HYDROGEN AS A FUTURE ENERGY CARRIER

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CONTEXT

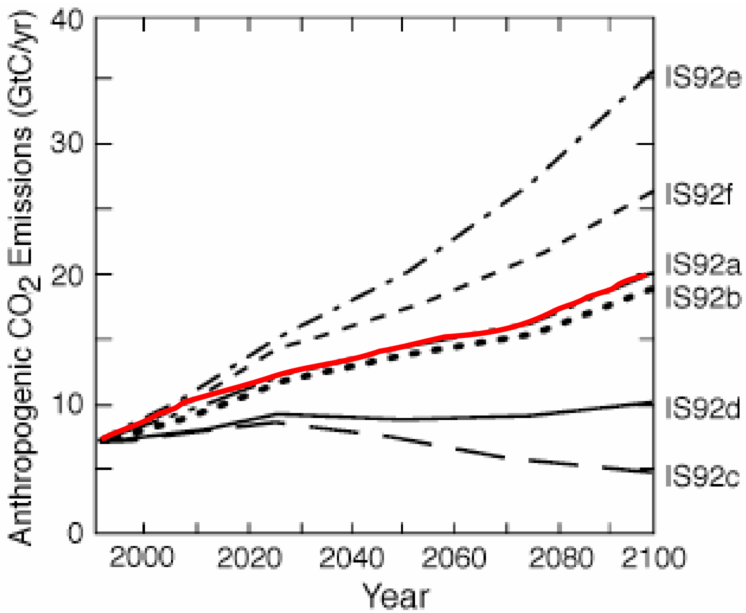
Primary energy use and energy-related emissions of greenhouse gases and air pollutants are projected to grow rapidly over the next few decades, especially in developing countries.

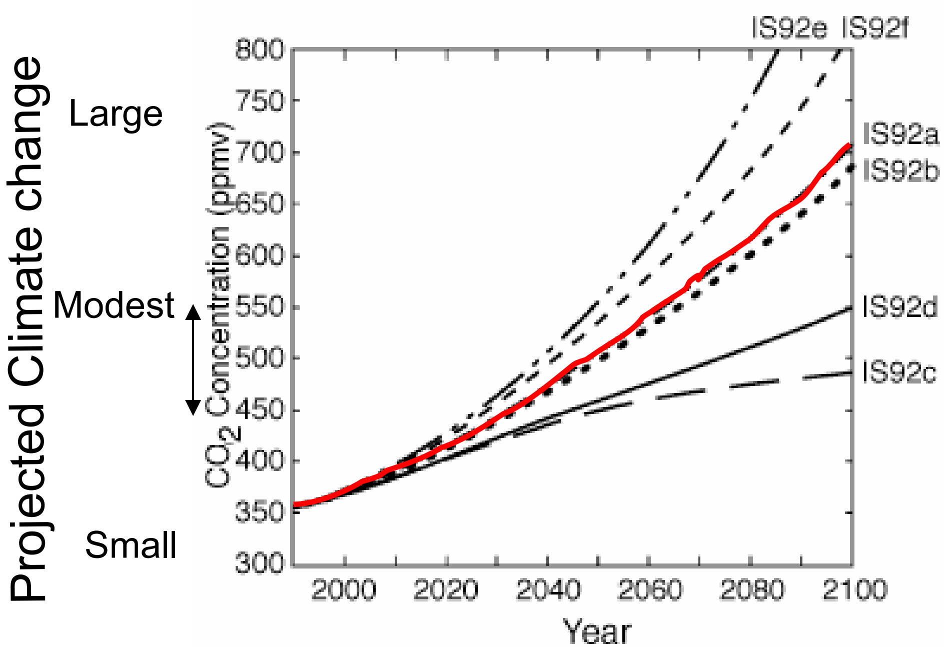
CHALLENGES FACING FUTURE ENERGY SYSTEM

- Diversity/Security of Energy Supply, especially in transportation sector
- Air Pollutant Emissions
- Greenhouse Gas Emissions (GHG)

FUEL SECTOR IS IMPORTANT

- Direct combustion of fuels for transportation and heating accounts for about 2/3 of primary energy use and GHG emissions, and a large fraction of air pollutant emissions.
- The world transportation sector is heavily dependent on oil.





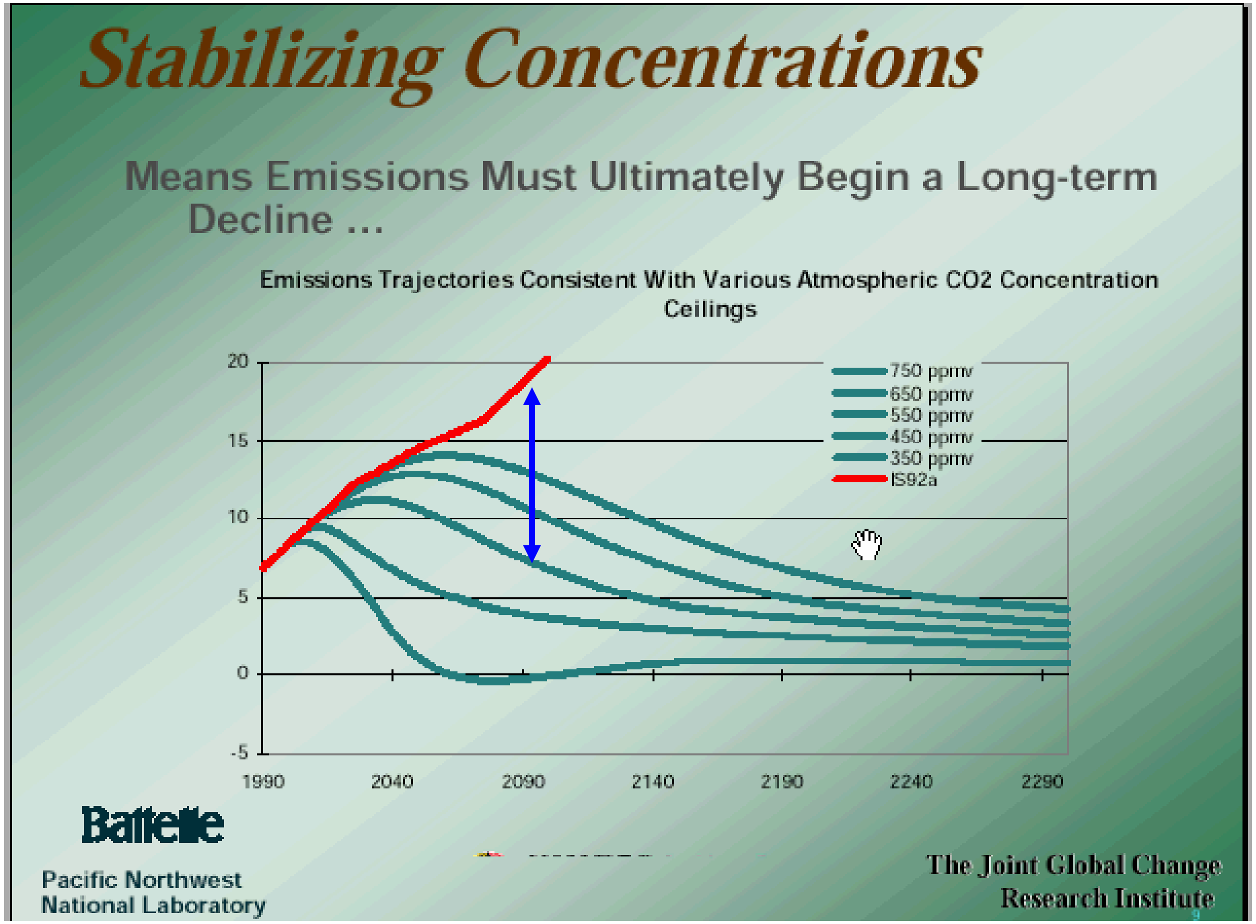
Projected Carbon Emissions

&

Atmospheric CO_2 Concentration

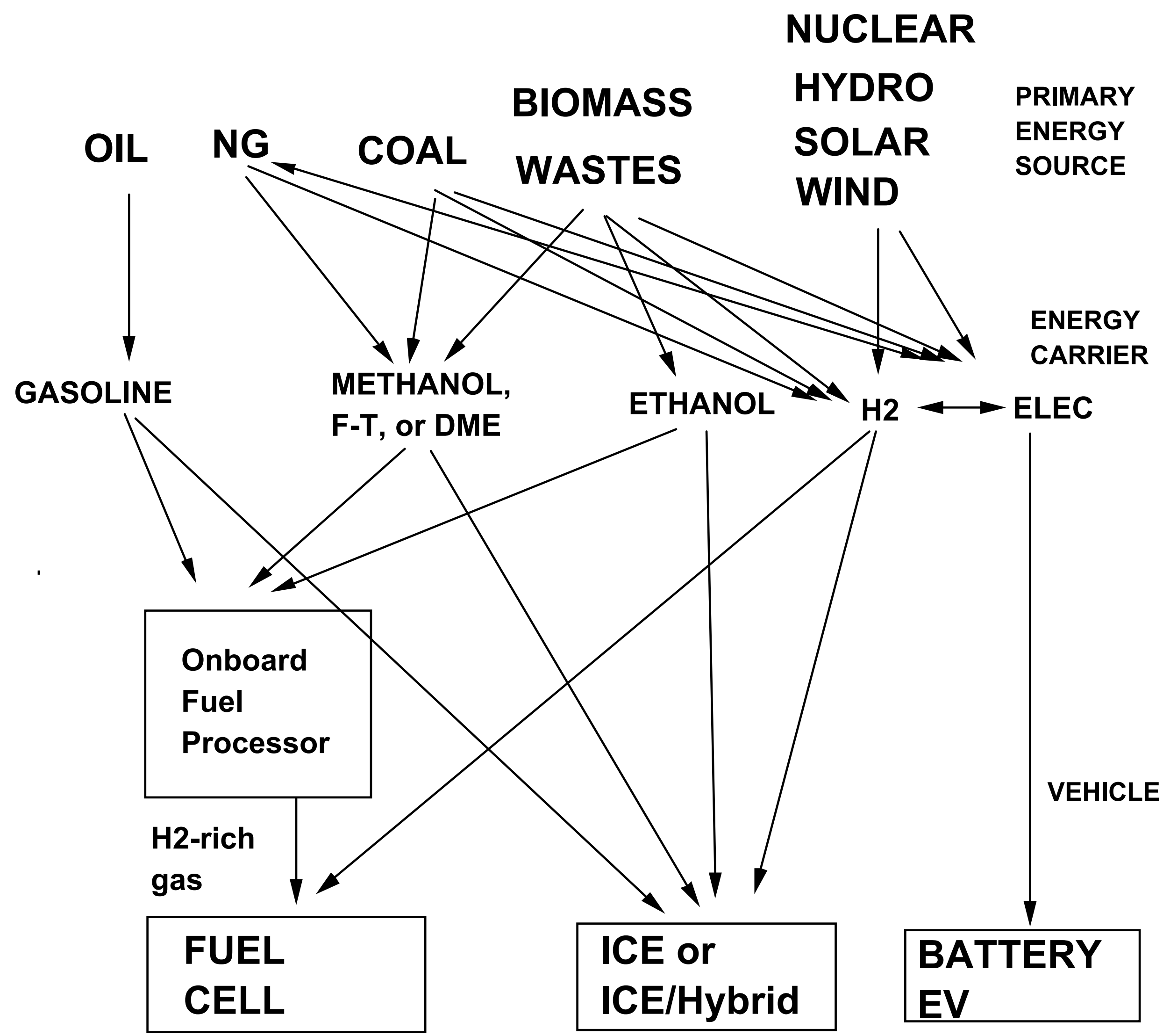
for IPCC Energy Scenarios

(IS92a="business as usual")



To stabilize CO_2 concentration, need to decarbonize the energy system at several times the historical rate of 0.3%/y. Even if electric sector is completely decarbonized by 2100, stabilization at 550 (450) ppm => 3 (5) fold reduction in carbon emissions from direct fuel use vs. IS92a.

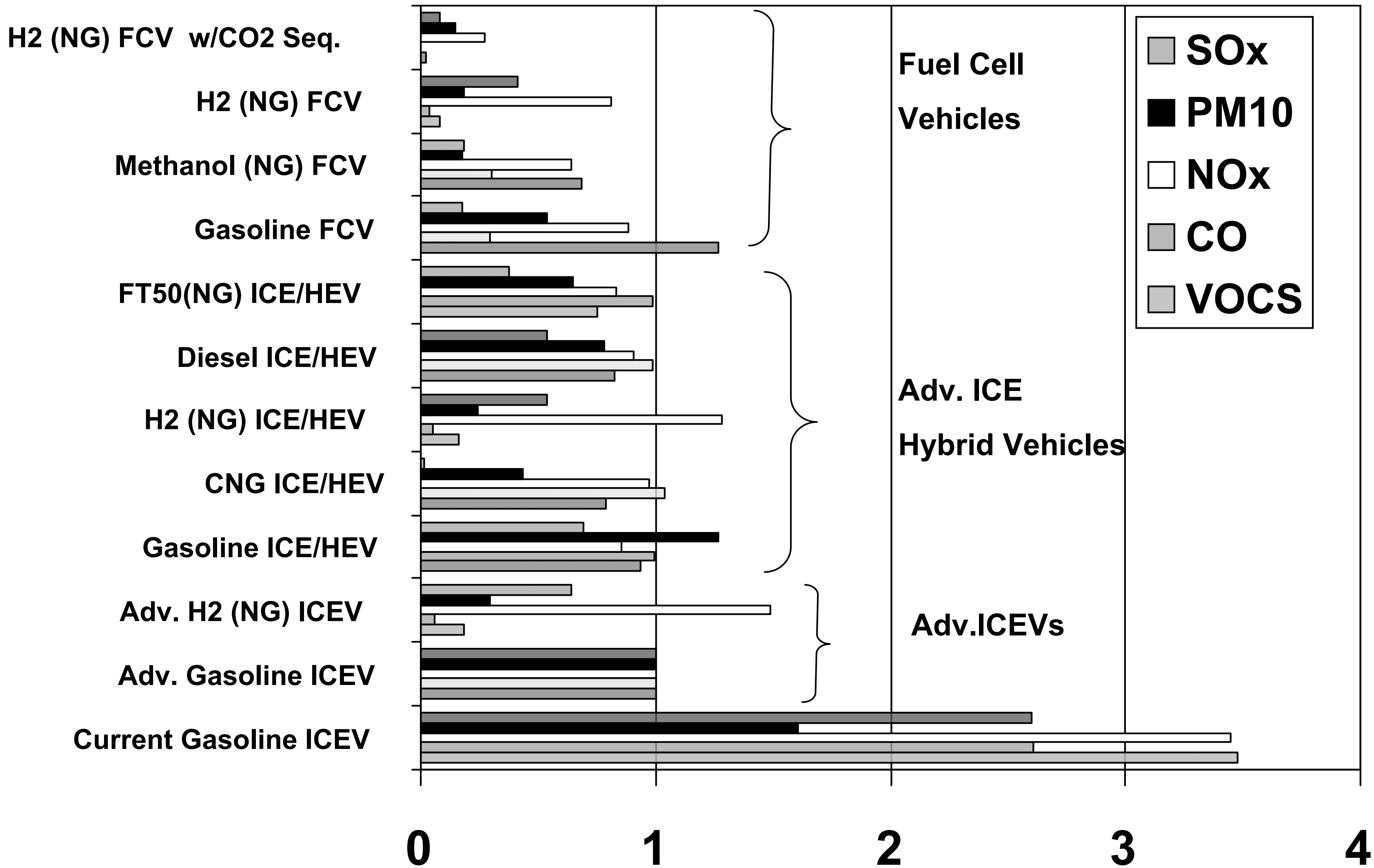
FUEL PATHWAYS FOR ALTERNATIVE VEHICLES



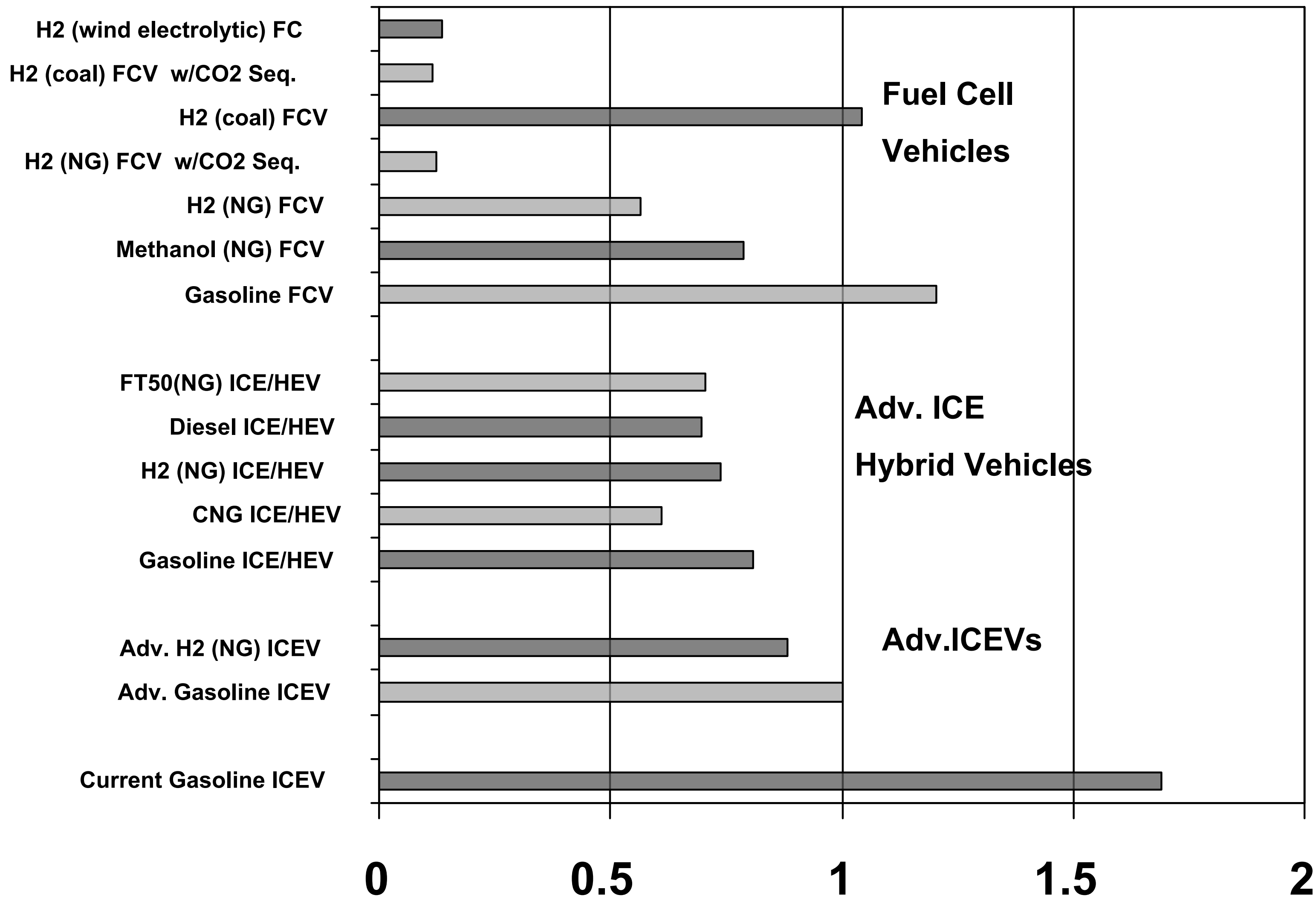
H_2 OFFERS POTENTIAL BENEFITS AS A FUTURE ENERGY CARRIER

- Zero or near-zero emissions at point of use
- Low to zero full fuel cycle primary emissions of both air pollutants and greenhouse gases
- H_2 can be made from widely available primary resources (fossil, renewable, nuclear)
- Rapid progress in H_2 and fuel cell technologies

Full Fuel Cycle Emissions of Air Pollutants
(Normalized to Adv., Lightweight Gasoline ICEV)



FULL FUEL CYCLE GREENHOUSE GAS EMISSIONS
(Normalized to Adv. Lightweight 46 mpg Gasoline ICEV)



BARRIERS TO A HYDROGEN ECONOMY

- current lack of widespread H_2 infrastructure
- current high cost of H_2 end-use technologies
- Technical maturity: need to adapt current H_2 technologies for a H_2 energy economy and develop emerging tech for H_2 vehicles, H_2 storage, zero emission H_2 supply.
- “Chicken & Egg Problem” for vehicles. (More generally, problem of matching H_2 supply and demand during transition.)
- lack of policies reflecting the external costs of energy

CURRENT US H_2 INFRASTRUCTURE

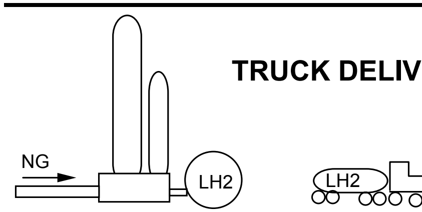
US HYDROGEN PRODUCTION FOR ONSITE CHEMICAL AND REFINERY APPLICATIONS

Now: 1.5 EJ/yr (4.1 million GJ/day)

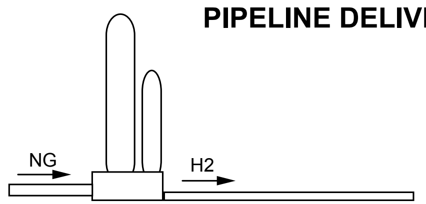
Projections for 2010 : 6 EJ/yr (16.4 million GJ/day)

US MERCHANT HYDROGEN DELIVERY INFRASTRUCTURE

TRUCK DELIVERY: 36,000 GJ/day



PIPELINE DELIVERY: 66,000 GJ/day

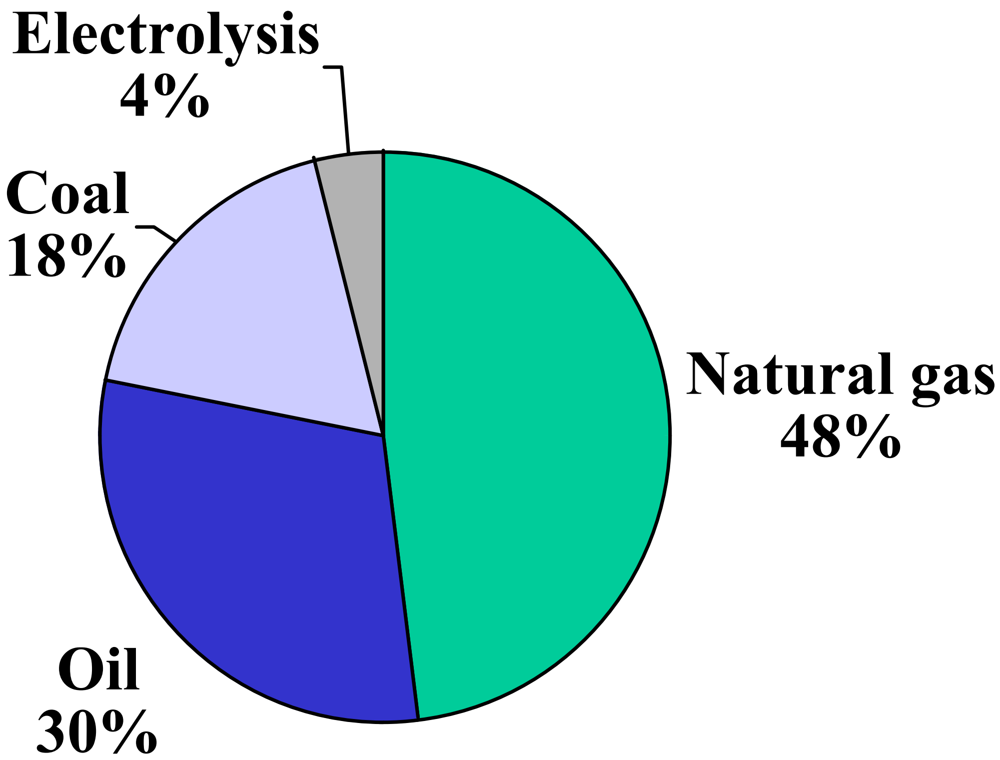


Merchant H2 infrastructure could supply enough energy to fuel about 1-2 million H2 fuel cell vehicles

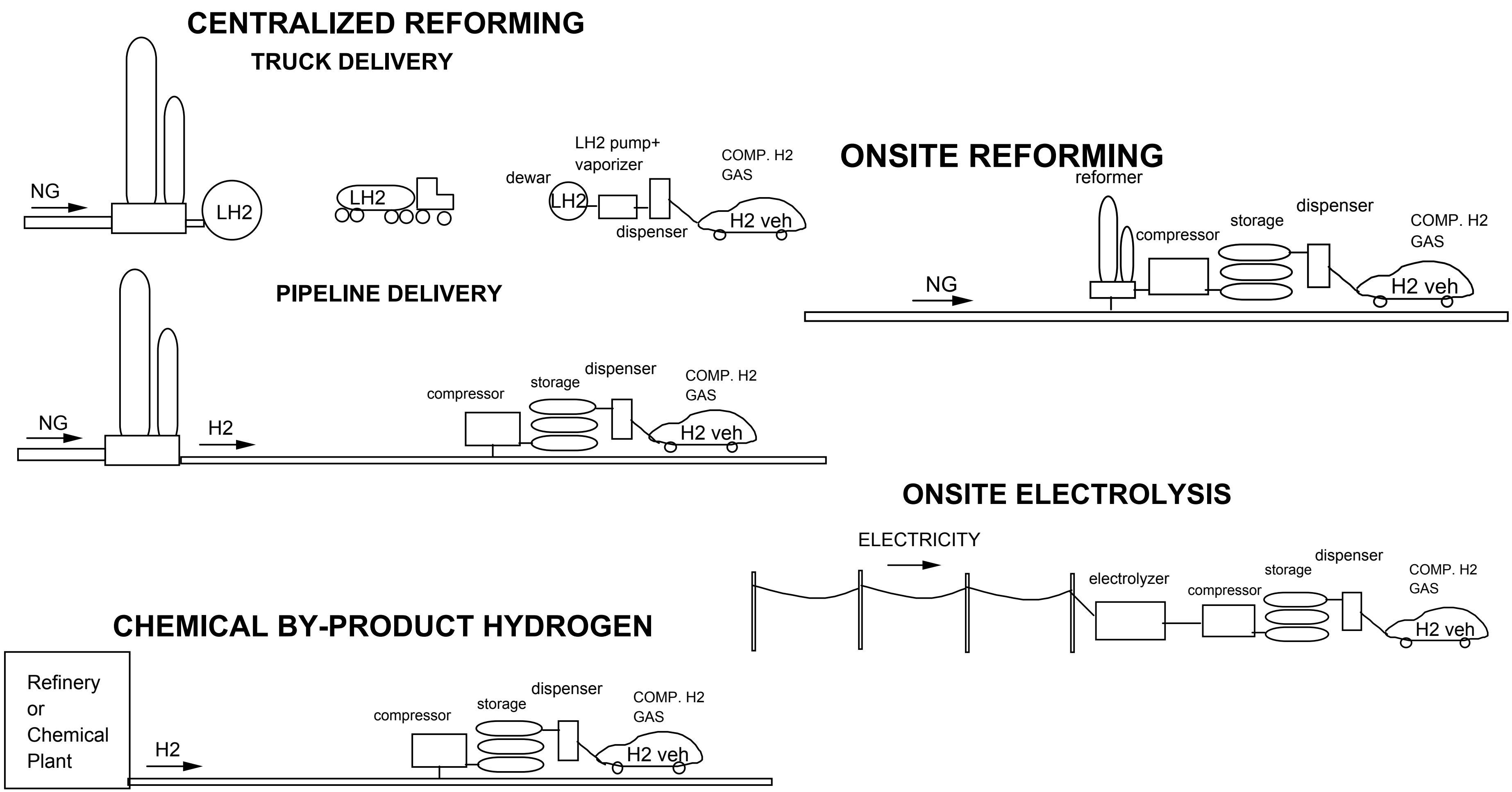
> 1% of US primary energy use and 5% of natural gas use goes to H2 production

Current US merchant H2 system could serve ~ 1% of US cars

GLOBAL H_2 PRODUCTION BY SOURCE (1999)

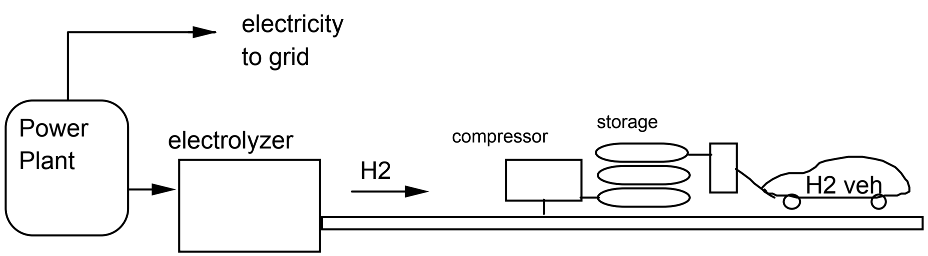


Near term H_2 Supply Options

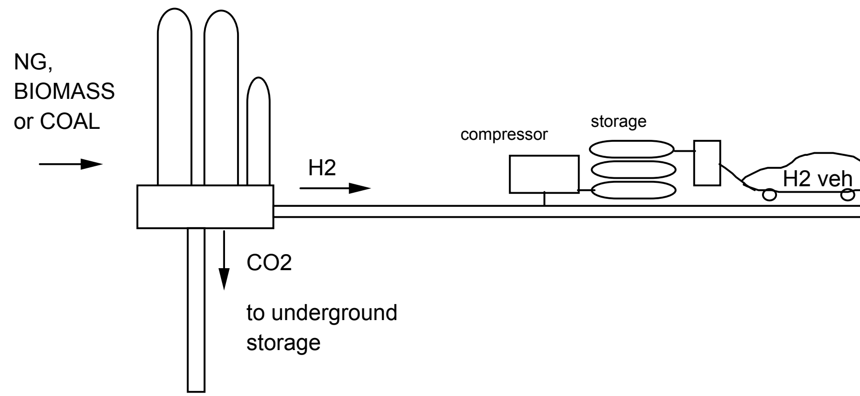


Long term H_2 Supply Options

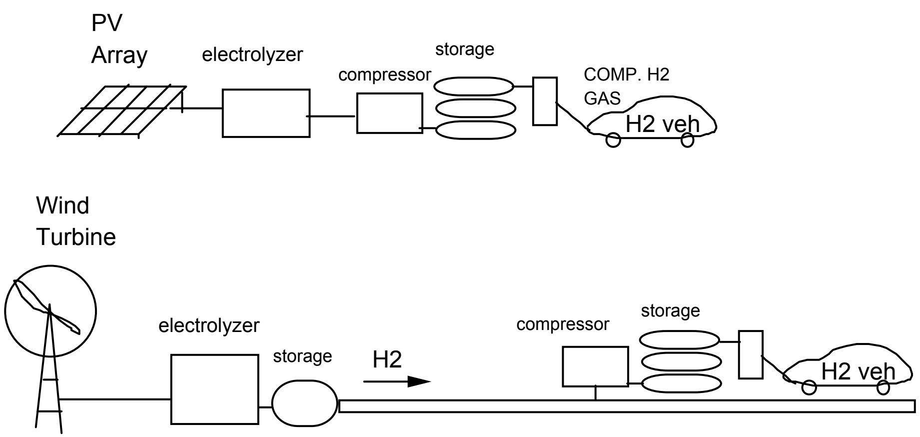
CENTRALIZED PRODUCTION OF ELECTROLYTIC H2



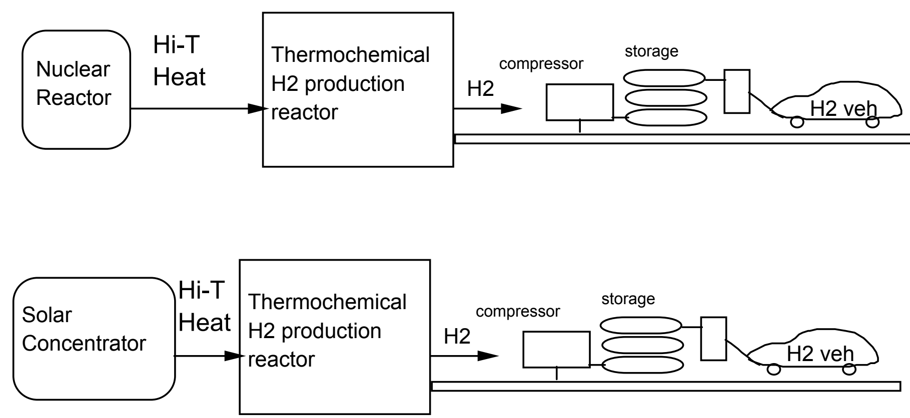
H2 FROM HYDROCARBONS w/CO2 SEQUESTRATION



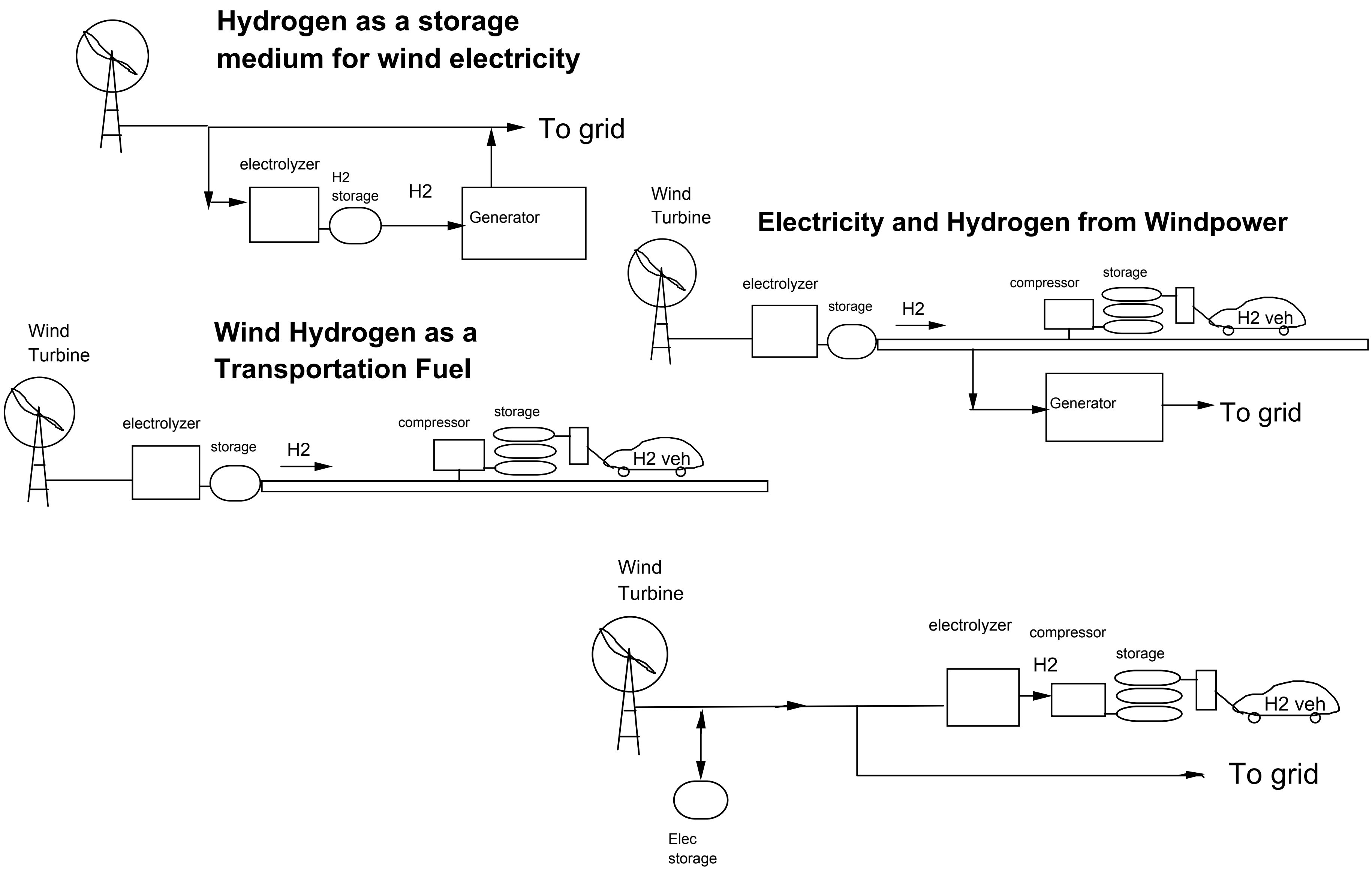
SOLAR or WIND ELECTROLYTIC H2



H2 PRODUCTION VIA THERMOCHEMICAL CYCLES POWERED BY NUCLEAR OR SOLAR HEAT

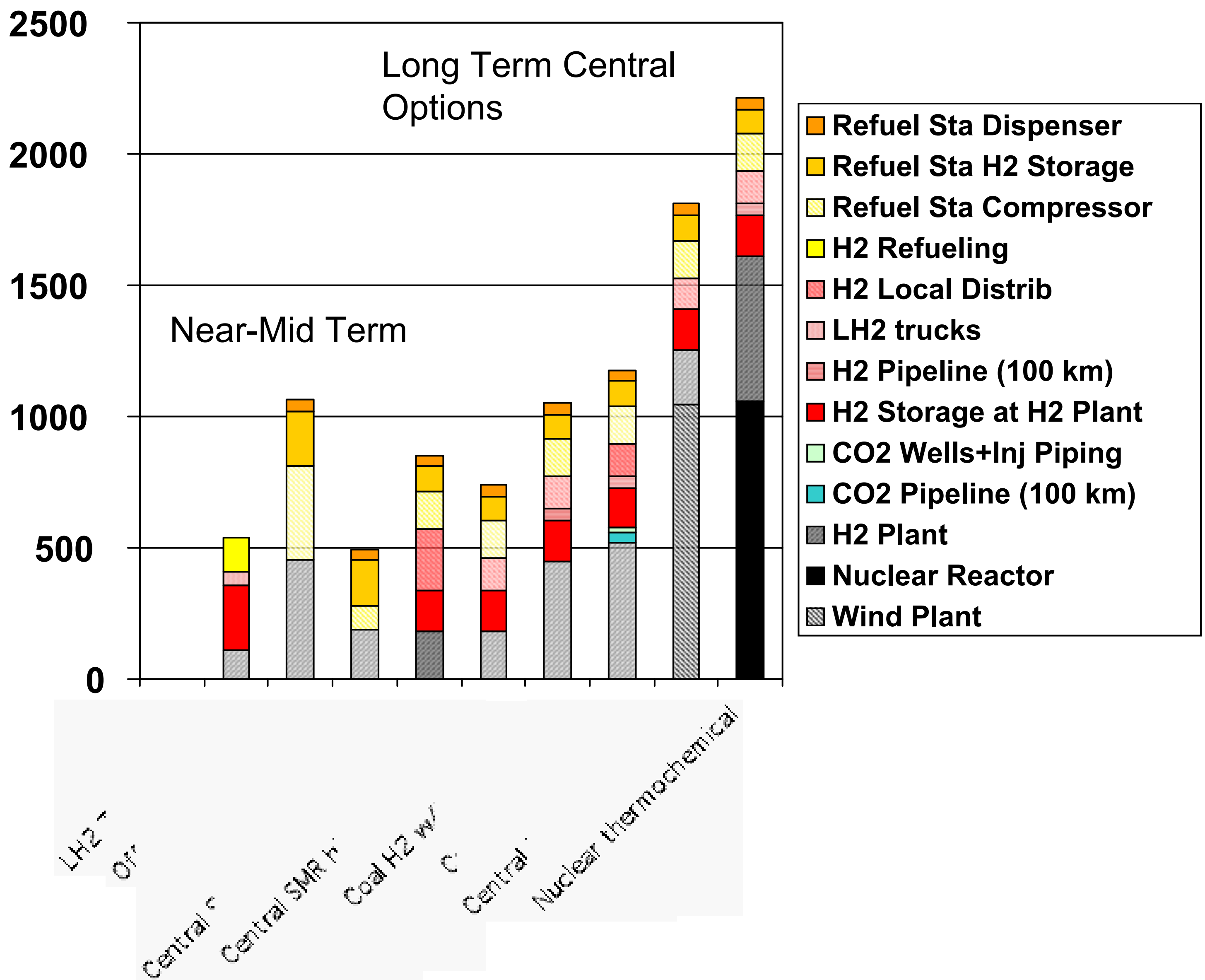


Wind Hydrogen Systems



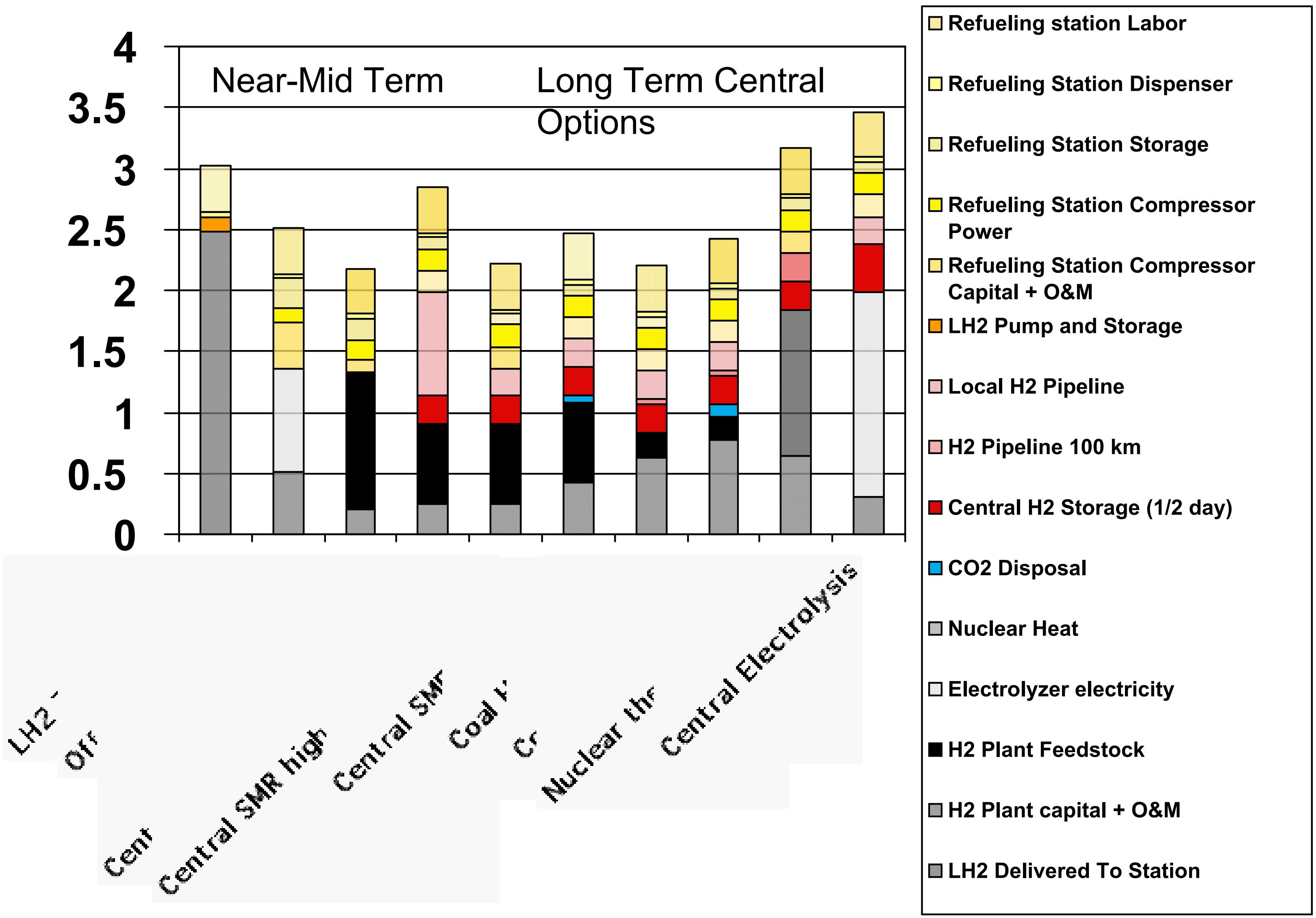
Capital Cost of H_2 Infrastructure ($/car)

Long term options produce 252 million scf H_2/day, serve 1.4 million H_2 cars



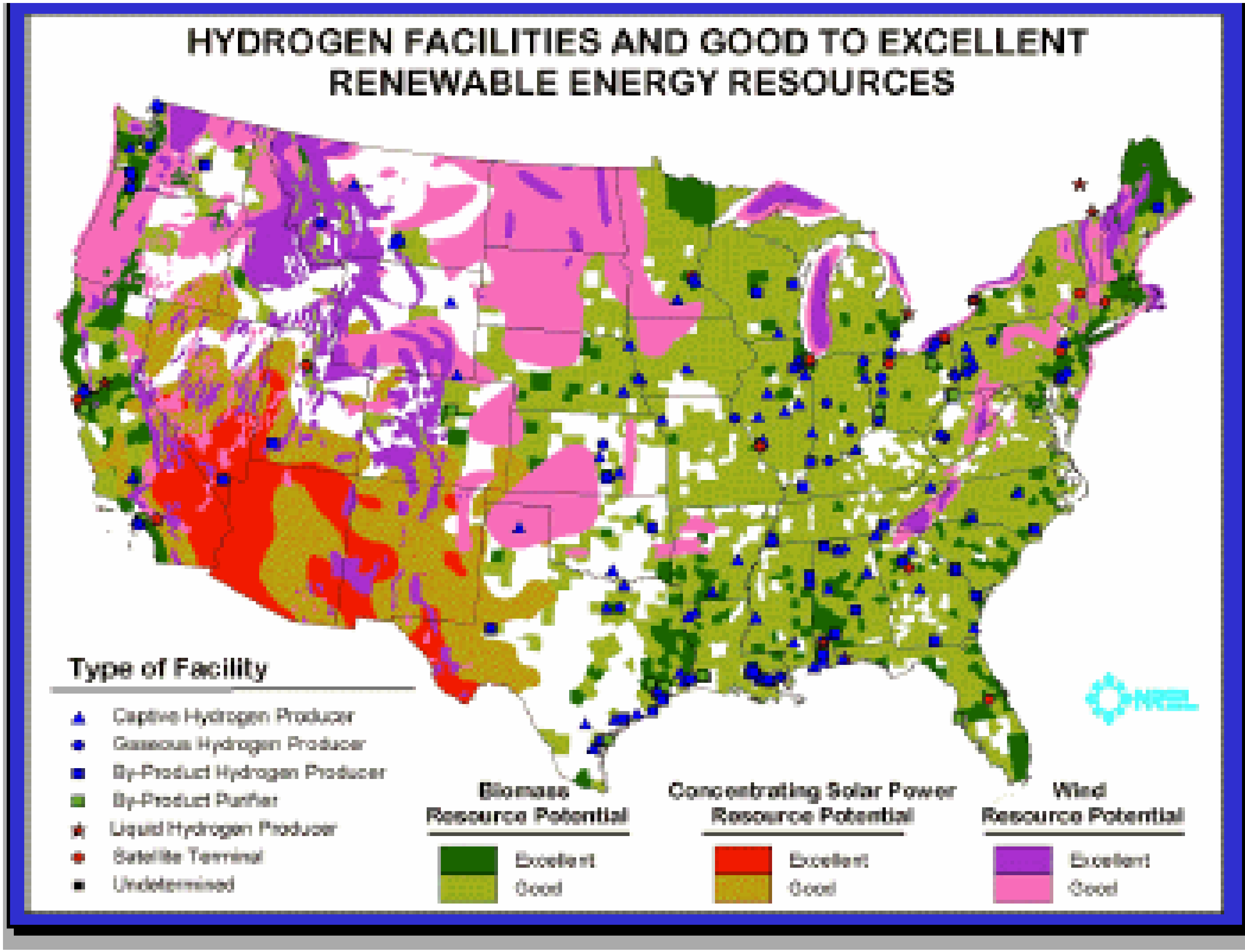
Delivered Cost of H_2 ($/kg H2)

$1/gallon gasoline ~ $1/kg



WHERE WILL H_2 COME FROM?

- **H_2 Demand**
  - Number of light duty (gasoline) vehicles in US c. 2000 ~ 200 million
  - Current gasoline energy use per light duty vehicle (20 mile per gallon, 11,000 mi/y)= 72 GJ/y
  - H2 vehicles are projected to be 2-4X as efficient as current gasoline vehicles
  - **Projected H2 energy use for 100 million vehicles = 1.8-3.6 EJ/y**
- **H_2 Supply for 100 million LDVs (if all H_2 comes from one source)**
  - Projected NG use, if H2 is made at 80% conversion eff. (HHV) = 2.2-4.5 EJ/y **(10-20% of total NG use today)**
  - Projected coal use for 100 million light duty vehicles, if H2 is made at 65% conversion eff. = 2.8-5.5 EJ/y **(14-28% of total coal use today)**
  - If H2 is made from off-peak power 12 h/d, need 140-280 GW, or **18-36% of total installed electric capacity in US, used off-peak**.
  - If H2 is made from wind power via electrolysis at 76% efficiency, (**8-16% of class 4,5 and 6 wind-power sites in US)**.
  - NREL study shows that **2.7 EJ H2/yr could be made via biomass gasification**, using 0.17 million km^2 in energy crops, plus agricultural and forest residues, landfill gas, municipal waste and manure. (Total US cropland and range land = 4 million km$^{2)}$

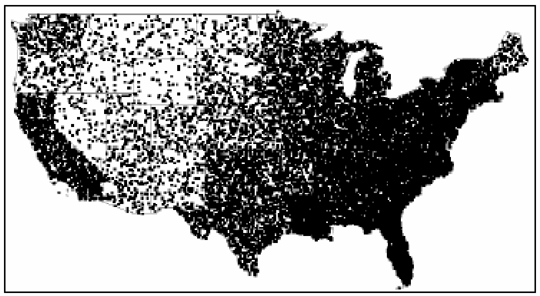

HYDROGEN FACILITIES AND GOOD TO EXCELLENT
RENEWABLE ENERGY RESOURCES
Type of Facility
Captive Hydrogen Producer
Gaseous Hydrogen Producer
By-Product Hydrogen Producer
By-Product Purifier
Liquid Hydrogen Producer
Satellite Terminal
Undetermined
Biomass
Resource Potential
Excellent
Good
Concentrating Solar Power
Resource Potential
Excellent
Good
Wind
Resource Potential
Excellent
Good
NREL

TRANSITION TO H_2 FOR VEHICLES: FLEETS -> GENERAL MARKETS

- ASSUMPTION: All H_2 vehicle owners must have ready access to H_2 fuel during the transition
- CHALLENGE: Design a flexible and relatively low cost H_2 fuel delivery infrastructure that serves a growing number of consumer vehicles. (H_2 could be supplied at home, work, or public refueling stations.)

REFUELING STATIONS FOR GASOLINE AND ALTERNATIVE FUELS

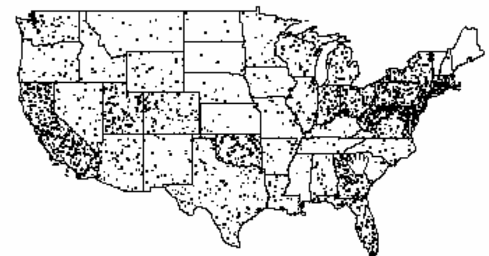
Figure 8: Gasoline Refueling Stations*, 1999



* Please note one dot = 10 stations and does not represent actual locations.

Source: General Accounting Office, *Limited Progress in Acquiring Alternative Fuel Vehicles and reaching Future Goals*, GAO/RCED-00-59, February 2000.

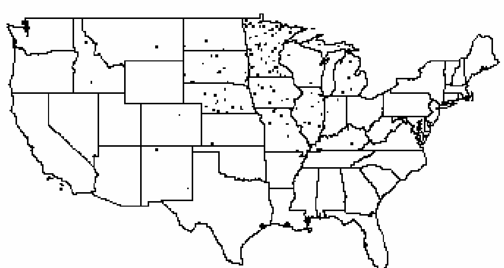
Figure 3: CNG Refueling Stations*



* Dots do not represent actual station locations

Data Source: Alternative Fuels Data Center, "U.S. Refueling Site Counts by State and Fuel Type as of 6/16/2000," available at http://www.afdc.doe.gov/refuel/state_tot.shtml, June 2000.

Figure 6: Ethanol Refueling Stations*



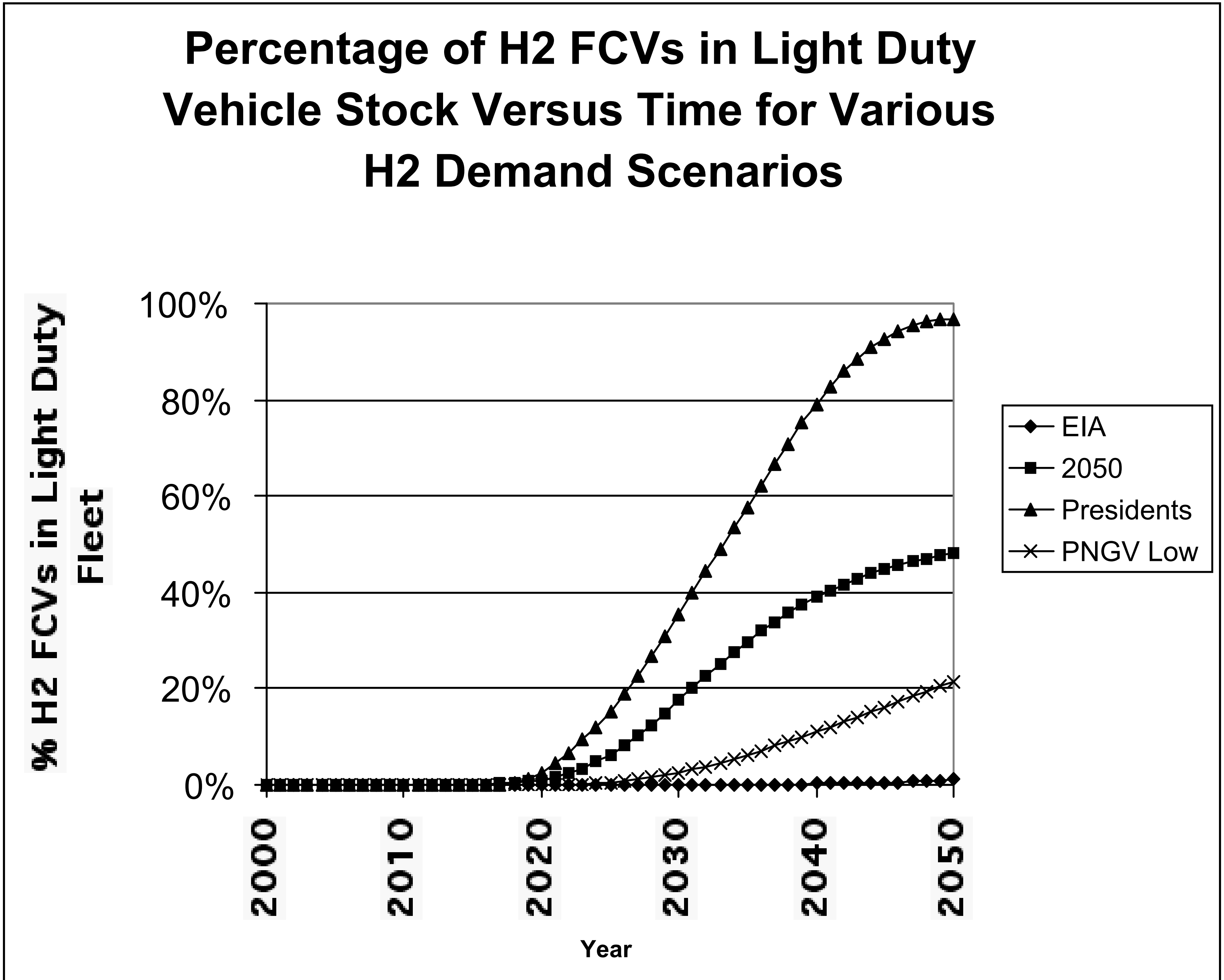
* Dots do not represent actual station locations

Data Source: Alternative Fuels Data Center, "U.S. Refueling Site Counts by State and Fuel Type as of 6/16/2000," available at http://www.afdc.doe.gov/refuel/state_tot.shtml, June 2000.

Figure 4: Methanol Refueling Stations*

* Dots do not represent actual station locations

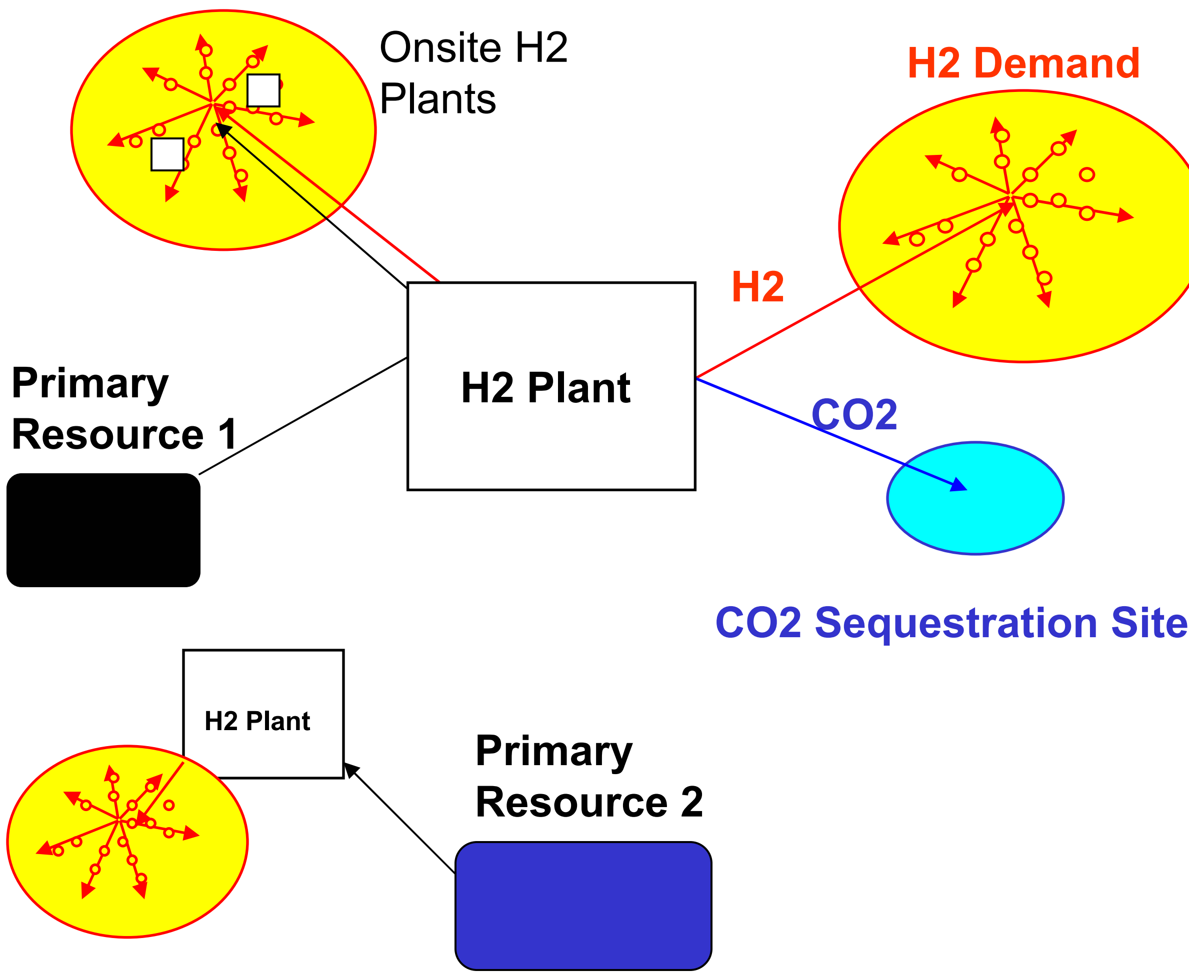
Data Source: Alternative Fuels Data Center, "U.S. Refueling Site Counts by State and Fuel Type as of 6/16/2000," available at http://www.afdc.doe.gov/refuel/state_tot.shtml, June 2000.



Percentage of H2 FCVs in Light Duty Vehicle Stock Versus Time for Various H2 Demand Scenarios
% H2 FCVs in Light Duty Fleet
100%
80%
60%
40%
20%
0%
2000
2010
2020
2030
2040
2050
Year
EIA
2050
Presidents
PNGV Low

H_2 Infrastructure Over Time

What is the lowest cost system for producing and delivering H_2 to serve a growing demand ?



- **H_2 Plants: Size and Location?**
- **Resources for H2 production: Characteristics, distance from H_2 plant?**
- **Use existing energy infrastructure/rights of way?**
- **Interactions with rest of energy system?**
- **Optimum paths for H_2 infrastructure over time?**

CONCLUSIONS

- H_2 offers multiple benefits w.r.t. energy supply security/diversity and reducing emissions of greenhouse gases and air pollutants to near zero.
- Because H_2 can be made from a variety of primary sources, and at a variety of scales, H_2 energy systems could evolve in many ways, and could be regionally specific (similar to the electricity system today). The infrastructure design depends on the type, size, geographic density, and location of demand, and on available primary resources for H_2 production.
- Technologies exist to produce, store, and distribute H2 on a large scale, but these need to be adapted for use in a H2 energy system. Hydrogen end-use technologies and zero emission supply technologies rapidly developing.

CONCLUSIONS (continued)

- In the near term, in the US, and many regions of the world, fossil H_2 is likely to be the lowest cost option. Renewable ◘ H_2, H_2 from off-peak power also locally important.
- In the longer term, to fully realize H_2's potential benefits, and enable radical cuts in GHG emissions, it will be important to implement zero (or near-zero) emission H_2 supplies. Zero emission H2 supplies are generally more costly than today's fossil H2 technologies, and face technical, cost, security, and/or environmental issues.
- There are many uncertainties in the timing of a H2 economy, w.r.t. technical and economic progress, but also in how we as society value externalities. Even under optimistic scenarios, it will take several decades before use of H_2 vehicles can impact emissions on a global scale.
- While developing H2 vehicles over the next few decades, it will be important to develop zero emission H2 supply technologies (including enabling technologies like wind power, carbon sequestration, electrolysis...)

FINAL THOUGHTS

- H_2 and fuel-cell technologies, although high-risk and long-term, have a potentially very high payoff. Therefore, they deserve significant government support now, as “insurance,” to be ready in 15-20 years, if and when we need to deploy them widely.

- Consistent policies are needed to encourage use of cleaner transportation systems with lower carbon emissions and to move away from our almost exclusive dependence on crude oil-derived transportation fuels
- Low polluting, efficient ICEVs will be very important over the next few decades to address energy related problems. With continued development, H_2 could be poised to make major contributions to solving environmental and oil security concerns starting in 2nd quarter of this century.
- Comprehensive strategy: Encourage use of clean, efficient internal combustion engine vehicles in the near term, coupled with a longer term strategy of research, development and demonstration of H_2 and fuel cells.