Research & Development in the U.S. for a Hydrogen Economy

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Prospects for a European Hydrogen Economy

Referenced papers are available at stoft.com

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Hydrogen as the Universal Fuel

Water decomposed … by electricity … will one day be employed as fuel. Hydrogen and oxygen … will furnish an inexhaustible source of heat and light. Some day steamers and locomotives ….

“I should like to see that,” observed the sailor.

“You were born too soon, Pencroft,”

Jules Verne, *The Mysterious Island*, **1874.**

(explained by a fictitious American engineer)

Sustainable H_2 Economy (HE)

- Rows of metallic windmills which supply very high voltage.
- Surplus power used for the electrolytic decomposition of water.
- Gases will be liquefied and stored in vacuum jacketed reservoirs.
- In calm the gases will be recombined, probably in oxidation cells.
- Obvious advantages … no smoke or ash will be produced.

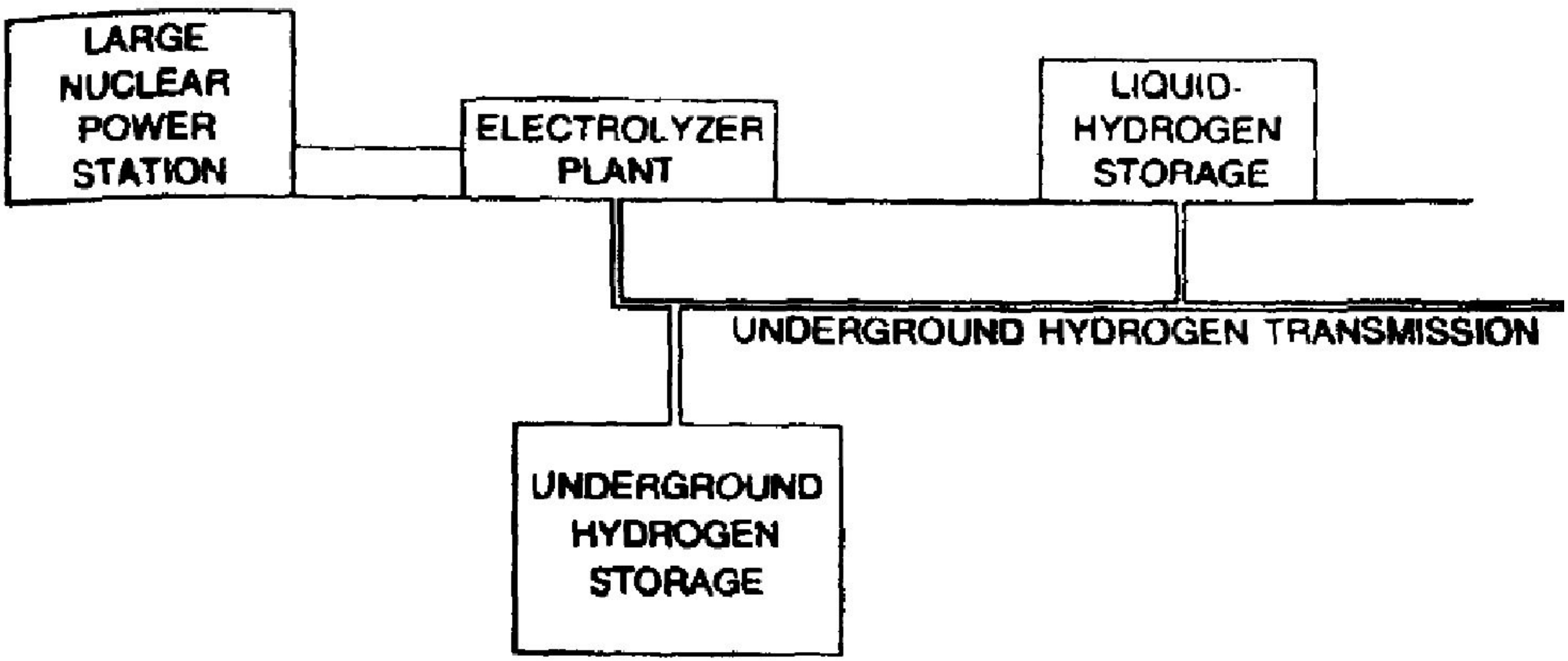
John Haldane, to the Heretics Society,
Cambridge University, **1923**

Predicted for **2323**

Scientific American, January 1973

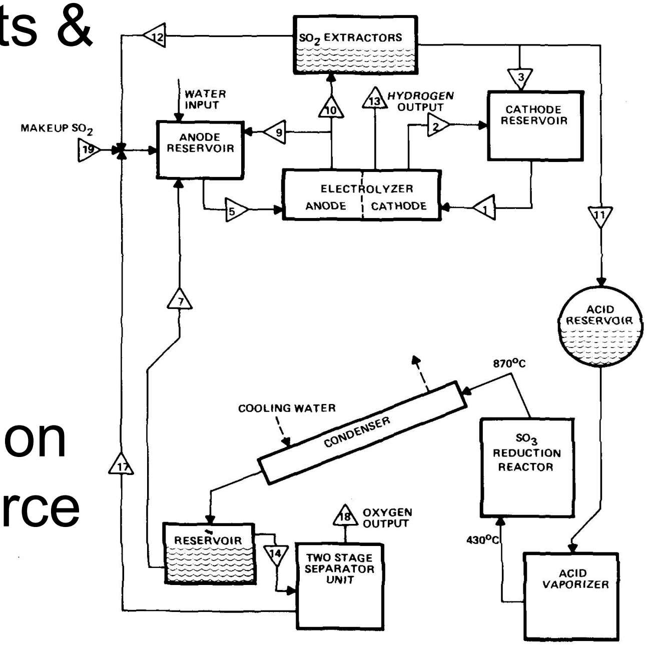
The Hydrogen Economy

"A case is made for an energy regime in which all energy sources would be used to produce hydrogen."



Westinghouse Sulfur Cycle - History

- Initial development by Westinghouse between 1973-83 with DoE support from 1976 to 1983
- Development of electrolyser components & the H_2SO_4 decomposition reactor
- Integrated laboratory demonstration in 1978 produced 120 L/hr H_2
- Development of commercial design / flowsheets, including process optimisation and integration with nuclear energy source



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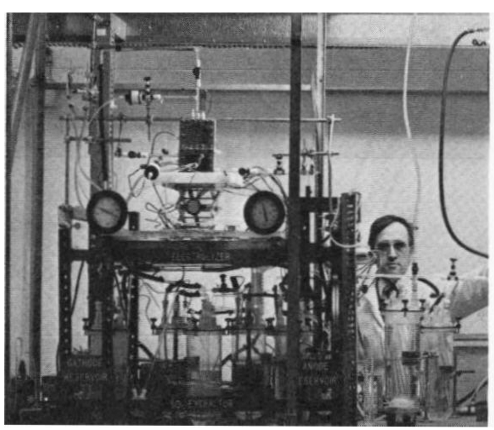
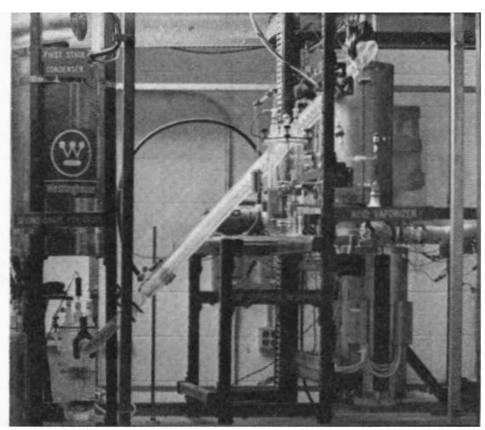




Westinghouse slide from 2000, pushing re-start of the nuclear industry.

Current US DOE Programs

- FreedomCAR (from 2002)
- FutureGen (from 2002)
- Hydrogen Fuel Initiative (from 2003)

US DOE* R&D Programs

- FreedomCAR and Fuel Partnership:
  - Hydrogen, Hybrids, etc.
  - Started in Fiscal Year (FY) 2003 (Oct. 2002—Sept. 2003)
- FutureGen, started FY 2003
  - Coal gasification with carbon sequestration project
  - $1 billion, then more, now mainly cancelled.
- Hydrogen Fuel Initiative, FY 2004 – 2008, now continuing
  - 1.2 Billion in 5 years
  - Commerce-ready automotive H fuel-cell technology by 2015
  - Significant fuel-cell car production by 2020
- Part of FreedomCAR and Future Gen that concern H are counted under the Hydrogen Fuel Initiative

* DOE = Department of Energy

International Competition

- The funding for continued development of the ICE and vehicle electrification seem appropriate. The international competition is fierce, maintaining a presence within that community and an awareness of technological developments outside the United States continue to be important.

  —The National Academy

- No similar statement about Hydrogen Fuel Cells

H2: What R&D Do We Need?

- **Fuel Cells? Yes.** Still ¼ the life and 4 x the cost. Most important: Time to succeed is unknown.
- **Onboard H_2 Storage? Yes.** High pressure thought to be wrong answer. Other options meet none of the criteria.
- **H2 Production Delivery? Low Priority.** High volume delivery costs only \$2 – \$3/kg. Currently: 1.1×10^{10} kg/year in US. Do R&D needed for CCS electricity.
- **CO_2 Sequestration? Yes.** Required for CO_2 benefit. Slow to start. 3×10^{11}kg/yr of CO_2 already captured at SMR (H2) plants. Also needed for Plug-in HEVs.
- **Market Transformation? No.** Regulators should relax. Look at cell phones, HDTV, Find niches for FCVs. Many paths available. Governments guess wrong.

What R&D Do We Get?

- Advance car budget, FY04–FY08 = \$1.7 B (10^9)
- H budget, FY04–FY08 = \$1.2 B
- Below: Spending in \$M (10^6)

Fiscal Year	‘04	‘05	‘06	‘07	‘08	‘09
Clean Coal (CCS)	~10	~10	~10	~10		
H2 Fuel Cell				55	61	
H2 Storage	Low		26	35	44	
Total H2	156	222	232	270	283	236
Batteries			24	41	42	
Total Cars + H2	243	307	339	401	436	

FY = Fiscal Year = ends Sept. 30.

Fuel Cells

- DOE has been funding research on PEM Fuel Cells Since the late 1980s.
- Steady progress, but meeting the 2015 deadline for a commercial fuel cell for transportation looks very unlikely.

Fuel Cells: How Much Progress?

- DOE targets: 2006 = \$110,   2010 = \$45,   2015 = \$30 / kW
- \$30 × 80 kW = \$2,400 total cost.
- According to National Academy of Sciences, 2008:
  - Fuel-cell durability about ¼ what is needed
  - Cost ~ **\$100/kW** for 500,000/year*
  - Possibly \$67/kW for new laboratory technologies
- Experimental fuel cell systems: **efficiencies approaching 50 percent** over a fairly wide range of operation.
- Dropped gasoline in favor of H_2 fuel cell in 2004.

*Note that this is cheaper than any other form of electricity generation. A gas turbine costs about \$500/kW. The \$100 value may well be wrong, but it is the value reported by DOE and accepted by The National Academy

DOE’s Fuel Cell Claim

- H2 Posture Plan, DOE, December 2006
  - After 3 years of H Research. (No subsequent report.)
  - Made only 2 claims of technical progress
  - (For second claim, see Hydrogen Fuelling Stations)

1. Reduced the cost of automotive fuel cells
   - \$275/kW (50kW system) in 2002
   - \$110/kW (80kW system) in 2005.

PEM Fuel Cell Price Drop

- $275 □ $110 in 3 years = –26% / year
- How did they do it?
- By “using **innovative processes** developed by **national labs** and fuel cell developers for **depositing platinum catalyst**.”
- Note: values based on selling 500,000/year.

PEM FC Price: Platinum $

- At first TIAX modeled a re-design that greatly reduced platinum loading: 2002□0.8, 2004□0.3 g/cm^2
- But next year: “The question of stack performance and **platinum loading** are key technical inputs into the cost projection and are also **closely held data within the industry**.” –TIAX (Arthur D. Little)
- “Based on discussions with various developers, it became clear that in stacks being evaluated in vehicles today, the **catalyst loading** was ~ **0.75** mg/cm^2 total platinum.” –TIAX
- A new platinum loading for 2005 □ 0.75 g/cm^2
- Platinum remains at huge cost factor, and the price keeps going up. 2002□$450, 2005□$900, $2007□$1400

PEM FC Price Drop: One Clear Factor.

- In a supporting document, DOE says:
  - "The decrease in costs is mainly attributed to a **70% increase in power density** from 350 to 600 mW/cm^2."
- This document refers to a TIAX document that says:
  - "Table 7 compares the fuel cell system design assumptions for the **2001 reformate system** and the **2004 direct hydrogen** case. Changing to direct hydrogen **increased the power density** of the stack and fuel utilization leading to **reductions in stack size and cost** and increases in efficiency."
- Switching from gasoline to H2 made fuel cells cheaper, but introduced problem of on-board hydrogen storage.

About the Cost Modeling

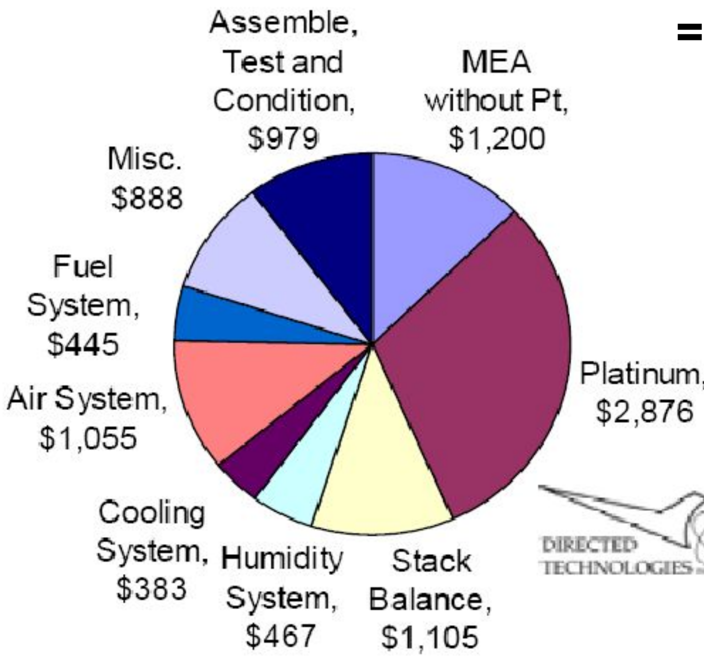
- Modeled fuel cells have never been built.
- TIAX builds models, not fuel-cells.
- Cost estimates change a lot from year to year
- TIAX knows what target DOE needs to hit.
- "The numerous assumptions that underlie the aforementioned cost projections may have to change as the development process proceeds.
  —National Academy of Sciences, 2008

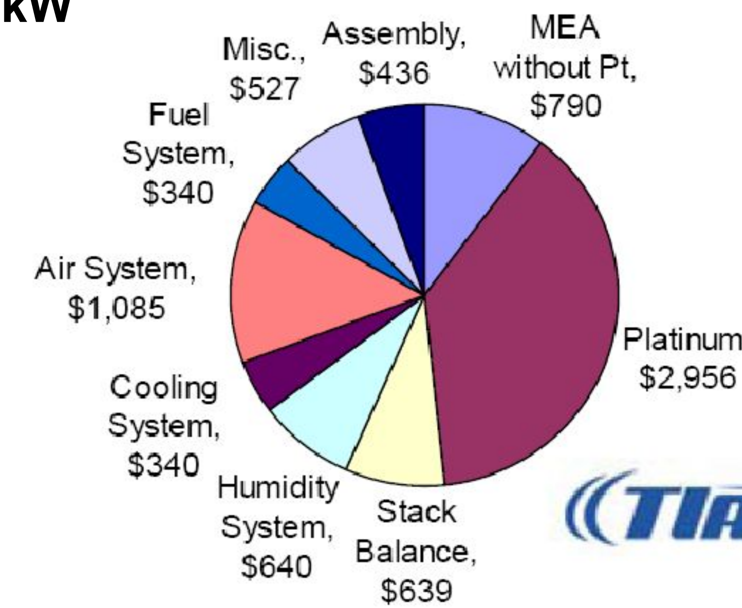
Fuel-Cell Costs Based on 100,000/year

DTI Fuel Cell System 80 kW Direct H_2
Cost = \$118/kW (net), \$9412

TIAX Fuel Cell System 80 kW Direct H_2
Cost = \$97/kW (net), \$7760

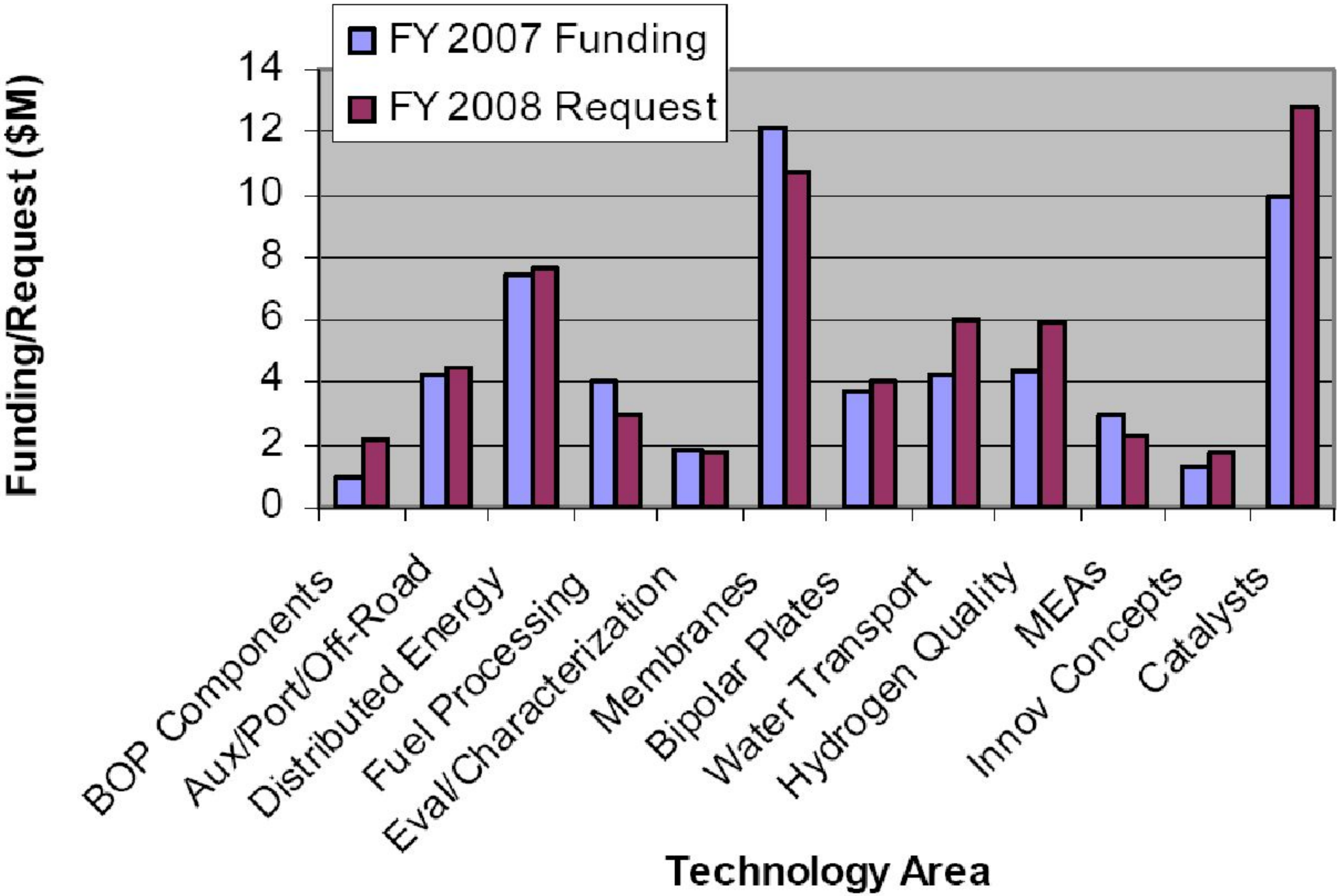
DOE's 2006 Target = \$110/kW





- **The differences between the DTI and TIAX estimates are: the cost of the MEA and seals in stack balance and DTI included Test & Conditioning**
- **The 2015 cost target is \$30/kW, \$2400.**

Fuel-Cell R&D Funding



Hydrogen Fueling Stations

- DOE's <u>second claim</u> in 2006 report: Hydrogen can be generated locally from methane for $3 / kg.
- Calculations do not appear convincing.

Progress on Cheaper H_2 Stations?

- (natural gas) (electricity + H2) station
  - $5.00 per kg in 2003
  - $3.00 per kg in 2005
- How did they figure $5.00 / kg?
- That is exactly the 2003 DOE cost target.
- So… **in 2002**, they built an H_2 station in Las Vegas, and …

The Cost of H2 in 2003

- “Based on the economic assumptions provided by the DOE Multi-Year Program Plan, the test results confirm the ability to meet the **$5/kg 2003 target** for the cost of hydrogen.”
- Note. They do not say “the cost was $5/kg.”

The Cost of H2 in 2005

- “Further economic analysis was performed to evaluate **[the exact same station]** ….
- The **analysis was scaled based on higher production capability** and **better economies of scale for larger production volume.**
- The technology is capable of achieving an integrated co-generation cost of hydrogen of **less than $3.60/kg** and **$0.08/kWh cost of power.”**
- 68% efficiency (LHV). (70% should be possible.)

The Cost of H2 in 2005

- To compute the cost of H, they include profits from selling electricity at 8¢/kWh, about twice the wholesale cost of power.
- There was no technical progress at all.
- On top of this, the fuel cell used to produce the power failed to work:
  - The 50-kW PEM fuel cell was started-up in August 2002. … continued to experience operational issues … [and] will be replaced the week of July 16, 2004 and restarted.

Hydrogen Fuel Tanks

- The following observations are all those of The National Academies, 2008.

Onboard Hydrogen Storage

- Substantially improved techniques for storing hydrogen must be developed to meet the [national] goals. Efforts to discover a viable <u>alternative to compressed hydrogen</u> gas are in their very early stages—too early to have confidence in their ultimate success.
- Almost all current auto company field-test vehicles use 5,000 to 10,000 psi (350 to 700 bar).
- Meeting the program storage goals almost certainly will require a storage technology as yet undiscovered

—The National Academies, 2008

High Pressure Tanks

- Carbon fibers make up more than half of the weight and cost of compressed gas tanks, but little progress seems to have been made in reducing the cost of these fibers below \$25-\$35/kg.
- Compressed gas tank temperatures are limited to about 85°C by the materials used. This necessitates precooling of the hydrogen and/or communication between the vehicle and the fueling station to fast-fill a nearly depleted 700-bar storage tank.
- liquid storage introduces many new problems

New Storage Technologies

- Three new research centers have been established to study new storage technologies
  - Metal hydride
  - Hydrogen sorption
  - Chemical hydrogen storage
- Each has reported substantial progress in the understanding of candidate materials.
- This approach has best chance for success—if, indeed, suitable materials exist.

Plug-In Hybrids

- [Batteries] are critical to the development of HEVs, which would play <u>at least a key transitional role</u> in achieving long-term goals … and <u>may become central</u> to achieving these goals if development of fuel cells and fuel cell vehicles is not sufficiently successful to result in their large-scale commercial introduction.

—The National Academies, 2008

The Hydrogen-Battery Link

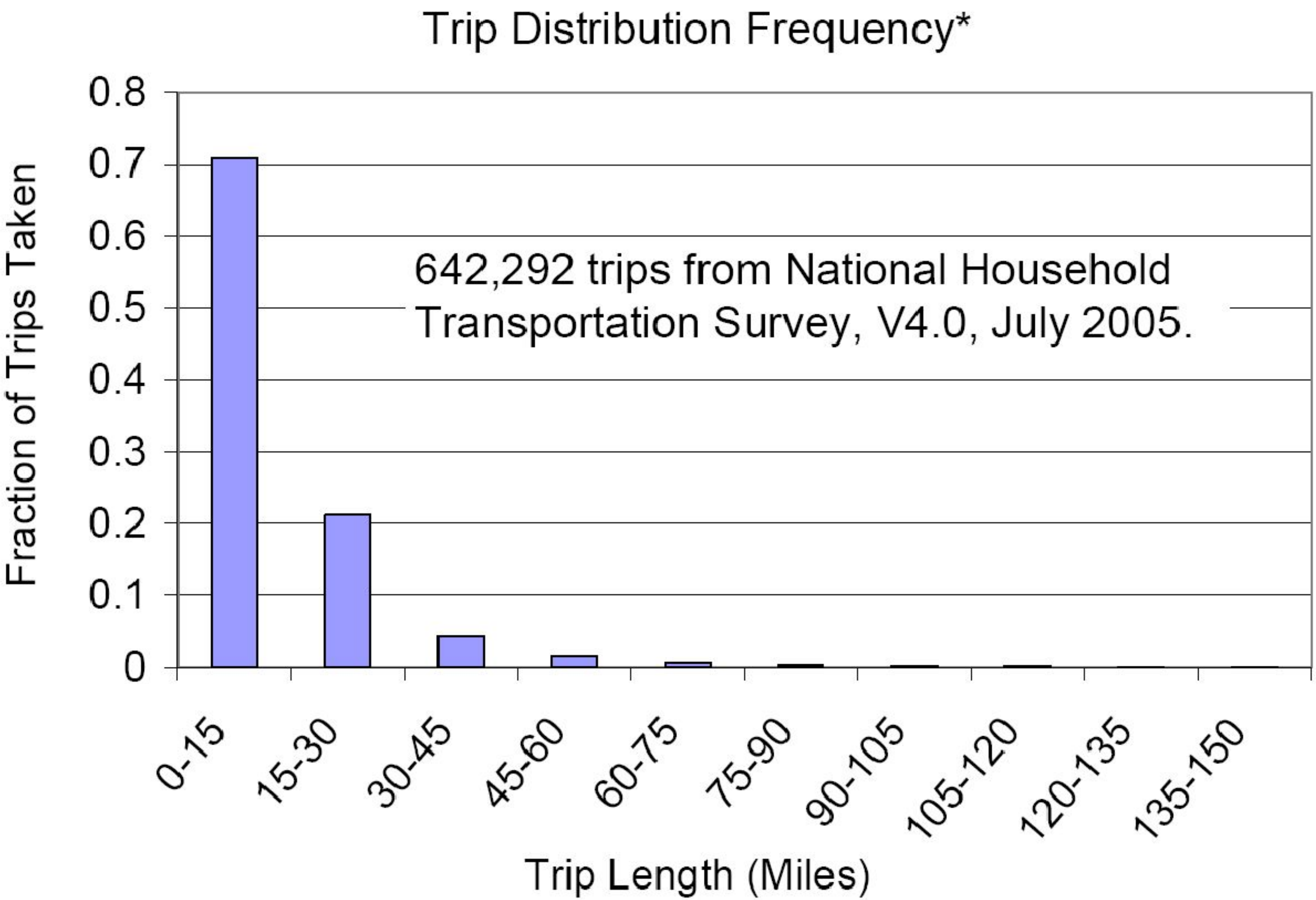
- H transition is slow use batteries.

- H must compete for at least 50 years or it’s not really worth the expense of a new infrastructure.
- Over 50 years, batteries will likely be tougher competition for hydrogen than gasoline alone.
- Gasoline is not the right comparison.

The Current Battery Threat

- "If we get lithium-ion to 300 miles, Why do you need fuel cells? We are nowhere [near] where we need to be on the [fuel-cell] costs curve," —GM Vice Chairman Bob Lutz, Wall Street Journal, March, 2008.
- Toyota President Katsuaki Watanabe echoed the concern about the high costs of fuel cells.
- Toyota & GM are both going with Li-ion.

[In testimony before the Senate in July 2005, GM, Shell and Ballard all concurred that the U.S. could see a manufacturable fuel cell vehicle by 2010-2012 that would be competitive with other cars then available for sale]



* A “trip” is one-way. Driving to work and home again is 2 trips.

The Plug-In Advantage

- A H-Fuel-Cell car with a 50 km range is a failure.
- A Plug-in hybrid with a 50 km range is 75% successful at replacing gasoline—in the US.
- Probably a 35 km range would do the same in the EU.
- US DOE's 2016 goal for 64 km Li-ion battery:
  - 12 kWh
  - 120kg, 80 liters (43 cm cube)
  - $2,400
  - 58 MWh lifetime throughput = $5,800 of retail electricity.

Battery vs Hydrogen R&D

- Very significant progress has been made during the last 2 years.
- Cost is the largest remaining barrier, with estimates of current cost about two times the 2010 goal.
- The potential benefits of PHEVs in reducing petroleum consumption have been recognized by the Partnership [DOE and industry], yet there seems to be a lack of urgency in finalizing and executing the R&D plan for PHEVs. The Partnership should move forward aggressively with completing and executing its R&D plan for plug-in hybrid electric vehicles.

—The National Academies, 2008

Nuclear Hydrogen Production

- The Hybrid-Sulfur hydrogen production process:
  - Developed by Westinghouse in 1973
  - Used in 2000 to advocate restarting the US nuclear industry for a hydrogen economy.
  - Center of current DOE nuclear-hydrogen research

Nuclear-Hydrogen Economy

- Nuclear H2 production studied during 1970s.
- 3,000 H2 production methods suggested, 115 in literature, 3 final thermochemical candidates
- Thermal □ H2 efficiency:
  - 36% for conventional electrolysis
  - 40-50% for high temperature electrolysis
  - 55% for thermochemical cycles
- SI = Sulfur Iodine is most developed
- HyS = Hybrid Sulfur, simpler (49% efficiency).

Savannah River National Lab, Nov. 2005

		SI*	HyS
Plant Rating	MW_{th}	2400	2400
Plant Efficiency	% (HHV basis)	52-42	48.8**
Hydrogen Output	Tonnes/Day	760-614	580
Electric Output	MWe	0	216
Reactor System Cost	$M	1,150	1,198
Electrolyzer Cost	$ per m^2	N/A	2000
Hydrogen Plant Cost	$M	819	516
Electricity @ 3¢/kWh	$M/yr	N/A	(51)
Total Annual Cost	$M/yr	413-399	306
Net Hydrogen Cost	$ per kg	1.65-1.98	1.60
- with O2 credit		1.36-1.69	1.31

Nuclear-Hydrogen Economy

- 187 nuclear plants (2.4GW thermal) needed to power cars + light trucks.
- First live test of HyS will be in 2017.
- Generation IV nuclear reactors are be needed, for a significant efficiency gain. Significant nuclear hydrogen not expected until 2030.

The Cost of Hydrogen (an example)

- $3/kg from nuclear generation.
- $4/kg from methane.
- How should we generate hydrogen?

  Uranium or Methane ?

- **Economic** cost is opportunity cost.

Opportunity Cost of H2 with nuclear

- 100 MWh Thermal 50 MWh H2
- 100 MWh Thermal 50 MWh E (electricity).
- Suppose we make 50 MWh of H2 with nuclear.
- Making 50 MWh of H2 means 50 MWh E must be replaced.

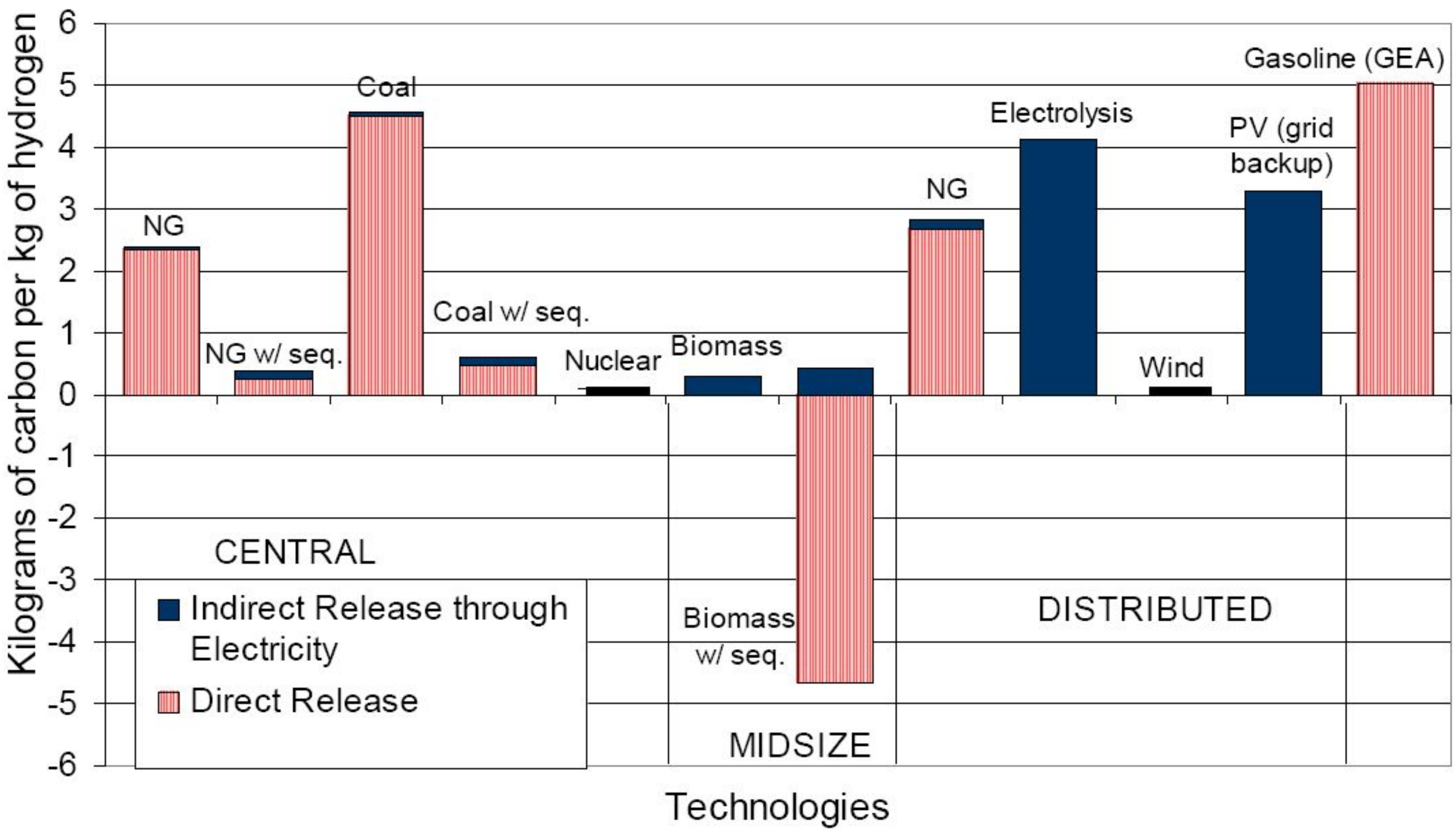
Opportunity Cost of H2 Using CH4

- 100 MWh CH4 81 MWh H2
- 100 MWh CH4 60 MWh E
- So making 50 MW E requires (50/60)×100 MWh CH4, or 83.3 MWh of CH4.
- But 83.3 MWh of CH4 would make 67.5 MWh H2.
- So we could have had 67.5 MWh of H2 instead of only 50 MWh of H2, if we had used methane instead of nuclear, holding electricity constant.
- So it’s cheaper to use methane.

Implications of Opportunity Cost

- If nuclear, wind, solar, or clean-coal plants are in short supply, then the opportunity cost of using them to make hydrogen matters.
- Wind, solar, and nuclear (in the US) will be in short supply for a long time.
- Their opportunity costs for making H are high both in euros and in CO_2 emissions.
- All US government calculations seem to have gotten this wrong, and this is by far the easiest calculation needed to analyze a market transition.

CARBON RELEASED DURING H_2 PRODUCTION, DISPENSING & DELIVERY (FUTURE TECHNOLOGIES)



Transition to Hydrogen

- Even the most optimistic scenario for introducing fuel cell vehicles into the market requires several decades before market penetration becomes sufficient to have a measurable impact on petroleum consumption and CO_2 emissions.

—The National Academies, 2008

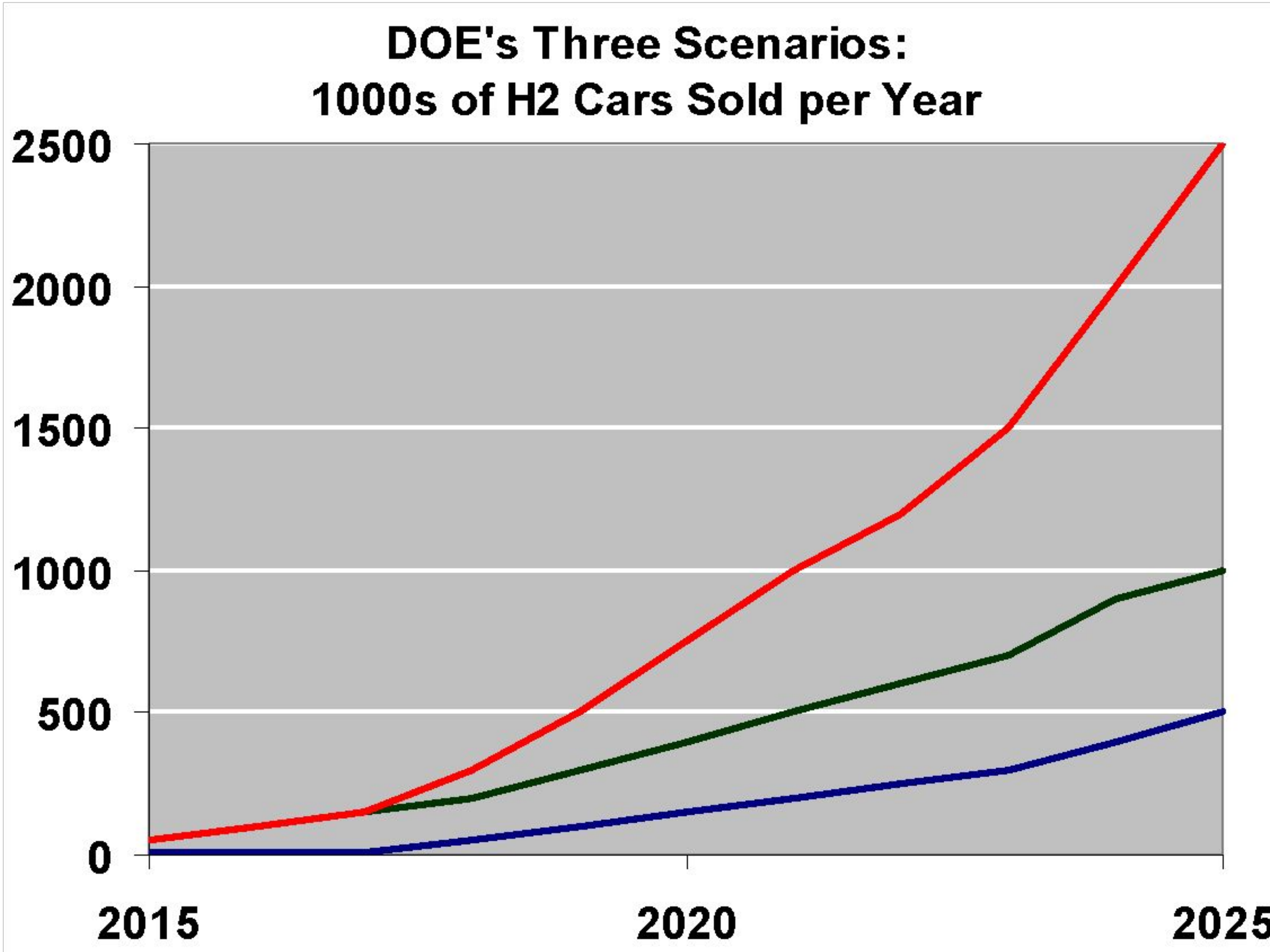
Fuel Cell Progress Is Slow

- If natural gas is used to produce hydrogen, and if, on the margin, natural gas is imported, there would be little if any reduction in total energy imports.
- Impacts on oil imports and CO_2 emissions are likely to be minor during the next 25 years.
- The government has been active in fuel cell research for ~40yr, and PEM fuel cells since the late 1980s.
- The near-term DOE milestones for FCVs are unrealistically aggressive.

—The national Academies, 2004

GAO: Need Science

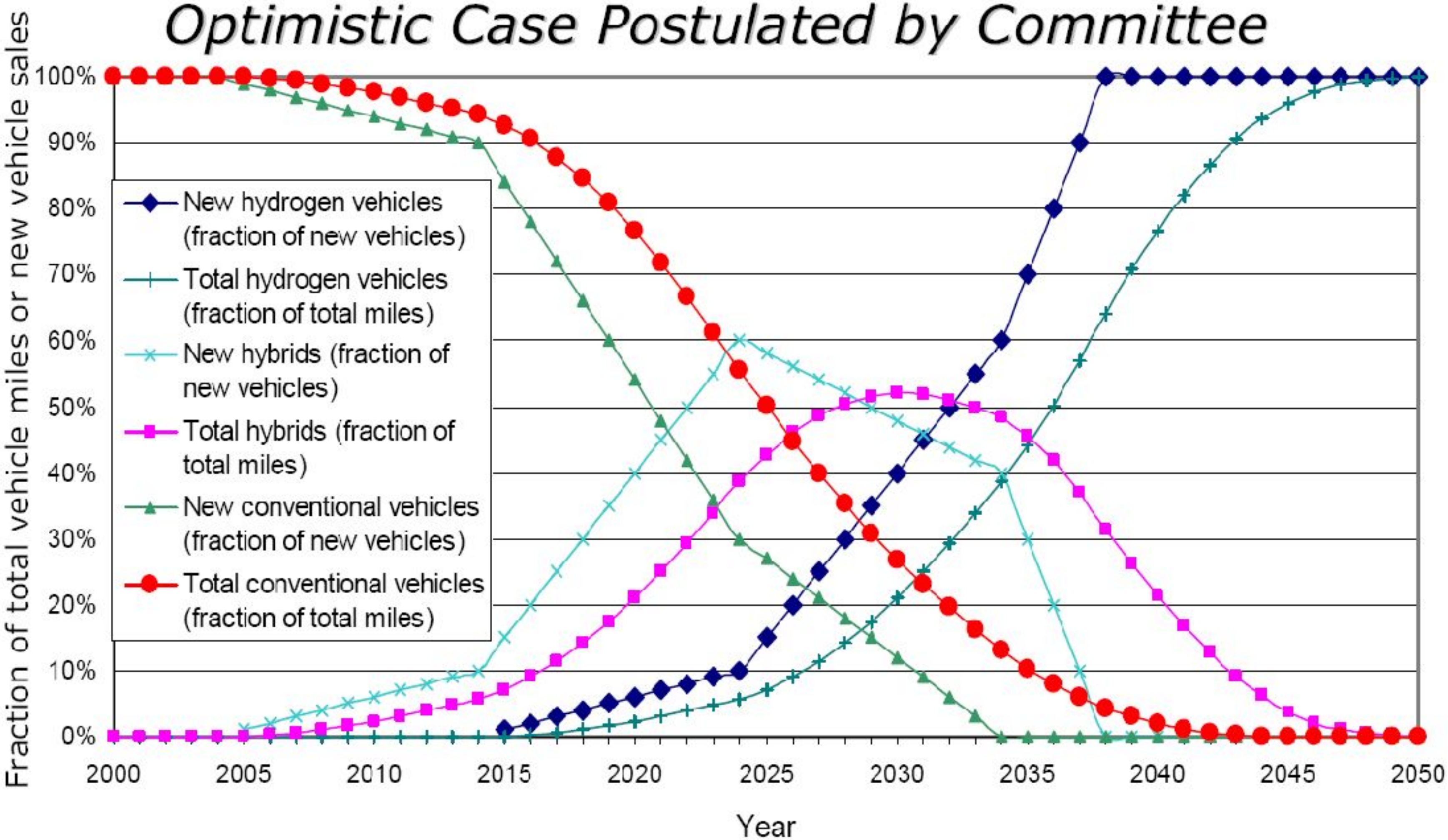
- Government Accountability Office, 2008
- DOE officials and industry representatives stated that achieving targets for **hydrogen storage will require fundamental breakthroughs.**
- Achieving targets for **other technologies will require significant scientific advances** and cost reductions.



DOE's Three Scenarios:
1000s of H2 Cars Sold per Year
2500
2000
1500
1000
500
0
2015
2020
2025

PENETRATION CURVES FOR FUEL CELL VEHICLES

Optimistic Case Postulated by Committee



• *Complete replacement of ICE vehicles with fuel cell vehicles in 2050*

Carbon Capture & Sequestration

- Reducing Carbon emissions with hydrogen requires a carbon-free source of energy that is not needed for producing electricity.
- That mainly leaves coal.

FutureGen is History

- From February 2003 until February 2008, FutureGen was to be a $1 billion coal gasification and CO_2 sequestration demonstration project, with international cooperation.
- In November Texas lost it’s bid for the site, and another state got it. DOE said they just figured out it was two expensive, but Bush had known of the expense as far back as 2006.
- They still intend to subsidize private projects, but perhaps none with carbon sequestration.

The End