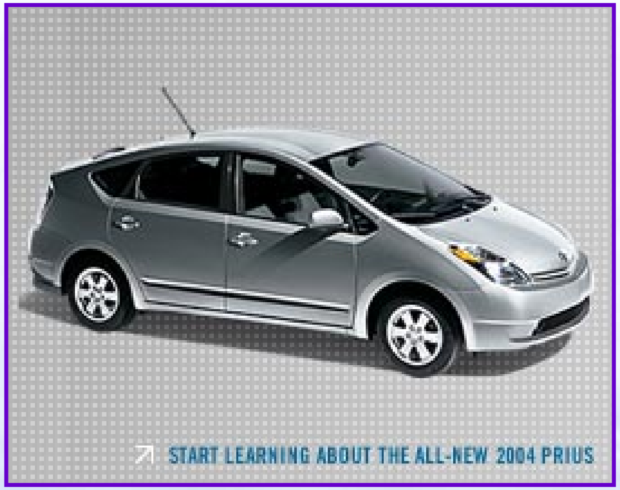
Why Hydrogen? It's abundant, clean, efficient, and can be derived from diverse domestic resources.



Hybrids are a Bridge

***Hybrid vehicles** are a bridge technology that can reduce pollution and our dependence on foreign oil until long-term technologies like hydrogen fuel cells are market-ready.*





FreedomCAR and Fuel Partnership Established

New Energy Company/DOE Technical Teams

- Production
- Delivery
- Fuel Pathway Integration

New Joint Auto/Energy/DOE Technical Teams

- Codes and Standards
- Hydrogen Storage

International Partnership for the Hydrogen Economy

Russian Federation

USA

Canada

Iceland

Japan

South Korea

China

India

IPHE Partners' Economy:

- Over $35 Trillion in GDP, 85% of world GDP
- Nearly 3.5 billion people
- Over 75% of electricity used worldwide
- > 2/3 of CO_2 emissions & energy consumption

United Kingdom

France

Germany

Italy

An IPHE Vision:

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

- Secretary Abraham, April 2003

Australia

Brazil

Norway

European Commission

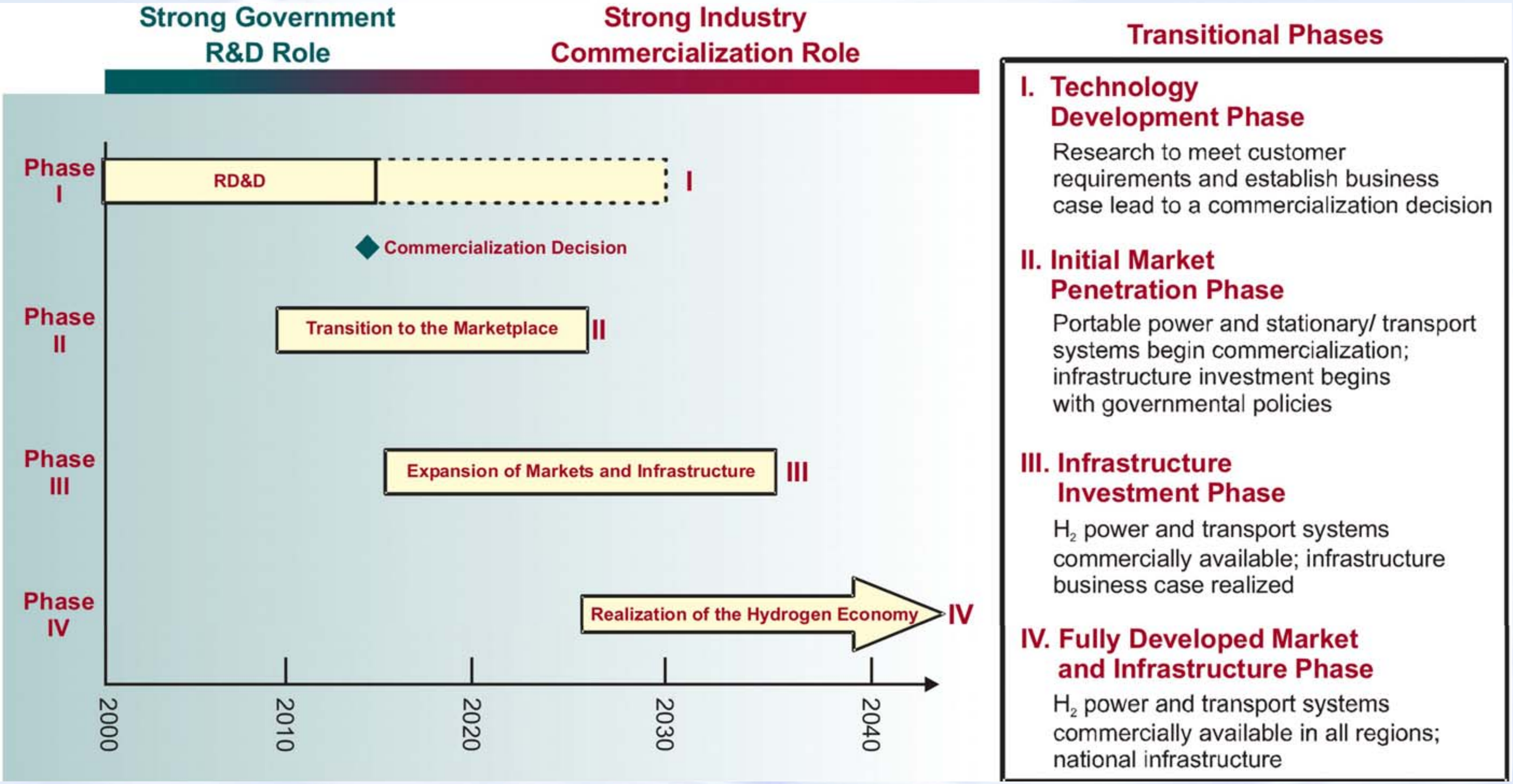
DOE Intra-Agency Collaboration

DOE Posture Plan

- EERE
- Fossil Energy
- Nuclear Energy
- Office of Science

- EERE
  - Hydrogen, Fuel Cells, Infrastructure Program
  - Vehicle Technologies Program
  - Solar Program
  - Wind Program
  - Biomass Program

Timeline for Hydrogen Economy



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

Program Elements

- Hydrogen Production
- Hydrogen Delivery
- On-Board Vehicle Storage
- Fuel Cells
- Safety, Codes & Standards
- Systems Analysis
- Education

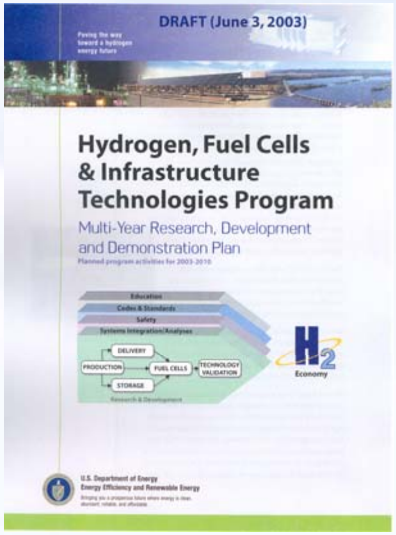
Barriers to a Hydrogen Economy

<u>Critical Path Technology Barriers:</u>

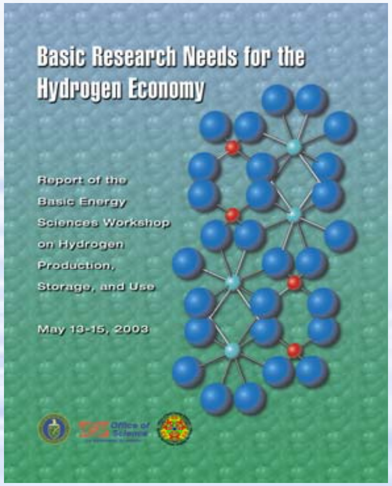
- Hydrogen Storage (>300 mile range)
- Hydrogen Production Cost ($1.50-2.00 per gge)
- Fuel Cell Cost (< $50 per kW)

<u>Economic/Institutional Barriers:</u>

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



http://www.eere.energy.gov/hydrogenanfuelcells/mypp/



http://www.er.doe.gov/production/bes/hydrogen.pdf

Hydrogen Production Technologies

- Distributed natural gas reforming
- Distributed bio-derived liquids reforming
- Electrolysis
- Coal gasification with sequestration(FE)
- Nuclear driven HT thermochemical cycles (NE)
- Photoelectrochemical hydrogen production
- Reforming biomass producer gas from gasification/pyrolysis
- Biological hydrogen production
- Solar driven HT thermochemical cycles

Analysis is Crucial to Success

- The envisioned Hydrogen Economy and the Transition is complex, highly interactive, and has many dimensions
  - Technologies
  - Markets: transportation, power, all hydrogen markets, all energy markets, and interacts with chemicals, food and feed, etc. through feedstock use
  - Time frames: short term (2010-2030), mid term (2030-2050) and long term
  - Geography: local, regional, national, global
  - Costs and Benefits
  - Policy

Types of Analyses

- Resource Analysis
- Existing Infrastructure
- Technology Characterization (TEA & Enviro)
- Macro-System Models
- Integrated Baseline Analysis
- Market Analysis
- Infrastructure Transition Analysis
- Benefits Analysis

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

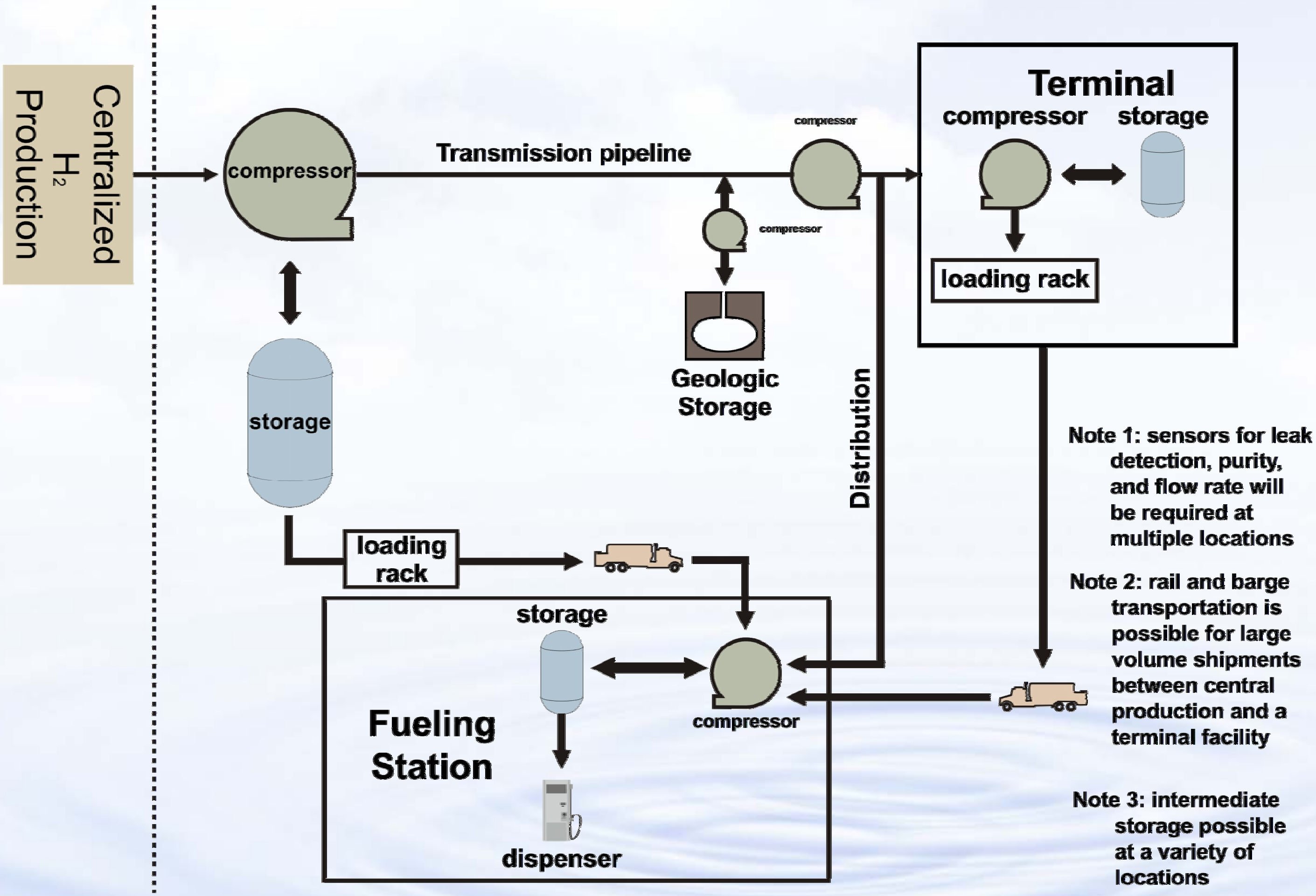
From the end point of central (or distributed) production (300 psi H_2) to and including the dispenser at a refueling station or stationary power site

(Includes forecourt compression, storage and dispensing)

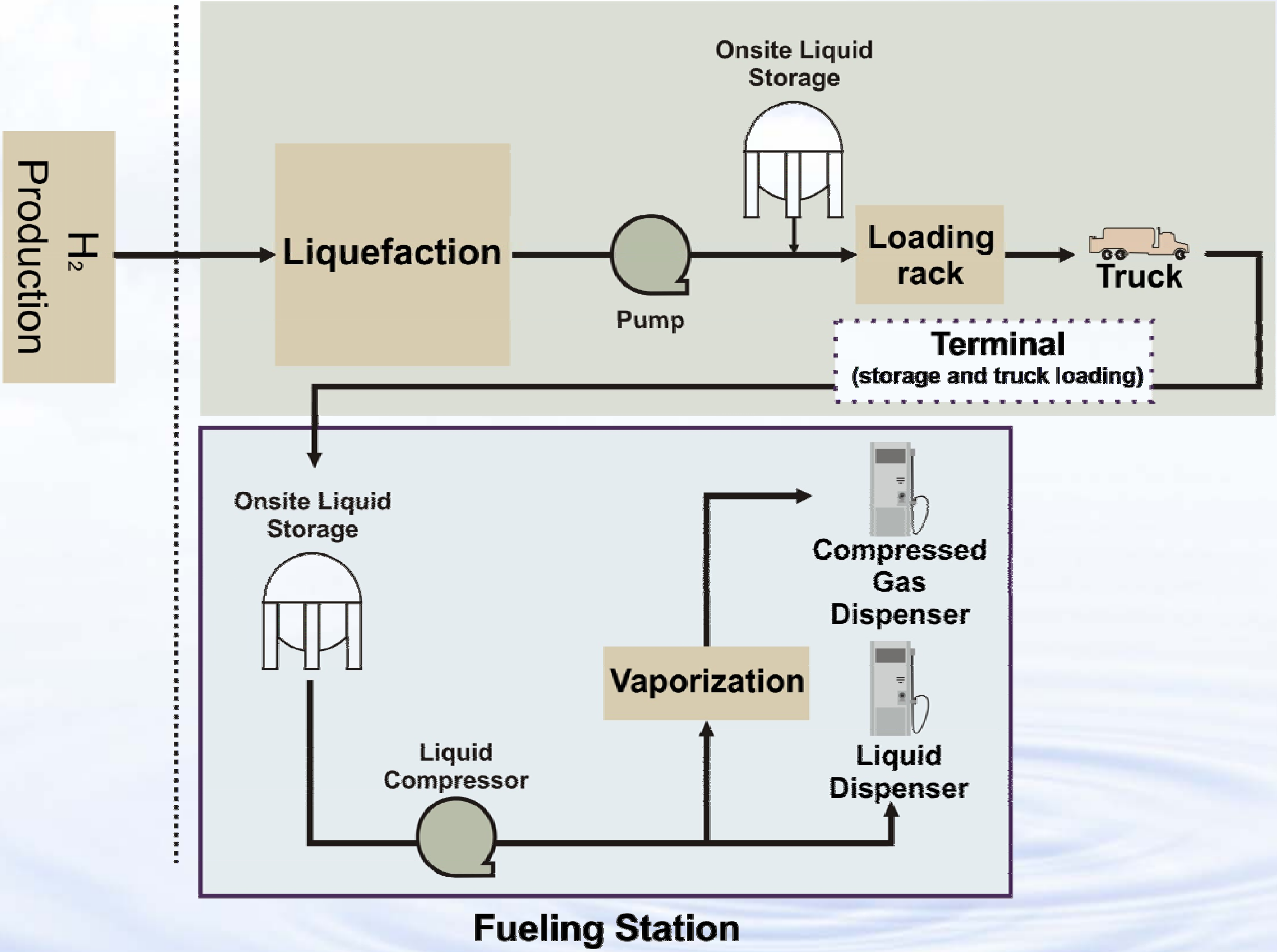
Technical Objectives

- By **2006**, define 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.

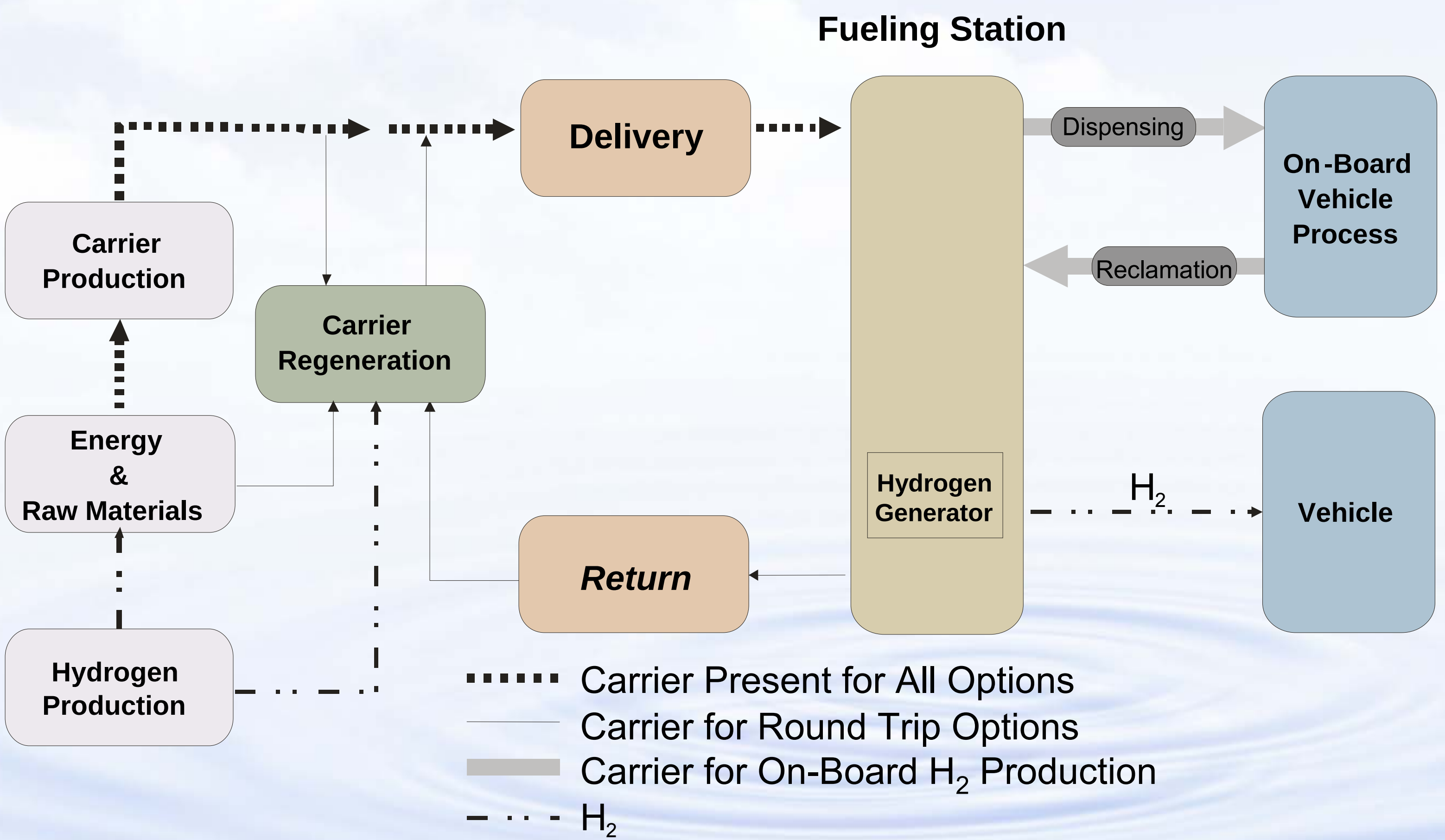
Gaseous Hydrogen Delivery Pathway



Liquid Hydrogen Delivery Pathway



Hydrogen Carrier Delivery Pathway



Research Areas

- Pathways
  - Gaseous Hydrogen Delivery
  - Liquid Hydrogen Delivery
  - Carriers
- Components

Including mixed pathways

Pipelines
Compression
Liquefaction
Liquid and Gaseous Storage Tanks
Geologic Storage
GH2 Tube Trailers, Cryogenic Liquid Trucks, Rail, Barge, Ships

Terminals
Separations/Purification
Dispensers
Carriers & Transformations
Mobile Fuelers
Other Forecourt Issues

Carriers

- Liquid, solid, or slurry phase under favorable temperature and pressure conditions
- High hydrogen capacity with reasonable volumetric and energy densities
- Simple, low-cost, high energy-efficiency transformation process for discharging hydrogen
- Simple and low-energy path to recharging with hydrogen (in the case of two-way carriers)
- Safe and environmentally benign

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.

  $(H_2O)_n(CH_4)_m(H_2)_p \rightarrow nH_2O + mCH_4 + pH_2$
- ***Metal Hydrides***
- ***Nanostructures:*** *S*ingle-wall carbon nanotubes (SWNTs). Other Nonostructures
- ***Bricks or Flowable Powders:*** 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.

Key Learnings/Challenges

- Forecourt costs are significant and need to be reduced
  - Compression reliability needs to be improved
  - Need a breakthrough in high pressure storage or carrier system for low pressure storage
- Pipelines are the current low cost pathway for the long term, but:
  - Must resolve embrittlement, and find reasonable cost ROW
  - Reduce capital costs with alternative materials and or joining technology
  - Need new/improved pipeline compression technology
  - Can existing NG pipelines be used for H_2/NG mixtures and/or pure H_2
  - How to move to pipelines (at least transmission) earlier?

Key Learnings/Challenges

- Storage needs for market demand fluctuations need further understanding and technology solutions
  - NG relies heavily on geologic storage: Can H_2 utilize geologic storage?
  - Terminal storage and other storage needs may need improved technology
- Can carriers change the delivery paradigm?
- Transition
  - Low volumes means much higher delivery costs
  - Need a breakthrough: liquefaction, higher pressure tube trailers, or a liquid carrier approach
- Additional delivery infrastructure analysis of options and trade-offs is essential

Back-Up Slides

Hydrogen Delivery Targets

Category	2003	2005	2010	2015
Total Capital Cost ($M/mile)[2]	$1.20	$1.20	$1.00	$0.80
Pipelines: Distribution				
Total Capital Cost ($M/mile)[2]	$0.30	$0.30	$0.25	$0.20
Pipelines: Transmission and Distribution				
Reliability (relative to H_2embrittlement concerns, and integrity)[3]	Undefined	Undefined	Understood	High (metrics TBD)
H_2 Leakage[4]	Undefined	Undefined	<2%	<0.5%
Compression: Transmission				
Reliability[5]	92%	92%	95%	>99%
Hydrogen Energy Efficiency (%)[6]	99%	99%	99%	99%
Capital Cost ($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

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_2Production 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)			

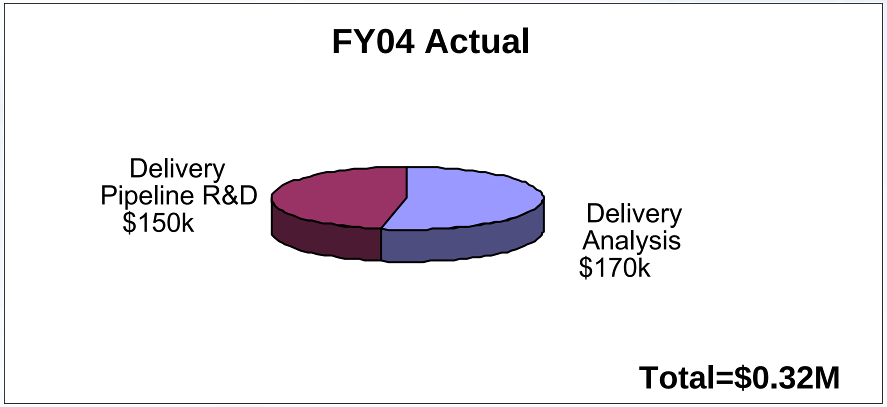
Delivery Projects

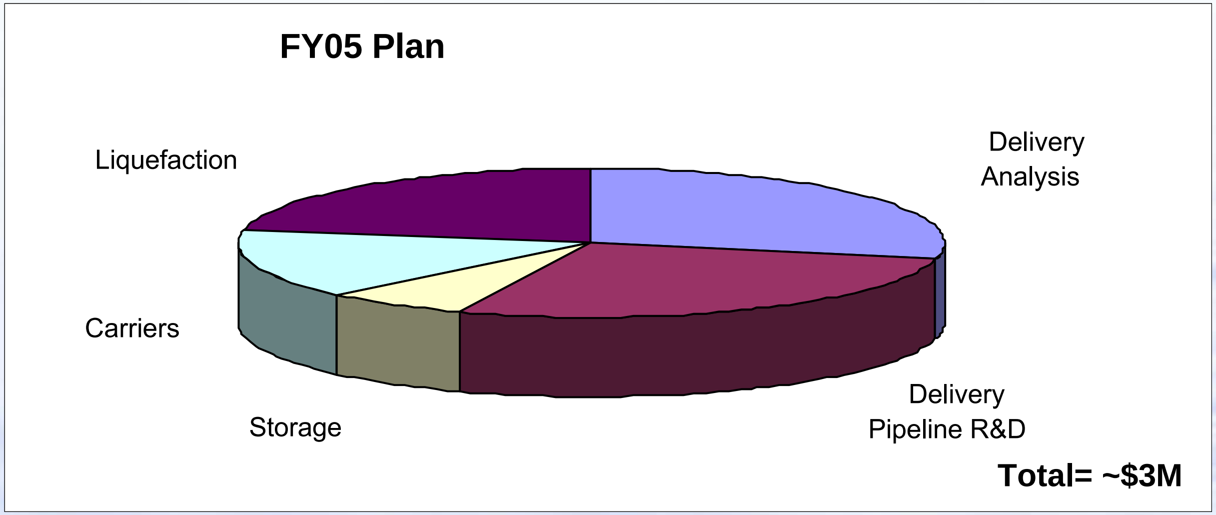
- Delivery Analysis
  - H2A Delivery Effort (ANL, NREL, J. Ogden)
  - Nexant collaborative project
- Compression
  - ANL: Novel Screw Compressor
  - HERA: Hydride Compression (integrated with production distr. production project)
- Liquefaction
  - GEECO: Advanced turbo compression/expansion
  - NCRC: Magnetic Liquefaction

Delivery Projects (Cont'd)

- Off-Board Storage
  - GTI: Forecourt analysis/underground liquid storage
  - LLNL: Composites for high pressure storage and tube trailers
- Pipelines (H_2 and mixed H_2/NG)
  - National Lab projects (ORNL, SRNL)
  - SECAT collaborative project
  - U. of Illinois
  - CTC: PA Earmark
  - NG Infrastructure: GTI
- Carriers
  - APCi, UTRC, Penn State U: Liquid Hydrocarbon

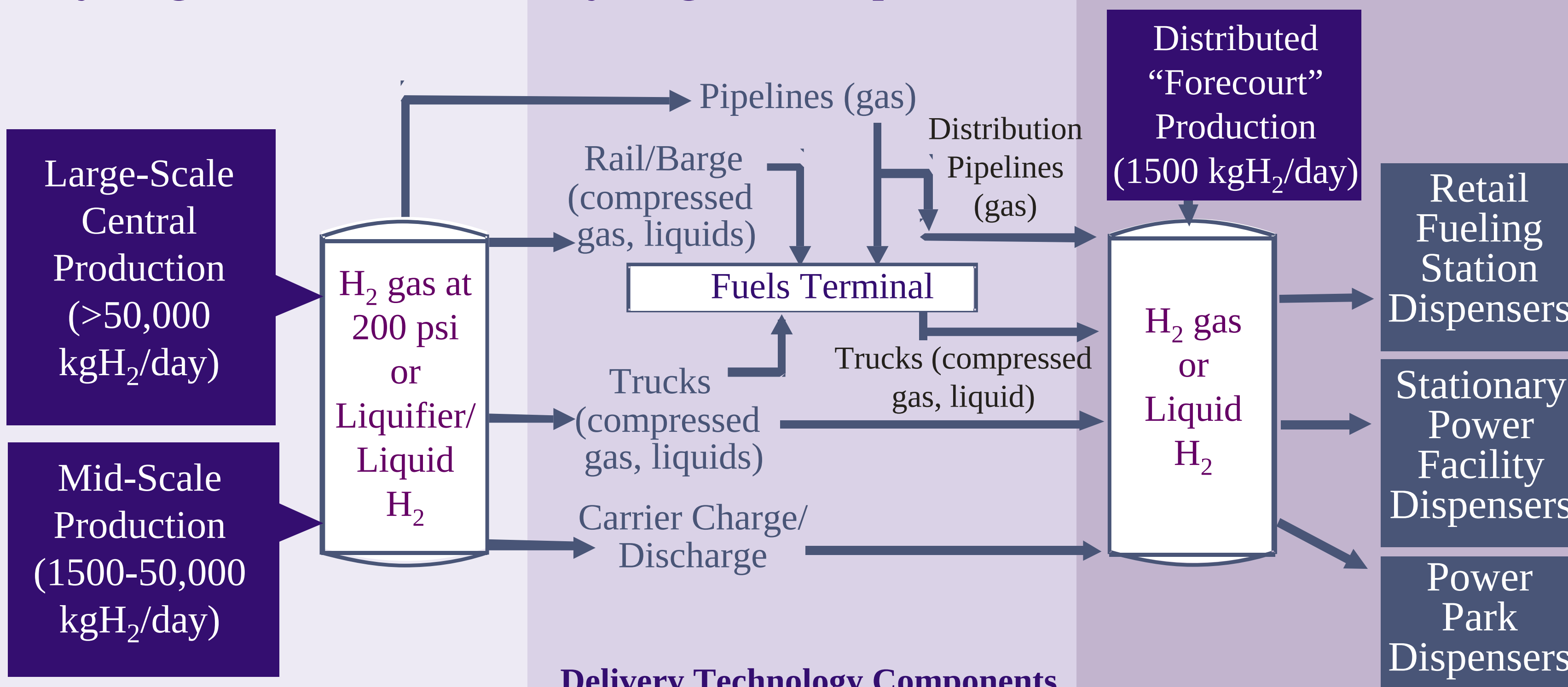
Delivery Funding





Hydrogen Delivery Infrastructure

Hydrogen Production | Hydrogen Transportation | End-Use Station



Delivery Technology Components
- Storage at Production Site
- Liquefier
- Carrier Production/Regeneration

Delivery Technology Components
- Pipelines (transmission & distribution)
- Trucks, Rail, Barges
- Compressors
- Liquid and Gaseous Storage Tanks
- Geologic Storage
- Terminals

Delivery Technology Components
- Carrier Transfiguration
- Separation/Purification
- Storage Tanks
- Compression/Vaporization
- Fuel Dispensers

Crosscutting Delivery Technology Components
- Sensors & Controls
- Health & Human Safety
- Codes & Standards
- Right of Ways/Permitting

DOE Hydrogen Budget

(EWD & Interior Appropriations in thousands of dollars)

MAJOR LINE ITEMS	FY 04 Appropriations	FY 05 Request	Omnibus Appropriations
Production & Delivery R&D (EE)	$22,564	$25,325	
Storage R&D (EE)	$29,432	$30,000	
Safety, Codes & Standards, and Utilization (EE)	$5,904	$18,000	
Infrastructure Validation (EE)	$18,379	$15,000	
Education and Cross-cutting Analysis (EE)	$5,712	$7,000	
EERE Hydrogen Technology Subtotal– (EWD)	**$81,991*** **(Net: $41,991)**	**$95,325**	**$95,325**** **(Net: $58,635)**
NE Hydrogen Subtotal – (EWD)	$6,400	$9,000	$9,000
FE Hydrogen Subtotal – (Interior)	$4,900	$16,000	$17,000
SC – (EWD)	$0	$29,200	$29,200
Hydrogen Technology Total	**$93,791**	**$149,525**	**$150,525**

* **Includes $40M of Earmarked projects**
** **Includes $36.7M of earmarked projects. Eliminates education.**

DOE Hydrogen Budget

(EWD & Interior Appropriations in thousands of dollars)

MAJOR LINE ITEMS	FY 05 Request	FY05 Plan*
Production & Delivery R&D (EE) Production Delivery	$25,325 ($21,325) ($4,000)	$14,600 ($11,900) ($2,700)
Storage R&D (EE)	$30,000	$24,800
Safety, Codes & Standards, and Utilization (EE)	$18,000	$5,900
Infrastructure Validation (EE)	$15,000	$9,800
Cross-cutting Analysis (EE)	$7,000	$3,525
Earmarks		**$36,700**
EERE Hydrogen Technology Subtotal– (EWD)	**$95,325**	**$95,325**

*** Tentative Plan**

HT Thermochemical Cycles

- Manganese Sulfate Cycle Example

$$MnSO_4 \rightarrow MnO + SO_2(g) + .5O_2(g) \quad 1150°C$$

$$MnO + SO_2 + H_2O \rightarrow MnSO_4 + H_2(g) \quad 120°C$$

HT Thermochemical Cycles

- Volatile Metal Cycle Example

$ZnO \rightarrow Zn + .5O_2$	~2100°K
$Zn + H_2O \rightarrow ZnO + H_2$	500°K

HT Thermochemical Cycles

- Sulfuric Acid Based Cycles
  - Hybrid Sulfur

$2H_2SO_4(g) \rightarrow 2SO_2(g) + 2H_2O(g) + O_2(g)$	950°C
$SO_2(g) + 2H_2O(g) \rightarrow H_2SO_4(l) + H_2(g)$ (elec)	77°C

  - Sulfur Iodide

$2H_2SO_4(g) \rightarrow 2SO_2(g) + 2H_2O(g) + O_2(g)$	850°C
$2HI \rightarrow I_2(g) + H_2(g)$	300°C
$I_2 + SO_2(a) + 2H_2O \rightarrow 2HI(a) + H_2SO_4(a)$	100°C